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Literature Review of the Effects of Oil and Oil Spills on Arctic and North Temperate Intertidal and Shallow Subtidal Ecosystems

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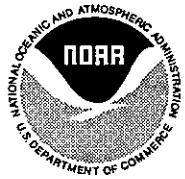

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NOTICE

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Introduction

This review of the effects of oil and oil spills on Arctic and temperate intertidal and shallow subtidal ecosystems was initiated following the *Exxon Valdez* oil spill in Prince William Sound, Alaska. This review updates the literature on oil spills because much of the literature on the effects of oil spills on marine communities has not been summarized in one publication. This report includes most of the currently published papers on the effects of oil spills on intertidal and shallow subtidal communities and also includes some of the unpublished reports on the effects of the *Exxon Valdez* oil spill on marine ecosystems.

One of the rationales for summarizing the current literature on oil spills is the role that the Hazardous Materials Response and Assessment Division (HAZMAT) of the National Oceanic and Atmospheric Administration (NOAA) provides following oil spills. One of the primary tasks that NOAA HAZMAT is responsible for is to provide scientific counsel and expertise to other agencies during emergencies such as oil spills. To obtain a better understanding of previous oil spills and the scientific studies that have been done following spills, a cooperative agreement was made between NOAA HAZMAT and the University of Washington Cooperative Fisheries Unit to provide an annotated review of cold-water oil spills.

The objectives of this report are to summarize pertinent literature on the effects of oil spills on Arctic, Antarctic (to a lesser extent), and north temperate intertidal and shallow subtidal community structure and to provide abstracts on studies following oil spills that have occurred in these "cold" waters. Effects of oil spills on biological communities are summarized by oil spill event. Initial references were found using the University of Washington Fisheries library CD-ROM database and oil spill-related literature with the abstracts was downloaded. In addition, personal libraries of the authors and NOAA personnel were used to supplement these references. Previous reviews for the Oil Spill Restoration Planning Office and the U.S. Environmental Protection Agency by Boland and Zedler (1992), Nur and Ainley (1992), Stewart et al. (1992), and Nevissi et al. (1993) were used extensively as well as a report by Auris Limited (1994) on criteria for optimizing oil spill cleanup operations. This report has updated and added references published since these reports and has included unpublished reports (for example the Final Report on the Comprehensive Assessment of Coastal Habitat done by the University of Alaska, 1993) and abstracts from scientific meetings such as the *Exxon Valdez* Oil Spill Symposium (1993) and the American Society for Testing and Materials (ASTM; 1993) meetings.

Acknowledgments

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Summary of Previous Oil Spills

Biological results from previous "cold water" oil spills are summarized below. A report that chronicled case histories of oil spills from 1967-1991 was used for some of the summary information on each incident (NOAA 1992).

Amoco Cadiz

The *Amoco Cadiz* oil spill occurred off the coast of Brittany, France on March 16, 1978, spilling about 1.62 million barrels (221,000 to 223,000 tons) of Arabian light crude, Iranian light crude, and Bunker C. About one-third of the oil came ashore and affected exposed and sheltered rocky shores, sand/gravel beaches, and estuarine marshes. Meiofauna were studied from 1978-1984, with two phases documented for the most abundant groups (Nematoda and Copepoda). An initial degradation phase resulted in lower abundance and diversity of the two groups (as well as in the Turbellaria) followed by a recovery phase in which abundance recovered to their former levels. The quick recovery of these meiofaunal groups was attributed to high reproduction rates, protection of brood, and adaptability to unsuitable habitats. Harpacticoid copepods were recommended as particularly suitable organisms to use as an indicator of ecological disturbance. Oysters were impacted by the spill for up to two years with oil residues remaining in the tissues even after two years; the initial oyster mortality from the spill was estimated at 9,000 tons. Fish did not appear to be impacted chemically by the spill. Benthic organisms in fine sediments were affected, particularly *Ampelisca* beds, some mollusks, and the sand dollar, *Echinocardium cordatum*. Certain polychaetes (especially species in rapidly colonizing Cirratulidae and Capitellidae families) showed increased abundance after the spill. Delayed effects of the spill on recruitment, growth, and mortality were observed three years after the spill; populations of several clam species exhibited unstable recruitment. Even after 8-10 years, amphipods had not recovered in sublittoral, sandy-mud, benthic communities.

References:
Anderson and Meade 1981; Atlas 1982; Baca et al. 1987; Badin and Boucher 1983; Bodin 1988; Bodin and Boucher 1981; Bodin and Boucher 1982; Bodin and LeMoal 1982; Bodin 1991; Boehm 1982; Cabioch 1980; Cabioch et al. 1980; Cabioch et al. 1981; Chasse 1978; Conan 1982; Courtot 1985; Dauvin 1982; Dauvin 1987; Dauvin and Gentil 1990; den Hartog and Jacobs 1980; Elkalm 1981; Gilfillan et al. 1987; Glemarec 1986; Glemarec and Hussenot 1982; Glemarec et al. 1982; Gourbault 1987; Gundlach et al. 1981; Jacobs 1980; Laubier 1980; Levasseur et al. 1981; Levasseur and Jory 1982; Malins 1982; Oudot et al. 1981; Renaud-Mornant and Gourbault 1980; Riaux-Gobin 1985; Seneca and Broome 1982; Winfrey and Ward 1981; Winfrey et al. 1982; Wolfe et al. 1981.

Antonio Gramsci

On February 27, 1979 about 5,000-6,000 tons of crude oil were discharged onto exposed rocky shores at Ventspils in the Baltic Sea, USSR. Short-term effects were mild in the upper intertidal in the *Cladophora* zone but more severe in the lower *Fucus* zone. Crustacean and molluscan meiofaunal densities were decreased by the spill, but long-term changes in macrofauna could not be linked to the spill.

Reference:
Bonsdorff 1981.

Arco Anchorage

The tanker *Arco Anchorage* ran aground in Port Angeles harbor, Washington on December 21, 1985. It was carrying 814,000 barrels of Alaska North Slope crude oil. Only 5,690 barrels were lost, affecting gravel, sand, and exposed rocky shores. Sampling of infauna was done and biomass, density, and number of species was significantly higher over time at the oiled stations. No increase was seen at the reference sites. Samples of sea urchins showed no contamination of the urchins.

References:
Blaylock and Houghton 1989; Lindstedt-Siva et al. 1987; Mancini et al. 1989

Argo Merchant

The tank *Argo Merchant* went aground on Nantucket Shoals, Massachusetts on December 15, 1976 carrying 183,000 barrels of No. 6 fuel oil and cutter stock. By December 21, the vessel had broken in two, spilling about 36,000 barrels. The prevailing currents carried most of the oil away from shorelines, raising concerns about fish resources around the Georges Bank. Oil contamination was seen in fish, shellfish, ichthyoplankton, and zooplankton samples. Declines in sandlance were seen, but could not be associated with the spill. Benthic animals were sampled two months and seven months after the spill and minor effects of oiling were noted on the macrobenthos.

References:
Brown and Cooper 1978; Ruhnhold 1978.

Arrow

The tanker *Arrow* went aground in Chedabucto Bay, Nova Scotia, Canada on February 4, 1970. It broke into two on February 12, spilling 77,000 to 85,000 barrels of Bunker C oil, impacting salt marshes, sand and gravel beaches, and exposed rocky shorelines. Residues of Bunker C oil were seen six years after the spill, especially in the upper intertidal and sublittoral sediments. The upper intertidal had a sediment mixture of "pavement" and oil, while the sublittoral sediments contained hydrocarbons of petroleum origin. Long-term effects were seen in populations of *Fucus spiralis* on rocky shores and *Mya arenaria* and *Spartina alterniflora* in lagoons. Recolonization proceeded from lower to upper intertidal areas and delayed recolonization appeared to be related to long-term toxicity. Populations of the soft-shell clam, *Mya arenaria*, were studied in an oiled lagoon and a reference lagoon. Oiled populations were lower in numbers with fewer mature adults, a lag of one to two years in growth, lower shell growth rate, and a reduced carbon flux. It was concluded that recovery potential of clams from the oiled lagoons was low and remained under stress six years post-spill. *Littorina littorea* showed significantly lower length and weight values at control stations than at oiled stations. A recommendation was made to remove only heavy oil deposits mechanically in the intertidal, with the remainder left to degrade naturally.

References:
Gilfillan and Vandermeulen 1978; Keizer et al. 1978; Thomas 1973; Thomas 1977; Thomas 1978; Vandermeulen 1977.

Baffin Island Oil Spill (BIOS)

The Baffin Island Oil Spill Project was an experimental release of oil at Cape Hatt, northern Baffin Island, Canada. Four shallow bays were used for the experiment with about 15 cubic meters ($m^{3)}$ of Lagomedio crude oil released on the surface of one bay and 15 m^3 of dispersed oil (10 Lagemedio:1

Corexit 9527) released underwater in three other bays. Exposure of oil in the three bays with dispersed oil varied from a light exposure to a very heavy exposure. Biological sampling of infauna, epibenthos, and macroalgae was done during August and September from 1980 to 1983. Filter-feeding invertebrates took up oil rapidly from the water column while deposit-feeders took up oil less rapidly from the sediment. All species depurated oil after one year, but deposit feeders continued to uptake oil from contaminated sediments two years following the spill. The dispersed oil release caused immediate adverse effects on infauna, including narcosis, emergence of animals from substratum, and death, but no mass mortality of benthos was seen. No prolonged effects of oil on infauna was seen, except for effects on populations of *Serripes groenlandicus* (decrease in condition from prolonged exposure), *Macoma calcarea* (disruption of seasonal changes in condition), and *Spio* sp. (failure or retardation of natural population increase). Epibenthic animal densities were not affected by the releases which was probably due to the short time that the dispersed oil was in the water column and the relatively low levels of oil in the sediments. No oil effects were seen on biomass, number of species, and reproductive condition of dominant understory algae at 3 m depth, which was partly attributed to lack of effects on herbivores and vegetative mode of reproduction in the dominant algal species.

References:
Blackall and Sergy 1981; Blackall and Sergy 1983; Boehm et al. 1985; Bunch 1987; Bunch et al. 1981; Cretney et al. 1987; Cross and Thomson 1987; Cross et al. 1987a; Cross et al. 1987b; Humphrey et al. 1987; Mageau et al. 1987; Sergy 1985.

Bahia Paraiso

The *Bahia Paraiso* ran aground near Arthur Harbor, Antarctica on January 28, 1989 spilling over 3700 barrels of diesel fuel Arctic (DFA) onto exposed rocky shores. Tissues of limpets, macroalgae, clams, bottom feeding fish, and birds collected immediately after the spill were contaminated with DFA. A study of intertidal limpet populations showed a reduction of 50 percent of the population after the spill with only partial recovery one year later.

References:
Kennicutt et al. 1992a; Kennicutt et al. 1992b.

Blue Magpie

On November 19, 1983, about 284,000 liters of Bunker C and diesel fuel were spilled at the mouth of Yaquina Bay, central Oregon following the wreck of the freighter *Blue Magpie*. Oil was deposited on subtidal benthic habitats in the estuary. Bioassays were done on the amphipod *Rhepoxynius abronius* which showed that the oil globules were not acutely toxic except at concentrations of greater than 1 part per thousand (ppt).

Reference:
Kemp et al. 1986.

Bouchard #65

The barge *Bouchard #65* ran aground in Buzzards Bay, Massachusetts on January 28, 1977 spilling 1,932 barrels of No. 2 fuel oil. Much of the oil pooled within rafts of drifting ice in the bay and was removed. Two weeks following the spill, qualitative sampling of dead and moribund invertebrates

was done in tide pools 5 km from the spill. A total of 4,360 invertebrates of 105 species and two fish species were collected. Effects of the oil on salt marsh plants were also reported.

Reference:
Hampson and Moul 1978.

Ekofisk Bravo oil field

A production platform in the Norwegian Ekofisk field had an oil and natural gas blowout on April 22, 1977. A total of 202,381 barrels of Ekofisk crude oil was discharged into the North Sea before the well was capped on April 30, 1977. Changes in benthic fauna in response to oiling included increased abundance of some species and changes in the presence and absence of some rare species. Opportunistic species dominated under severe pollution.

Reference:
Mackie et al. 1978.

Eleni V

The tanker *Eleni V* lost 52,500 barrels (about 5,000 tons) of heavy fuel oil on May 6, 1978 following a collision with the vessel *Roseline* in fog off the southeast coast of England. Oil was washed ashore onto sand/gravel beaches on English and Dutch coastlines. The spill affected shellfish areas and recreational beaches. Hydrocarbon concentrations of water and mussel tissue returned to background levels 300 to 400 days following the spill. Growth of *Fucus* was unaffected and barnacles survived where they were not completely smothered.

Reference:
Blackman and Law 1981.

Ella Hewirt

The trawler *Ella Hewirt* sank in Church Bay, Rathlin Island, United Kingdom in November 1962. Small quantities of bunker oil continued to leak from the vessel from 1962 to 1978 when the vessel was destroyed with controlled explosions resulting in about 170 tons of oil washing ashore in Church Bay. Transects were sampled in May 1979 and November 1980 in unoiled and oiled areas. Abundances of invertebrates and algae were similar in both areas except the sea anemone, *Actinia equina*, which was abundant in the unoiled area and rare at the oiled area. By November 1980 abundances were similar and it was concluded that recovery from the spill had occurred.

Reference:
Flower 1983.

Esso Bernicia

The *Esso Bernicia* spilled 8000 barrels of Bunker C oil in December 1978 near Sullom Voe Oil Terminal, Scotland. About 100 miles of rocky, cobble, and gravel shoreline were heavily oiled. Oiled shorelines were surveyed from 1979 to 1987 (except 1982 and 1983). Areas accessible to heavy equipment were stripped of oiled rock, cobble, and gravel or were hand-cleaned. Areas inaccessible were not cleaned. Mechanical cleaning resulted in complete removal of the intertidal communities. After one year the biological communities in the rocky intertidal returned to near normal conditions

in areas that were not mechanically cleaned. In contrast, the areas that were mechanically cleaned had not fully recovered nine years following the spill. It was concluded that physical stabilization and biological recovery would take decades.

Reference:
Rolan and Gallagher 1991.

Exxon Valdez

The oil tanker *Exxon Valdez* ran aground on Bligh Reef, Prince William Sound, Alaska on March 24, 1989 spilling 240,500 barrels (10.8 to 11.6 million gallons) of Prudhoe Bay crude oil. The 1,100 miles of shorelines impacted included exposed and sheltered rocky shores, coarse gravel beaches, mixed sediment beaches, boulder/cobble beaches, and vertical rocky shores. Natural Resource Damage Assessment studies were done by Exxon and the University of Alaska. NOAA's Hazardous Materials Response and Assessment Division conducted studies to evaluate the effects of hot-water, high-pressure washing on intertidal communities. The Exxon studies relied on a "sediment quality triad" approach for pollutant impact assessment. Chemistry results showed that oil removal was rapid due to natural processes and the cleanup efforts. Toxicological results indicated that toxic effects of the oil were limited to the first few months to one year following the spill. It was concluded that the weathered oil had a negligible effect on the environment compared to other ongoing stresses in the sound and that complete recovery of the environment should have taken place within a few years after the spill. The University of Alaska studies showed that the spill had serious and long-lasting effects on intertidal algae. Biomass and percent cover were lower on oiled sites compared to unoiled sites. Effects on *Fucus* reproduction were also seen at oiled sites. Recovery of the intertidal zone has proceeded at varying rates depending on what habitat and zone was affected. Trends in invertebrate numbers showed that organisms at sheltered and exposed rocky habitats were in a state of recovery by 1991. However, trends at coarse textured and estuarine habitats showed lower diversity and richness at oiled sites, which indicated that these habitats were not recovering. Although intertidal communities showed widespread impact from the oiling and cleanup, algae, invertebrates, and intertidal fishes showed recovery to some extent and full recovery of the intertidal is expected. Results from the NOAA studies on epibiota showed that some treated rocky beaches were stripped of flora and fauna at mid- and upper intertidal elevations and showed relatively little colonization by mid summer 1990. On other oiled rocky beaches that received less severe or no treatment, the majority of the community dominants remained in place and significant recolonization was underway. NOAA concluded that hydrocarbon contamination and high pressure, hot-water treatment each caused major adverse impacts to the intertidal biota of western Prince William Sound, but that effects of the treatment predominated. Other biological studies have shown that *Fucus* at upper intertidal areas have been very slow to recover to pre-spill conditions, probably due to grazing pressure and loss of the protective canopy for germlings.

References:
Babcock et al. 1993; Dean and Jewett 1993; Dean et al. 1993; DeVogalaere and Foster 1994; Driskell et al. 1993; Duncan et al. 1993; Ebert et al. 1993; Fleeger et al. 1993; Foster et al. 1990; Gilfillan et al. 1993; Highsmith et al. 1993; Hooten and Highsmith 1993a; Hooten and Highsmith 1993b; Houghton et al. 1991a; Houghton et al. 1991b; Houghton et al. 1993a; Houghton et al. 1993b; Houghton et al. 1993c; Jewett and Dean 1993; Jewett et al. 1993; Juday and Foster 1990; Koons and Jahns 1992; Kvenvolden et al. 1993; Lees et al. 1993; Maki 1991; Mearns and Shigenaka 1993; Rounds et al. 1993; Shigenaka and Henry 1993; Short and Rounds 1993; Stekoll et al. 1993a; Stekoll et al. 1993b; Stoker et al. 1993; Teal 1991; University of Alaska 1993; van Tamelen and Stekoll 1993; Wolfe et al. 1994.

Florida

On September 29, 1969, the barge *Florida* spilled 175,000 gallons of No. 2 fuel oil, which spread into salt marshes in Buzzards Bay, Massachusetts. A study on the marine estuarine benthos was done along an onshore-offshore gradient of pollution. Densities and species composition remained stable temporally at the unoiled and lightly oiled stations, but fluctuated with high changes at the heavily oiled stations. In 1970, the opportunistic polychaete species, *Capitella capitata*, colonized the disturbed areas (at an oiled station, 99 percent of the individuals found were *Capitella*). After another year, abundance of *Capitella* dropped to almost zero. Tissue contamination in the fish, *Fundulus*, was almost at zero after one year, but the crab *Uca pugnax* remained heavily contaminated for at least four years. High oil in sediments resulted in reduced ratio of female to male *Uca*, reduced juvenile settlement, heavy overwinter mortality, incorporation of oil in body tissues, locomotion impairment, and abnormal burrow construction. Five years after the spill, effects on biota were still detected, and partially degraded No. 2 fuel oil was still present in sediments in the estuary. Sediments were resampled 20 years after the spill and analyzed for fuel oil hydrocarbons. Trace concentrations of weathered and biodegraded fuel oil aromatic hydrocarbons and cycloalkanes were found which appeared to induce cytochrome P4501A in *Fundulus heteroclitus*.

References:
Burns and Teal 1979; Krebs and Burns 1977; Michael et al. 1975; Sanders 1978; Sanders et al. 1980; Teal et al. 1992.

General M.C. Meigs

The troopship *General M.C. Meigs* grounded on the open Washington coast on January 6, 1972, spilling 440,000 liters of Navy Special Fuel oil into exposed rocky intertidal areas. Sites from the upper to low intertidal were sampled for five years following the spill. Abnormal and dead urchins were seen immediately after the spill. Algal species were seen with bleached thalli and frond loss in oiled areas, but not in unoiled areas. After five years, it was concluded that the community balance in the intertidal was not markedly altered.

References:
Clark et al. 1973; Clark et al. 1975; Clark et al. 1978.

Golden Gate Bridge spill

Two Standard Oil tankers collided under the Golden Gate Bridge, San Francisco, California on January 18, 1971. About 840,000 gallons of Bunker C fuel oil were spilled and affected moderately exposed rocky shores and rocky reefs. Studies in the intertidal were done and an estimated 4.2 to 7.5 million intertidal invertebrates, primarily barnacles (an estimated 35 percent of the population present), were smothered by the oil. Many crabs, chitons, mussels, limpets, and anemones also were killed by the oil. The first colonizers observed were littorine snails, *Littorina scutulata* in April 1971. By summer of 1971, recruitment of marine life was good, especially in marine algae such as the filamentous green algae, *Urospora penicilliformis*. By summer 1972, filamentous green algae density was reduced to 25 percent of the 1971 density, probably due to a large recruitment of limpets. In summer 1973, little filamentous green algae was left and a large recruitment of barnacles settled onto bare surfaces. After five years of observations (1976) densities were observed to have

significantly increased showing no long-lasting effects of the oil on populations of marine invertebrates within the transect sites.

References:
Chan 1975; Chan 1977.

Irini

On October 6, 1970 the tanker *Irini* ran aground in the South Stockholm Archipelago, Baltic Bay losing about 1000 tons of medium and heavy fuel oil. Sheltered rocky shores with sandy beaches were affected. Most of the littoral fauna of a small bay in Gastviken was killed. Recruitment of the *Fucus vesiculosus* community was observed over a five-year period. Mean number of individuals of all species rose from 280 to 1,000 per 100 grams of *Fucus* dry weight from 1971 to 1976. Mussels, amphipods, isopods, and gastropods all increased in number over that time period. Chironomid larvae were the only group with decreased densities during the time period sampled.

Reference:
Notini 1978.

Long Cove, Searsport, Maine

An oil spill of No. 2 fuel oil and JP 5 jet fuel into Long Cove, Searsport, Maine began on March 16, 1971 and continued until at least June 30, 1971. Concentrations measuring greater than 250 parts per million (ppm) were found in intertidal sediments resulting in mortalities of soft-shelled clams. Successive year classes of clams were killed until at least 1976.

On August 19, 1981 experimental test spills of Murban crude oil were made at Long Cove, Searsport, Maine to examine the effects of dispersants and undispersed oil on benthic communities. No significant effects of dispersed oil were seen on biological communities; undispersed oil was incorporated into sediments and animal tissues.

References:
Dow 1975; Dow and Hurst 1975; Dow 1978; Gilfillan et al. 1983; Gilfillan et al. 1985; Page et al. 1983.

Metula

The Very Large Crude Carrier *Metula* ran aground on Satellite Bank, near the western end of First Narrows in the Strait of Magellan, Chile on August 9, 1974. Light Arabian crude oil and Bunker C oil (about 398,000 barrels) were spilled onto sand and gravel beaches, exposed tidal flats, and salt marshes. Dark brown mousse was deposited above the spring high-tide line and in the marshes while a lighter mousse ended up in the intertidal zone. Sheltered tidal flats had a thick asphalt-like covering which persisted over 12 years without any significant weathering. The heavily oiled salt marsh showed dead vegetation (*Salicornia ambigua* and *Suaeda argentinensis*) over five years later while the less heavily oiled marsh showed signs of recovery after 5 months. Clearing of thick deposits of oil in intertidal areas was done in 1976 and recolonized by *Enteromorpha intestinalis*, *Ulva lactuca*, and *U. flacca*. However, invertebrates were just starting to recolonize intertidal areas by 1976. In 1990-1991 (16 to 17 years post-spill), mousse deposits were still visible at the surface. Conclusions made about the spill include the observation that in the absence of clean-up, natural recovery could be expected to take three to five years in rocky shores and salt marshes. It was also concluded that cleaning would not reduce natural recovery due to the fact that natural recovery

processes of immigration, settlement, and growth could not be accelerated (i.e. with respect to shore organisms on rocky shores and salt marshes, cleanup methods do not significantly promote ecological recovery).

Reference:
Guzman and Campodonico 1981.

M/V Lee Wang Sin

On December 25, 1979, about 2381 to 7143 barrels of heavy bunker fuel oil and diesel oil were spilled following the wreck of the *M/V Lee Wang Sin* off the southern edge of the Alaska panhandle. Over 350 miles of shoreline were contaminated, placing shellfish, fish, bird, and mammal resources at risk.

References:
Bayliss and Spoltman 1981.

Nella Dan

The Australian supply ship *Nella Dan* ran aground at Macquarie Island on December 3, 1987. About 270,000 liters of light marine diesel was released into the sea. After the spill, thousands of invertebrates were washed up dead along 2 km of the shore. One year after the spill, studies were made at 2 oiled and 2 unoiled locations. Densities of invertebrates were reduced in lower littoral and sublittoral oiled areas, while algal cover and invertebrate densities were similar at oiled and control locations.

References:
Pople et al. 1990.

Nestucca

The barge *Nestucca* ruptured off the mouth of Grays Harbor, Washington in December 1988, spilling 230,000 gallons (5,500 barrels) of Bunker C fuel oil. Subtidal benthic surveys were done by divers in oiled and unoiled sites at Grays Harbor and in the Olympic National Park. No evidence of subtidal oil was found and no sediment samples collected showed oil or grease above detection limits. No tissue contamination of shellfish was seen nor were any fisheries closed.

References:
Carney and Kvitek 1990; Strand et al. 1992.

Santa Barbara Well Blowout

The Union Oil Company well number 21 under Platform A blew out on January 28, 1969. A total of 100,000 barrels of California crude oil spilled into the sea about 5.5 miles southeast of Santa Barbara, California, impacting seawalls, sand/gravel beaches, and exposed rocky shores. Most of the resulting damage to intertidal areas was to eelgrass communities and barnacles. Up to 100 percent of *Phyllospadix* at heavily oiled stations was killed. Upper intertidal algae were also covered with oil and damaged. Highest mortalities of invertebrates occurred with the barnacle, *Chthamalus fissus*. Cleanup methods resulted in additional damage on rocky and sandy shores.

References:
Davis and Spies 1980; Foster et al. 1971a; Foster et al. 1971b; Foster and Holmes 1977; Harger and Straughan 1972; Straughan 1971.

Seto Inland Sea oil spill

A fuel oil tank at the Mizushima Refinery of Mitsubishi Oil ruptured on December 18, 1974, spilling 50,000 barrels of fuel oil into the Seto Inland Sea. Marine life recovered by 1975 and the effect of the oil on the marine environment was not as bad as initially suspected since much of the oil was quickly recovered.

Reference:
Hiyama 1979.

Tanio

The tanker *Tanio* broke in two on March 7, 1980 off the coast of Brittany, France, spilling 98,955 barrels of No. 6 fuel oil. Sand/gravel beaches, tidal flats, and marshes were impacted by the spill. These areas had previously been impacted by spills by the *Torrey Canyon* in 1967 and *Amoco Cadiz* in 1978. Shellfish were lost from the Roscoff, Kefissien, and Loquivy sur la Mer areas with Loquivy losing about 60 tons of crabs, clams, and periwinkles.

References:
Bodennec et al. 1983; Gundlach et al. 1981.

Tenyo Maru

The fish processing vessel *Tenyo Maru* collided with the Chinese freighter *Tuo Hai* about 20 miles west of Cape Flattery, Washington and 20 miles south of Vancouver Island, British Columbia, Canada on July 22, 1991. The *Tenyo Maru* sunk in 350 feet of water, carrying 6500 barrels of intermediate fuel oil and 2166 barrels of diesel oil. Oil washed ashore along the exposed coastline of Washington. Lab studies were done using the bull kelp, *Nereocystis luetkeana*. Based on photosynthetic rate studies, whole-plant experiments, and blade growth-rate measurements, the relative ranking of petroleum-treatment effects to kelp were weathered diesel> unweathered IFO> unweathered diesel> weathered IFO> unweathered crude> weathered crude.

Reference:
Thom et al. 1993.

Torrey Canyon

On March 18, 1967 the tanker *Torrey Canyon* grounded on Pollard Rock on Seven Stones Reef off Lands End, England. The whole cargo of 860,000 barrels of Kuwait crude oil was lost into the sea affecting sand and gravel beaches and exposed rocky shores. This was the first spill to draw the attention to the dangers of using dispersants. About 10,000 tons of dispersants were used during cleaning operations. More damage was done ecologically in areas that used dispersants than in areas that did not use dispersants. Many limpets and barnacles were killed due to the toxicity of the dispersant. The general recolonization sequence showed first a greening of shores by *Enteromorpha* and *Ulva* followed by a heavy settlement and growth of *Fucus* leading to loss of surviving barnacles. Next limpets and other grazers settled with eventual removal or loss of brown algae. The final phases were a reduction in limpet populations and a resettlement of barnacles.

Lightly oiled areas with light dispersant treatment showed the most complete return to normal conditions after about five to eight years while heavily oiled areas that received repeated treatments of dispersants have taken nine to ten years and had not returned to normal conditions. One of the main conclusions reached in biological studies was the importance of biological interactions in controlling the structure of intertidal communities. It was also found that pollution disturbances affected the herbivores more than plants.

References:
Butler, M.J.A. and F. Berkes 1972; Southward and Southward 1978.

Tsesis

About 1,000 tons of medium-grade fuel oil was discharged from the *Tsesis* on October 26, 1977. The fuel oil affected sheltered rocky shores near the archipelago south of Stockholm, Sweden, in the Baltic Sea. *Mytilus* populations were heavily impacted by the spill. Sediment trap samples taken after the spill showed that large quantities of weathered oil were available for uptake by benthos. Within six days the amphipod *Pontoporeia* and the polychaete *Harmothoe sarsi* showed reductions to less than five percent of pre-spill biomasses at the most impacted station. The clam, *Macoma balthica*, was more resistant to the oil, but showed heavy tissue burdens of about 2000 micrograms per gram (µg/g) dry weight total hydrocarbons. The first signs of recovery were in the second summer following the spill, but *Pontoporeia* biomass was still depressed in the most heavily impacted area three years after the spill. Full recovery was estimated to take at least five years to a decade or more.

References:
Boehm et al. 1982; Elmgren et al. 1983; Linden et al. 1979.

Urquiola

The tank vessel *Urquiola* began to leak light Arabian crude oil and Bunker fuel oil after striking a submerged object off La Coruña, Spain on May 12, 1976. About 733,000 barrels of oil affected sand and gravel beaches, exposed rocky shores, tidal mudflats, and marshes. In addition, over 2,000 tons of chemical dispersants were applied to the spill. High mortalities of bivalves and gastropods occurred in the top 15 centimeters of sediment. The dominant bivalve, *Cerastoderma edule*, population was reduced by over 70 percent and other bivalves such as *Scrobicularia plano*, *Tellina tenuis*, and *Venerupis decussata* were reduced 10 to 30 percent. Due to the slow growth of these bivalves, it was expected that recovery of these populations would also be slow. In the marsh area, cockles and sandworms were immediately affected but *Spartina* and shore crabs, *Carcinus maenas*, did not suffer much damage.

Reference:
Gundlach et al. 1977.

World Prodigy

On June 23, 1989 the Greek tank ship *World Prodigy* ran aground on Brenton Reef near Narragansett Bay, Rhode Island. About 6,900 barrels of No. 2 heating oil was released and affected exposed seawalls, piers, exposed rocky shores, and coarse sand and gravel beaches. A study was done on the effects of the oil on subtidal kelps *Laminaria saccharina* and *L. digitata*. Kelp

condition, growth rates, and pigment acclimation were compared with pre-spill information collected from the same sites in 1984-1987. No evidence was found that the oil adversely affected the kelps.

Reference:
Peckol et al. 1990.

References Cited Not in Annotated Bibliography

Auris Limited. 1994. *Scientific Criteria for Optimising Oil Spill Clean-up Operations and Effort.* Final Rpt; May 1994. London: British Petroleum Plc, Elf Akamiljo, Exxon Research & Engineering Company, Marine Pollution Control Unit, Marine Spill Response Corporation, Shell International Petroleum Maatschappij B.V., The International Tanker Owners Pollution Federation Ltd., and The Steamship Mutual Underwriters Association Ltd.

Boland, J. and J.B. Zedler. 1992. *Comprehensive review and critical synthesis of the literature on recovery of ecosystems following disturbances: marine invertebrate communities.* Anchorage: Oil Spill Restoration Planning Office and EPA. 121 pp.

Exxon Valdez Oil Spill Trustee Council, University of Alaska Sea Grant College Program, and American Fisheries Society, Alaska Chapter. 1993. *Exxon Valdez* Oil Spill Symposium Program and Abstracts. February 2-5, 1993, Anchorage, Alaska. 356 pp.

NOAA. 1992. *Oil Spill Case Histories 1967-1991.* Summaries of Significant U.S. and International Spills. Report No. HMRAD 92-11. Springfield, Virginia: National Technical Information Service.

Nevissi, A.E., T.H. Sibley, and C. Chang. 1993. *Comprehensive review and critical synthesis of the literature on recovery of ecosystems following disturbance (fish and shellfish).* Anchorage: Oil Spill Restoration Planning Office and EPA.

Nur, N. and Ainley, D.G. 1992. *Comprehensive review and critical synthesis of the literature on recovery of marine bird populations from environmental perturbations.* Anchorage: Oil Spill Restoration Planning Office and EPA. 38 pp.

Stewart, B.S., P.K. Yochem, and J.R. Jehl Jr. 1992. *Review and critical synthesis of the literature on recovery of ecosystems following man-induced and natural-phenomena-related disturbances: harbor seals and killer whales.* Anchorage: Oil Spill Restoration Planning Office and EPA. 81 pp.

University of Alaska. 1993 Comprehensive Assessment of Coastal Habitat Final Status Report; Volume I; Coastal Habitat Study No. 1A. Fairbanks: School of Fisheries and Ocean Sciences. 488 pp.

Alongi, D.M., D.F. Boesch, and R.J. Diaz (1983)
Colonization of meiobenthos in oil-contaminated subtidal sands in the lower Chesapeake Bay

Mar. Biol. 72: 325-335

ABSTRACT
In-situ manipulative experiments were conducted over a three-month period (May-August 1980) to examine the rate at which meiobenthos colonizes oiled and untreated azoic fine sands at a shallow subtidal site in the lower York River, Virginia. Three concentrations of fresh Prudhoe Bay crude oil were added to sediments: 100, 2500 and 10,000 mg oil kg^{-1} dry weight sediment. Untreated azoic and natural sediments served as controls. Within 16 days meiofauna densities in all treatments were comparable to natural populations in surface oxidized sediments, but densities fluctuated greatly during the remainder of the sampling period. Nematodes slowly colonized the subsurface anoxic sediments below the redox potential discontinuity (RPD); some less common species did not significantly recover below the RPD in the two more heavily oiled treatments. Analysis of nematode community composition by reciprocal averaging ordination and numerical classification revealed generally lower abundance's, but no distinct differences, in species composition in the oiled substrates as compared to untreated and natural community controls. Ordination of sequential samples suggested that the nematode species assemblages in the untreated controls fully recovered from these small-scale disturbances by 90 days. Life history characteristics and frequent tidal transport combine to make estuarine meiobenthos highly resilient following disturbance. Contrary to prior recolonization studies, a successional sequence was found for the colonizing nematodes which may be analogous to models of macrobenthic colonization (e.g., McCall 1975). The comesomatid nematode *Sabatieria pulchra*, which is frequently dominant in polluted sediments, colonized relatively late in the experiment. Consequently, stress resistance and resilience may not be as coincident in meiofauna as in macrofauna because of differences in factors affecting their dispersal.

Anderson, J. W., J.M. Neff, B.A. Cox, H.E. Tatem, and G.M. Hightower (1978)
Characterization of dispersions and water-soluble extracts of crude and refined oils and their toxicity to estuarine crustaceans and fish

Mar. Biol. 27: 75-88

ABSTRACT
The quantitative hydrocarbon composition and behavior in seawater of water-soluble fractions (WSF) and oil-in-water dispersions (OWD) of four oils was investigated. Two crude oils, South Louisiana crude and Kuwait crude, and two refined oils, No. 2 fuel oil and bunker C residual oil, were used in these investigations. The WSFs of the crude oils had higher total oil-hydrocarbon concentrations and were richer in light aliphatics and single-ring aromatics than were the WSFs of the refined oils. The WSFs of the refined contained significantly higher concentrations on naphthalenes than did those of the crudes. The hydrocarbon composition of the aqueous phase of OWDs closely resembled that of the parent oils. Gentle aeration of the OWDs resulted in a loss of 80 to 90 percent of the aqueous hydrocarbons in 24 hours. Alkanes disappeared from the dispersions more rapidly than aromatics. The WSFs and OWDs of the refined oils were considerably more toxic to the 6 test species than were those of the crude oils. The test species can be ranked

according to increasing sensitivity to oil as follows: *Cyprinidon variegatus, Menidia beryllina, Fundulus similus, Penaeus aztecus* postlarvae, *Palaemonetes pugio* and *Mysidopsis almyra*. The results of this investigation are discussed in relation to the potential impacts of oil spills on the marine and estuarine environment.

Anderson, J. W., R.G. Riley, and R.M. Bean (1978)
Recruitment of benthic animals as a function of petroleum hydrocarbon concentrations in the sediment

J. Fish. Res. Bd. Can. 35: 776-790

ABSTRACT
Three separate field installations, consisting of clean and oiled sediment in fiberglass trays, were placed in the intertidal zone of Sequim Bay, Washington, to determine rates of hydrocarbon depuration and recruitment of benthic organisms. Detailed chemical analysis, with glass capillary gas chromatography and gas chromatography-mass spectroscopy, were conducted such that individual compounds and hydrocarbon classes associated with the sediment after varying periods of field depuration could be quantified. Depuration rates of hydrocarbon types in sediment receiving oil on the surface (installations I and II) decreased in the order of saturates, methylnaphthalenes, and methylphenanthrenes. Rates of specific compound and hydrocarbon class depuration followed the general pattern exhibited by total hydrocarbons (infrared analyses). In a period of 100 d, total hydrocarbons in surface-oiled, coarse sediments (I and II) decreased by 82 to 88 percent, while the amount in the finer substrate with mixed in oil (III) only decreased by about 21 percent and remained quite stable up to 290 d. The ratios of nC_{17}/pristane and nC_{18}/phytane were monitored for installations I and III (oiled mixed with sediment). The ratios remained constant for a period of four to six months and then dropped sharply, suggesting the presence of oil biodegradation. These results are discussed in relation to physical and chemical processes acting on the oil-contaminated sediments. Initial concentrations of oil in sediments upon field emplacement were about 5,000-6,000 ppm in installations I and II and approximately 700 ppm in installation II. At these concentrations, no substantial inhibition of recruitment by benthic organisms was observed. Future sampling of these populations and further analyses of all benthic organisms may provide a better evaluation of effects of specific hydrocarbon components in sediments on benthic recruitment. These results are discussed in light of oil spill studies and other field experiments.

Anderson, J. W., S.L. Kiesser, and J.W. Blaylock (1980)
Cumulative effect of petroleum hydrocarbons on marine crustaceans during constant exposure

Rapports & Proces-Verbaux Reunions Conseil Int Explor. Mer. 179:62-70. (Paper presented at ICES Workshop Biological Effects Marine Pollution and Problems of Monitoring, Beaufort, N.C. 1979).

ABSTRACT
A constant hydrocarbon exposure system was used to obtain mortality and hydrocarbon accumulation data for three species of marine crustaceans. Extracts of Prudhoe Bay crude oil containing 98 percent aromatics, which were largely (94 percent) monoaromatics, produced 50 percent mortality in mysids (*Neomysis awatschensis*), and two shrimp species (*Hippolyte clarkii* and *Pandalus danae*) in periods of 0-5 to 9 days at concentrations ranging from 0.36 to 6-35 ppm total hydrocarbons. The product of time (in days) and LC_{50} concentration (in ppm) was used as a "toxicity index" for a given species. These values (in ppm-days), plotted on a log-log regression, produce a linear (r=0.86-0.92) relationship with a common slope of -1.27. The formula, X1 d.27Y = C,

described the sensitivities of the three species, where C varied from 2-6 for mysids to 8-14 for *Hippolyte*. This relationship allows prediction of mortality over intervals likely associated with oil spills.

Anderson, J.W., S.L. Riesser, D.L. McQuerry, and G.W. Fellingham (1985)
Effects of oil and chemically dispersed oil in sediments on clams

Proceedings of the 1985 Oil Spill Conference, pp. 349-353

ABSTRACT
Several field experiments with natural sediments in the intertidal zone were conducted over a two-year period to compare the effects of Prudhoe Bay crude oil and this same oil dispersed with Corexit 9527 (1 part Corexit to ten parts oil) on the clams, *Protothaca staminea* and *Macoma inquinata*. Exposure periods ranged from one to six months. In a one-month exposure to about 2,000 ppm total oil in sediments, survival of *P. staminea* was two to three times greater than that of *M. inquinata*, and both species exhibited lower tolerance to oil alone than dispersed oil at the same concentration. However, uptake of naphthalenes and phenanthrenes by *M. inquinata* was greater from sediments mixed with dispersed oil than oil alone. Dispersed oil in this 30-day exposure also produced a decrease (compared to field controls) in the concentration of some of the free amino acids in the tissues of *M. inquinata*. Four- and six-month field exposures of small *P. staminea* to sediment containing oil or dispersed oil (about 2,000 ppm) reduced growth in both treatments (four-month exposure) or the chemically dispersed oil treatment (six-month exposure). In the latter experiment initial petroleum concentrations in the surface sediments (top three centimeters) were higher (about 3,000 ppm) for the dispersed oil than for oil alone. Surface layers in both conditions were free of contamination (down to 6 cm) after six months.

Anderson, R.C. and N.F. Meade (1981)

Measuring the economic impacts of the *Amoco Cadiz* oil spill: overview and status report. (In French)

Amoco Cadiz: Fates and Effects of the Oil Spill. Proceedings of the International Symposium. Centre Oceanologique de Bretagne, Brest, November 19-22, 1979, pp. 849-854

ABSTRACT
NOAA and several French and American universities and research institutions sponsored an economic damage assessment of the *Amoco Cadiz* oil spill to develop and test a series of methodologies for measuring the most significant economic costs associated with major oil spills. Categories for which cost estimated were made include: cleanup operations; market-valued social costs such as commercial fishing, kelp production, tourism and aquaculture; and non-market social costs such as recreation and esthetics. No attempt was made to establish economic values for damages to wildlife except to the extent that it was indirectly included in the above categories. This paper describes the methodologies used to establish the economic damages in each of the above categories and discusses some practical problems that were encountered in carrying out the assessments.

Anon, P. (1987)
Oil spill into the marine ecosystem. (in Spanish). Original title: (Derrame de petroleo en el ecosistema marino)

Pesca 48:33-36.

ABSTRACT
The effects of the spill of 16,800 barrels of crude oil off Conchan (Peru) beaches were studied. Results showed that in sandy beaches the oil affected the benthic and intertidal communities, while in the rocky beaches, oil had a continuum effect on the algae. The oil remaining in the open sea 18 days after the spill affected the artisanal fishing. Mollusks, crustaceans, and echinoderms showed oil traces ranging from 0.10-0.20 micrograms per organism.

Appeldoorn, R. S. (1981)
Response of soft-shell clam (*Mya arenaria*) growth to onset and abatement of pollution

J. Shellfish Res. 1:41-49

ABSTRACT
Length-frequency analysis was used to generate age-length curves for six populations of the soft-shell clam *Mya arenaria* exposed to a sudden pollution event. Five populations were each subjected to a single oil spill. A sixth population was subjected to the onset and subsequent abatement of the effluent from heavy metals mining. With one exception, the onset of pollution was accompanied by a noticeable break in the age-length curve representing a decrease in growth rate following the event. At the site where abatement occurred, the age-length curve showed a second break indicating resumption of near-normal growth. An attempt is made to relate severity and persistence of the pollution effect on growth to the degree of deflection in the age-length curve. A method that estimates prepollution growth is presented and applied to two populations.

Armstrong, D.A., P.A. Dinnell, J.M. Orensanz, J.L. Armstrong, T.L. McDonald, R.F. Cusimano, R.S. Nemeth, M.L. Landolt, J.R. Skalski, R.F. Lee, and R.J. Huggett (1995)
Status of selected bottomfish and crustacean species in Prince William Sound following the *Exxon Valdez* oil spill

In Wells, P.G., J.N. Butler, and J.S. Hughes (eds.), *Exxon Valdez Oil Spill: Fate and Effects in Alaskan Waters.* ASTM STP 1219. Philadelphia: American Society for Testing and Materials., pp. 485-547.

ABSTRACT
Exposure and possible adverse effects of the *Exxon Valdez* oil spill at depth were studied between 1989 and 1991 on several species of crustaceans, molluscs, and finfish that are characterized by ontogenetic shifts in distribution from meroplanktonic larvae to benthic and demersal juveniles and adults. Our approach was to search for 1) evidence of exposure to *Exxon Valdez* crude oil (EVC) at depth (generally between 20 to 150 m) and 2) measurable perturbations at both the individual and population levels. Primary species targeted were Tanner crab (*Chionoecetes bairdi*), several pandalid shrimps (*Pandalus platyceros, P. hypsinotus, P. borealis*), flathead sole (*Hippoglossoides elassodon*), and several bivalves including scallops (*Chlamys rubida*) and infaunal clams, (*Nuculana, Yoldia,* and *Macoma* spp.). Our survey design provided a comparison between variables measured in "oiled' bays around Knight Island and "non-oiled" bays at other locations within Prince William Sound. "Oiled" was defined in terms of degree of shoreline oiling, sediment and tissue hydrocarbon

concentrations with the EVC signature, elevated concentrations of fluorescent aromatic compounds (FACs) in bile of flathead sole, and frequency of oil in benthic trawls. Statistical analyses of catch-per-unit-of-effort (CPUE; relative abundance determined by pots and trawls) were focused on detection of differences in trends through time (that is, "time-by-oil" interaction) rather than on magnitude of differences, thereby avoiding the problem of inherent differences in baseline CPUE levels between bays and the influence of non-random application of oil to bays. Polycyclic aromatic hydrocarbons (PAHs) of petrogenic origin were measured in all bays sampled in this study and levels of PAHs derived from EVC were elevated in the "oiled" bays following the spill, yet attenuated to less than 200 ng/g sediment by 1991. Total PAHs in scallop tissues were higher in "oiled" bays in 1989 but decreased 15-fold to mean of 16 ng/g by 1990. Clam tissues from "oiled" bays in 1991 had higher PAH concentrations, but only samples from Bay of Isles had alkylated PAHs (about 90 ng/g) indicative of EVC exposure. Mean concentrations of FACs in flathead sole bile were significantly higher in "oiled" than "non-oiled" bays (about 27 and 14 nanograms per gram (ng/g), respectively) in both 1990 and 1991, and corresponded to elevated tissue levels of PAHs in clams, which are the major prey of sole in these bays. Virtually no evidence of significant adverse effects was detected at either the individual or population levels across all the life history stages sampled. Larval Tanner crabs were widely distributed in the plankton in early summer of 1989 and 1990; adult female fecundity and trends in CPUE of juveniles did not differ significantly between the two categories of bays. In spring of 1990, 16 dead juvenile Tanner crabs were caught in three "oiled" bays and mortality was significantly correlated with elevated FACs in bile of flathead sole. Such mortality was likely linked to inordinately low bottom-water salinity that spring, and dead crabs were not found on any other cruise prior to or after this event. Pandalid shrimp were ubiquitous throughout the study area, and no significant differences were measured between "oiled" and "non-oiled" bays in trends of CPUE of *P. borealis* (the best quantified) and fecundity of *P. platyceros*. Fecundity in the case of *P. hypsinotus* was reduced in 1990 compared with 1989 irrespective of bay, but fecundity was also about 30 percent lower among females from the "oiled" compared with "non-oiled" bays. In the case of flathead sole, mean abundance of young-of-the-year fish declined significantly in "non-oiled" bays and mean abundance of older fish increased significantly in "oiled" bays. In contrast to lack of evidence of adverse effects on target species caused by the EVOS, substantial declines in fishery landings of several crabs and shrimps had occurred in Prince William Sound, some to the point of closure, prior to the spill. Long-term trends in abundance of populations of these species due to natural environmental causes or fishing pressures are likely to be far more important than fluctuations attributable to the *Exxon Valdez*.

Atlas, R.M.A, A. Horowitz, and M. Busdosh (1978)
Prudhoe crude oil in Arctic marine ice, water, and sediment ecosystems: degradation and interactions with microbial and benthic communities

J. Fish. Res. Bd. Can. 35:585-596

ABSTRACT:
A variety of in situ models were used to simulate oil spills in different Arctic ecosystems. Numbers of oil-degrading microorganisms increased after oil contamination. Oil contamination of sediment resulted in mortality of indigenous invertebrates. Recolonization of oil-contaminated sediments began shortly after oil contamination but benthic communities were significantly different in oil-contaminated sediment compared with the control, 2 months later. Petroleum hydrocarbons were degraded slowly. Ice greatly restricted losses of light hydrocarbons. Following initial abiotic losses, biodegradation of oil was limited and did not significantly alter the relative percentages of hydrocarbons in the residual oil. The authors concluded that petroleum hydrocarbons will remain in Arctic ecosystems for prolonged periods after oil contamination.

Atlas, R.M. (1982)
Microbial hydrocarbon degradation within sediment impacted by the *Amoco Cadiz* oil spill

Ecological Study of the *Amoco Cadiz* Oil Spill: Report of the NOAA-CNEXO Joint Scientific Commission (E.R. Gundlach and M. Marchand, eds.) pp. 1-25.

ABSTRACT
The wreck of the *Amoco Cadiz* in March 1978 released over 210,000 tons of oil into the marine environment. As much as one third of the spilled oil may have been washed into the intertidal zone. The spill occurred during storm surges, thereby spreading the oil throughout the intertidal zone. Two years after the *Amoco* spill, the wreck of the tanker *Tanio* resulted in another oil spill that contaminated much of the same Brittany shoreline impacted by the *Amoco Cadiz*. This study was undertaken to determine the fate of petroleum hydrocarbons within surface sediments along the Brittany coast with reference to the role of microorganisms in the oil weathering process.

Babcock, M., G. Irvine, S. Rice, P. Rounds, J. Cusick, and C. Brodersen (1993)
Oiled mussel beds two and three years after the *Exxon Valdez* oil spill

Exxon Valdez Oil Spill Symposium Abstracts; February 2-5, 1993, Anchorage, Alaska; pp. 184-185.

ABSTRACT
In 1991, two years after the *Exxon Valdez* oil spill, scientists observed crude oil associated with some mussel beds that still smelled of fresh aromatic hydrocarbons. Coincidentally, biologists observed continued reproductive failure among harlequin ducks and oystercatchers in the spill area, and possible reduced survival among young sea otters and river otters. All of these higher order consumers are dependent on (*Mytilus trossulus*) for a large portion of their diets. We conducted surveys to determine the geographic distribution oiled mussel beds and the concentrations of oil in the beds inside Prince William Sound and along the northwestern shoreline of the Gulf of Alaska. Thirteen mussel beds with evidence of oil present were located in Prince William Sound in 1991, and samples of mussels and underlying sediments were taken from each for analysis of aromatic hydrocarbon content. In 1992, we resampled most of the 1991 sites and located and sampled 46 additional oiled mussel beds in Prince William Sound. At some sites we sampled more than one mussel bed. Cooperating in the survey and sampling were the Alaska Department of Fish and Game, Alaska Department of Environmental Conservation and the U. S. Fish and Wildlife Service.

Baca, B.J., T.E. Lankford, and E.R. Gundlach (1987)
Recovery of Brittany coastal marshes in the eight years following the *Amoco Cadiz* incident

Proceedings of the 1987 Oil Spill Conference, American Petroleum Institute; pp. 459-464

ABSTRACT
The salt marshes on the Brittany coast of France have undergone a number of changes and have been influenced by man-made and natural factors since the *Amoco Cadiz* spill of March 1978. This work catalogs the ecological changes which have occurred over the past eight years and presents original data on the present state of these marshes. The recovery of Brittany coastal marshes began following cleanup operations which were often damaging to marsh and marsh substrate. The physical and toxicological properties of the oil also were damaging in the short term, especially to

annual species. Natural recovery began primarily by invasion of exposed areas with annuals and rhizome spreading of perennials. Within four years, an almost logarithmic recruitment process was begun by annuals followed by perennials. Pioneer and opportunistic species increased, facilitated by partially vegetated substrates available for seed and seedling retention and by increased seed and rhizome production. Human-induced restoration was also important and was done largely by planting wild or cultured stock. The final stage of marsh recovery, as existing today, is the emergence of perennial species of high and low marsh at elevations and tidal exposures typical for their growth. These successional changes in a marsh following a major oil spill (and various other man-made impacts) provide an understanding of the complex processes involved in marsh recovery. This understanding allows the formulation of planning guidelines to predict the long-term impacts of future incidents and to make proper recommendations for cleanup and restoration to aid the recovery process.

Badin, P. H. and D. Boucher (1983)
Medium-term evolution of meiobenthos and chlorophyll pigments on some beaches polluted by the *Amoco Cadiz* oil spill. (in French) original Title: (Evolution a moyen terme du meiobenthos et des pigments chlorophylliens sur quelques plages polluees par la maree noire de l' *Amoco Cadiz*)

Oceanol. Acta. 6:321-332

ABSTRACT
The ecological monitoring undertaken after the *Amoco Cadiz* oil spill (March 16, 1978), on the beaches Brouennou and Corn ar Gazel (mouth of Aber Benoit) and Kersaint (near Portsall), was continued monthly until November 1980. Chlorophyll pigments were found to have suffered little, quantitatively, from the direct effect of pollution, but the study of temporal variations in meiofaunal densities revealed disturbances in seasonal cycles. other factors, e.g. hydrodynamic fluctuations and macrofaunal predation, may have acted as regulating mechanisms on the evolution of the populations. The effects of pollution are particularly evident in certain faunistic imbalances, as the study of harpacticoid copepods showed. However, particular evolutionary trends between and within ecological groups of species implied that recovery was nearly complete, at least on exposed beaches.

Baker, J.M., R.B. Clark, P.P. Kingston, and R.H. Jenkins (1990)
Natural recovery of cold water marine environments after an oil spill

Proceedings of the Thirteenth Annual Arctic and Marine Oil Spill Program Technical Seminar, 111 pp.

ABSTRACT
This review of published literature examines natural cleaning and natural recovery of ecosystems and biological communities following oil spills in cold water regions of the world. The scientific literature permits generalizations to be drawn; but oil spills in exceptional circumstances may produce exceptional effects. In a number of cases, long-term studies of recovery processes are incomplete, and recovery time scales suggested involve some extrapolation.

Bakke, T. (1986)
Experimental long term oil pollution in a boreal rocky shore environment

Proceedings of the Ninth Annual Arctic and Marine Oil Spill Program Technical Seminar, pp. 167-178

ABSTRACT

The paper presents the design, experimental range and an overview of the results of a large scale mesocosm experiment performed during 1979 to 1985 at the Marine Research Station Solbergstrand, Eastern Norway. The aim of the experiment was to investigate the effects of continuous sublethal exposure to diesel oil on a cold temperate rocky shore community. The monthly mean temperature range of the mesocosm was 0.6-18.9°C during the six years the experiment lasted. The mesocosm communities were established in 1979 by transplantation of rocks with sessile organisms to four flow-through concrete basins (8x5xl.5 meters) equipped with wave generators and tide simulation. The communities were allowed to develop undisturbed for three years, after which two of the basins were exposed continuously to a diesel oil in seawater emulsion at mean levels of 130 and 30 micrograms per liter (µg/liter), respectively (fluorescence analysis). The two remaining basins acted as controls. The oil exposure lasted from September 1982 to September 1984. After that the communities were followed for recovery for one year. The experiment covered a range of subprojects aimed at studying the effects on general community structure, community recruitment and metabolism, population dynamics and genetics, physiology, cell chemistry, histology and tissue hydrocarbon levels of key species. The effects ranged from population collapse (blue mussel, amphipods), reduced growth (bladder wrack, kelp, mussels) and recruitment (winkles, barnacles), reduced primary production, increased cover of opportunistic green algae, reduced feeding and energy utilization (mussels, winkles), accumulation of hydrocarbons in algae and animals, to cyto-and biochemical stress indications (mussels, winkles). The effects were in most cases dependent on season. Relation to dose was not always found. The population genetics did not indicate any short term selection due to the oil. After one year recovery, most responses were back to normal, and population regeneration of mussels and amphipods had started, but some physiological dysfunctions were still detected.

Barry, M. and P.P. Yevich (1975)
The ecological, chemical and histopathological evaluation of an oil spill site, Part III: Histopathological studies

Mar. Poll. Bull. 6:171-173

ABSTRACT
By July 1971, approximately 25 percent of the clams in Long Cove, Searsport, Maine, had been killed by the March 1971 oil spill. Collections of surviving clams were made for histological examination. These studies were continued through 1974 and revealed a high incidence of gonadal tumors in clams contaminated by the oil. The area of highest oil impact correlated with the highest percent of tumors. The tumors were found to be malignant neoplasms.

Bayliss, R. and R. Spoltman (1981)
The wreck of the Lee Wang Sin

Proceedings of the 1981 Oil Spill Conference, pp. 221-226.

ABSTRACT
Environmental effects and cleanup efforts involved in Alaska's largest (in terms of length of shoreline affected) marine oil spill are recounted. Some 2,381 to 7,143 barrels of heavy bunker fuel and diesel oil were released during high winds into Alaskan and Canadian waters as a result of the 1979 Christmas Day capsize of the Taiwanese ore freighter, *Lee Wang Sin*, off the southern edge of the Alaska panhandle. Over 350 miles of shoreline were contaminated within a week of the accident, and oil slicks identified as products of the spill were sighted a month later, 210 miles north of the

vessel's grounding site off the southeast tip of Prince of Wales Island. While being towed to a deep-water burial site, the vessel unexpectedly sank 8 miles from an internationally known seabird sanctuary. Overall, many sensitive fish, mammal, bird, and shellfish resources were potentially impacted, furbearers and waterfowl, probably most seriously. Moreover, severe weather conditions and rugged terrain presented unique problems for cleanup operations, access, and logistics.

Belkhir, M. and M. Hadj Ali Salem (1986)
Oil spill dispersant toxicity on fish and mollusks

Bulletin de l'Institut National Scientifique et Technique d'oceanographie et de Peche BNSSEE, 13:13-18

ABSTRACT
The toxicity of dispolene 32S (an oil spill dispersant) was tested on three kinds of fish (*Mugil ramada, Atherina hepsetus, Aphanius fasciatus*) and two kinds of mollusks (*Mytilus galloprovincialis* and *Tapes decussatus*). Determination of LC_{10}, LC_{50} and LC_{90} shows that dispolene 32S is very toxic and can be considered as a harmful product even when used at low levels. The reaction time differs from one test organism to another; *Mugil* and *Atherina* were more sensitive than *Aphanius* and the mollusks were the most resistant of the organisms tested.

Bender, M.E., E.A. Shearls, R.P. Ayres, C.H Hershner, and R.J. Huggett (1977)
Ecological effects of experimental oil spills on eastern coastal plain ecosystems

Proceedings of the 1977 International Oil Spill Conference, pp. 505-509.

ABSTRACT
Five segments of a mesohaline marsh located off the York River, Virginia were physically isolated from the surrounding area, except for allowing subtidal flow, and dosed with fresh and artificially weathered South Louisiana crude oil. The experimental design and field site used in this study are described. The mini-ecosystems each contained about 695 square miles (m^2) of marsh, 100 m^2 of open water and 15 m^2 of intertidal mudflat. In September 1975, three 570-liter barrels of each of the experimental oils were spilled into replicate systems. Overall, the artificially weathered oil was shown to have as great an ecological impact on the communities as the fresh crude. Phytoplankton and fish populations all showed declines following the spills in the weathered oil systems. Phytoplankton production declined immediately after both spills but had recovered to control values within seven days. Species composition was not affected by the oils, while periphyton biomass, as measured by ATP, increased after both treatments. Marsh grass production was reduced in both spill units. Benthic animals, showing population declines after both oil, included nereid polychaetes, insect larvae and amphipods. Oligochaete populations decreased shortly after the fresh crude spill, returned to normal within 30 days, and then declined again relative to the control in both treatments 11 weeks after the spill. Mortalities of fish, *Fundulus heteroclitus*, held in live boxes were noted only in the weathered treatment systems.

Berge, J.A. (1990)
Macrofaunal recolonization of subtidal sediments. Experimental studies on defaunated sediment contaminated with crude oil in two Norwegian fjords with unequal eutrophication status. I. Community responses

Mar. Ecol. Progr. Ser. 66: 103-115

ABSTRACT
Experiments were performed by placing oiled and unoiled defaunated sediment in boxes (0.2 m^2) on the sea floor in 2 Norwegian fjords, the eutrophicated Oslofjord (four boxes, April to July 1980) and the non-eutrophicated Raunefjord (12 boxes, February 1981 to March 1982). In the Oslofjord no negative effects of the added oil (3,920 ppm wet weight sediment) on macrofauna community structure were seen after 3 months. Thus restoration of the community took less than three months during a spring/summer situation in a soft bottom area with a species composition dominated by opportunistic species (*Polydora* spp.). In the Raunefjord the effect of the added oil (4,520 ppm) was shown in reduced species diversity after four months, and altered k-dominance curves, distribution of individuals among species, Hurlbert's rarefaction curves and multidimensional scaling plots. The added oil reduced the mean equilibrium number of species per box from 80 to 55. The time needed to reach 90 percent of this equilibrium was shorter in the oiled boxes (259 days) than in the control boxes (466 days). Effects were most severe after four months on the filter-feeders and surface deposit feeders, after nine and 13 months on subsurface deposit feeders. Immigration rates were similar (0.27 species d^{-1} box^{-1}) in both treatments during June to November; however, from November to March the rate was higher in control boxes (0.24) than in oiled boxes (0.17). Mean extinction rates in boxes (species/species d^{-1} box^{-1}) were, however, larger in the oiled boxes than in the control boxes during both periods (Oil: 0.0048, 0.0033; Control: 0.0027, 0.0024). For both fjords animals retained on a 250-micrometer (µm) sieve generally showed higher densities in the oiled sediment. It is concluded that restoration of the benthic macrofauna after oil contamination of sediment takes longer in a non-eutrophicated area than in a eutrophicated area. The reduced density of macrofauna in the oiled boxes in the Raunefjord was caused by toxic response to oil directly, or by secondary effects leading to increased mortality, rather than by reduced settlement. Macrofauna recolonization is easily affected by oil-contamination in a non-eutrophicated area; however separation of oil-specific responses in benthic communities from responses to other disturbances can hardly be demonstrated without relevant controls.

Blackall, P.J. and G.A. Sergy (1981)
The BIOS project - frontier oil spill countermeasures research

Proceedings of the 1981 Oil Spill Conference, pp. 167-172

ABSTRACT
After 18 months of planning, the Baffin Island Oil Spill (BIOS) Project was formally initiated in March 1980. This project marks a major new initiative in oil spill countermeasures development for Canada's northern frontiers. The primary objectives of this internationally funded project are (1) to determine if the use of chemical dispersants in the Arctic nearshore will reduce or increase the environmental effects of spilled oil, (2) to assess the fate of oil, and (3) to compare the relative effectiveness of other shoreline protection and cleanup techniques. This paper outlines the background and scope of the four-year project and provides an overview of the first field season's results. Highlighted are the preliminary oil discharges, which took place in August 1980, and which marked the start of studies on the long-term fate of oil on Arctic beaches. In addition, the results of the baseline physical, chemical, and biological studies are presented. The physical program

included detailed oceanographic, meteorological, and geomorphological studies. The chemical program determined the background hydrocarbon concentrations, the sediments, the water column, and the tissue of selected macrobenthic species; and also the environmental chemistry of the study area. The biological program characterized the macrobenthic flora and fauna and the micro-organisms that are potentially capable of biodegrading the oil. The physical, chemical, and toxicological properties of the oil were measured in laboratories and in the field. The ramifications of these results on the design of the oil spills scheduled for 1981 are discussed.

Blackall, P.J. and G.A. Sergy (1983)
The BIOS project - an update

Proceedings of the 1983 Oil Spill Conference, pp. 451-455

ABSTRACT
The Baffin Island Oil Spill (BIOS) Project, formally begun in March 1980, now is entering the fourth and final year of the planned field work. The primary objectives of this internationally funded project are (1) to determine if the use of chemical dispersants in the Arctic nearshore will reduce or increase the environmental effects of spilled oil, (2) to assess the fate of oil, and (3) to compare the relative effectiveness of other shoreline protection and cleanup techniques. This paper provides an overview of studies sponsored by the BIOS Project during the first three field seasons. Highlighted are the major oil discharges which involved a total of 40 cubic meters of medium gravity crude oil. In addition, the preliminary results of the pre- and post-spill physical, chemical, and biological studies are presented. The physical program predicted the proper time and location for the oil releases and monitored the subsequent physical fate and behavior of the oil. The chemical program studies monitored the pre- and post-spill hydrocarbon levels in the water, sediments, and tissue of selected macrobenthic species; and also the environmental chemistry of the study area. The biological program studies to date have characterized the macrobenthic flora and fauna, the micro-organisms, and the shorter-term effects of the oil releases on the subtidal biota. The potential ramifications of the BIOS Project's results on future oil spill countermeasure strategies are discussed.

Blackman, R.A.A. and R.J. Law (1981)
The *Eleni V* oil spill: return to normal conditions

Mar. Poll. Bull. 12:126-130

ABSTRACT
The fate and effects of *Eleni V* oil spilled in May 1978 were followed until May 1980. At a mechanically-cleaned and exposed beach the hydrocarbon concentrations of inshore water and mussel tissue returned to background values between 300 and 400 days after the beaches became visually clean. Oil remaining on the surface of a protected beach still showed little degradation compared to oil buried in a disposal pit. Even on mobile beaches subject to high wave-energy, mechanical retrieval and clean-up of such a persistent heavy fuel oil is considered necessary unless its redistribution by wave action over adjoining beaches and into sediments is considered acceptable.

Blaylock, W.M., and J.A. Houghton (1989)
Infaunal recovery at Ediz Hook following the *Arco Anchorage* oil spill

Proceedings of the 1989 Oil Spill Conference, pp. 421-426

ABSTRACT
The *Arco Anchorage* crude oil spill occurred near Ediz Hook, in Port Angeles, Washington, in 1985. Following the spill, replicate infaunal sampling was carried out during five summer and winter seasons at a series of transects that ranged from relatively clean and unaffected by the spill to industrialized sites that had received heavy oiling. Average wet weight biomass, abundance, species diversity, and number of species were calculated for all samples. Analysis of variance was used to test for differences in these parameters over time within a transect. A statistically significant increase in average biomass, density, and species diversity was seen at several heavily oiled stations over time. A similar pattern was not seen at an unoiled reference station. Biomass, density, and number of species had significant negative correlations with sediment hydrocarbon concentration. A widespread settlement of bivalves was observed in October 1986 samples. Several species from this settlement (*e.g., Macoma nasuta* and *Clinocardium nuttallii*) were present in successively larger-sized classes in subsequent samplings. The industrialized nature of Ediz Hook and pollution events unrelated to the oil spill probably limited the degree of recovery and recolonization documented at several of the transects.

Blumer, M., H.L. Sanders, J.F. Grassle, and G.R. Hampson (1971)
A small oil spill

Environment 13(2):2-12

ABSTRACT
Oil pollution of the ocean is an increasingly serious global problem. The oils in petroleum are different in composition and toxicity from those occurring naturally in living marine organisms. These differences present a threat to ocean life and ultimately to human welfare, particularly in view of the scope of today spills in coastal waters and harbors of the world produce chronic pollution much larger in volume and probably more severe in biological consequences. Chronic oil pollution contaminates nearshore waters that are the key to the survival of most marine animals that are taken for man's food. over a long period of time, this persistent pollution may interfere with the normal life processes of the organisms, as well as killing them outright at high concentrations. The result may be progressive disappearance of usually abundant fish and shellfish. Their decline would be accompanied by an increase in pollution-tolerant species that generally indicate an unhealthy state of biological affairs. Furthermore, remaining organisms of food value to man may be permanently contaminated with petroleum hydrocarbons that could be hazardous to health.

Blumer, M. and J. Sass (1972)
Oil pollution: persistence and degradation of spilled fuel oil

Science 176:1120-1122

ABSTRACT
In September 1969, approximately 600 metric tons of number 2 fuel oil were spilled in Buzzards Bay, Massachusetts. Two years later, fuel oil hydrocarbons still persisted in the marsh and in offshore sediments. Hydrocarbon degradation is slow, especially below the immediate sediment

surface and appears to proceed principally through microbial utilization of alkanes and through partial dissolution of the lower boiling point aromatic hydrocarbons. The boiling ranges of the spilled oil and the relative abundances of homologous hydrocarbons (for example, phytane and pristane) have been well preserved. The findings are in agreement with the known geochemical stability of hydrocarbons. Fuel oil is an appreciable fraction of whole crude oil. This fact suggests that oil product and crude oils have a considerable environmental persistence.

Bodennec, G., P. Pignet, and J.C. Caprias (1983)
The *Tanio* oil spill. Chemical survey of the oil pollution in water and sediments from March 1980 to August 1981(French) original Title: (Le *Tanio* - Suivi chimique de la pollution petroliere dans l'eau et les sediments)

Rapp. Sci. Tech. 52, 108 pp CNEXO, Paris

ABSTRACT
After the *Tanio* wreck (March 1980) in northern Brittany, oil pollution was surveyed during three months in seawater, and during 16 months in intertidal sediments. Dynamic processes (wind and tides) and coastal geomorphology have controlled pollution of the coast line. Sediments were analyzed by glass capillary gas chromatography and contained oil residue for a long time. Bunker C oil weathering is slower than for a light crude oil. Microbial degradation appeared to be a major weathering process.

Bodin, P. and D. Boucher (1981)
Temporal evolution of meiobenthos and microphytobenthos on some beaches polluted by the *Amoco Cadiz* oil spill (French). Original Title: (Evolution Temporelle du Meiobenthos et du Microphytobenthos sur Quelques Plages Touchees par la Maree Noire de 1' *Amoco Cadiz*)

Amoco Cadiz: Fates and Effects of the Oil Spill. Proceedings of the International Symposium, Centre oceanologique de Bretagne, Brest, France, pp. 327-345.

ABSTRACT
Meiobenthos and chlorophyllian pigments from the beaches of Corn ar Gazel and Brouennou (mouth of Aber Benoit) were studied from September and November 1978. Meiofauna was sampled regularly from March 1978, on the beach of Kersaint, near Portsall. Temporal variations of density of meiofauna and quantity of chlorophyllian pigments seem to show that microphytobenthos and meiofauna are more sensitive to the main ecological factors, hydrodynamism and climatic variations, than to the oil pollution of *Amoco Cadiz*.

Bodin, P. and D. Boucher (1982)
Mid-term evolution of meiobenthos and microphytobenthos on beaches touched by the *Amoco Cadiz* oil spill. (in French) Original Title: (Evolution a moyen-terme du meiobenthos et du microphytobenthos sur quelques plages touchees par la maree noire de 1' *Amoco Cadiz*)

Ecological Study of the Amoco Cadiz oil Spill: Report of the NOAA-CNEXO Joint Scientific Commission, pp. 245-268

ABSTRACT
The ecological follow-up undertaken after the *Amoco Cadiz* oil spill, on the beaches of Brouennou and Corn ar Gazel (mouth of Aber Benoit) and Kersaint (near Portsall), was continued until

November 1980. Chlorophyll pigments have suffered little quantitatively from the direct effect of pollution, but the study of temporal variations in the meiofaunal densities revealed disturbances in seasonal cycles. other factors, e.g. hydrodynamic fluctuations and macrofaunal predators, could act as regulating mechanisms on the evolution of the populations. The effects of pollution are particularly obvious in some faunistic imbalances, as the study of harpacticoid copepods showed. However, particular evolutionary trends between and within ecological groups of species implied that recovery was nearly complete, at least on exposed beaches. The conclusions drawn to date are tentative because of the lack of reference data, and it is intended to continue the survey annually in spring.

Bodin, P. and Y. Le Moal (1982)
Short-term effects on meiofauna and macrofauna, of the clearing of a beach polluted by hydrocarbons with utilization of an oil spill dispersant.(in French) Original Title: (Effets a court terme, sur la meiofaune et la macrofaune, du nettoyage d'une plage polluee par les hydrocarbures avec utilisation d'un dispersant)

Acta Oecol. 3:263-280

ABSTRACT
At the opportunity of a field experimental cleaning on a polluted beach by a recent oil spill dispersant (Finasol OSR-5), variations of meio- and macrofauna were observed during a month. Effects have resulted in an important reduction of densities, with complex fluctuations the modalities of which are discussed. A month after the cleaning, the population has not completely recovered.

Bodin, P. (1988)
Results of ecological monitoring of three beaches polluted by the *Amoco Cadiz* oil spill: development of meiofauna from 1978 to 1984

Mar. Ecol. Prog. Ser. 42:105-123.

ABSTRACT
Following the *Amoco Cadiz* oil spill, time-series sampling of the meiofauna was carried out from 1978 to 1984 in the intertidal zone of three sandy beaches on the northern Finistere coast (Brittany, France). Quantitative analysis documented two principal phases in the development of the main taxa (Nematoda and Copepoda). First came a degradation phase leading to impoverishment in density and diversity of the populations. This first phase could be subdivided into several stages corresponding mainly to the toxicity period and. on one beach (Kersaint), to a summer bloom. Then came a recovery phase corresponding to a quantitative and qualitative reconstitution of the meiofauna. Each phase lasted a greater or lesser time according to station exposure and the considered taxon. A qualitative analysis of harpacticoid copepods illustrated the development of population diversity and ecological groups. During the first phase, replacement of the original population by a substitute fauna was observed. Correspondence factorial analysis on the development of harpacticoid communities allowed a better understanding of the main pollution and recovery factors such as toxicity, organic matter, hydrodynamism, and zoological groups. Meiofauna, particularly harpacticoid copepods, are significant bioindicators of ecological disturbances.

Bodin, P. (1991)
Perturbations in the reproductive cycle of some harpacticoid copepod species further to the *Amoco Cadiz* oil spill

Hydrobiologia 209:245-257.

ABSTRACT
The reproductive activity of eight harpacticoid copepod species (*Canuella perplexa, Harpacticus flexus, Robertsonia celtica, Amphiascoides debilis, Amphiascoides debilis limicolus, Kliopsyllus constrictus, Paraleptastacus espinulatus* and *Asellopsis intermedia*) was observed from 1978 to 1984 on three sandy beaches of Brittany (France) polluted by the *Amoco Cadiz* oil spill. Species density, mean percentages of ovigerous females and of juveniles from the period of maximum pollution were compared to those of one or two years characteristic of the post-recovery period. During the year of maximum pollution (1979) the spring peak of density came often later than normal and was generally lower. The main effect of the pollution was on the reproductive cycles of the species. There was often a delay of one month or more in the appearance and peaks of both ovigerous females and juveniles. Moreover, the latter were often missing during strategic months of the usual reproduction period. The recovery generally occurred in 1980 or 1981.

Boehm, P.D. (1982)
Amoco Cadiz analytical chemistry program

Ecological Study of the Amoco Cadiz Oil Spill, pp. 35-99.

ABSTRACT
As part of the NOAA/CNEXO research program to examine the long-term fates and effects of the *Amoco Cadiz* oil spill, samples of frozen intertidal surface sediment, sediment cores, oysters, flatfish and macroalgae were examined by gas chromatography and mass spectrophotometry to study the weathering of *Amoco Cadiz* oil, persistent marker compounds residues in tissues and environmental variability of oil pollution. Results showed that oil was weathered rapidly by biodegradation and evaporation. Oil was buried in most sedimentary environments with burial and/or penetration down to 15 cm in fine-grained sediments and 20-30 cm in sandy sediments. Offshore sediments were impacted after the shoreline impact through leaching, sorption on intertidal sediments and offshore transport of these sediments. The presence of unresolved material, pentacyclic triterpanes, and alkylated phenanthrene and dibenzothiophene compounds is characteristic of *Amoco Cadiz* oil in sediments. Identifiable *Amoco Cadiz* oil residues persisted at the Ile Grande marsh. Oysters were initially heavily impacted by the spill and contained residues of *Amoco Cadiz* oil even after 2 years. Fish do not appear to have been directly impacted chemically by the oil spill to any significant extent. Compositional profiles traceable to *Amoco Cadiz* oil are likely to disappear from all sediments by the fourth year after the spill .

Boehm, P.D., J.E. Barak, D.L. Fiest, and A.A. Elskus (1982)
A chemical investigation of the transport and fate of petroleum hydrocarbons in littoral and benthic environments: the *Tsesis* oil spill

Mar. Environ. Res. 6:157-188.

ABSTRACT
The fate of saturated and aromatic hydrocarbons discharged into the coastal Baltic Sea environment from the *Tsesis* oil spill was studied in the acute and post-acute (one year) phases of the spill. Samples of *Mytilus edulis* from littoral zone stations and *Macoma balthica* from soft bottom stations were obtained as well as sediment trap samples and surface sediment samples. Sediment trap samples indicated that sizable quantities of chemically and microbially weathered oil were sedimented, and available for benthic uptake shortly after the spill. After initial uptake of sedimented oil (500 to 1,000 µg/g dry weight), *Macoma* populations appear to have begun slow depuration through the first winter after the spill, but *Tsesis* oil was again introduced to the benthic stations studied during the following summer. *Mytilus* populations were severely impacted by the oil. Initial depuration of spilled oil during the first month was rapid and nearly complete at all but the most heavily impacted stations one year after the spill. The post-spill depuration of assimilated hydrocarbons was characterized by a relative retention of alkylated dibenzothiophenes and alkylated phenanthrenes compared to their unsubstituted parent compounds, and compared with the entire homologous naphthalene series. These data suggest that petroleum hydrocarbons from the *Tsesis* spill have become a chronic source of degraded saturated and aromatic hydrocarbons to the soft-bottom benthic communities.

Boehm, P.D., W. Steinhauer, A. Requejo, D. Cobb, S. Duffy, and J. Brown (1985)
Comparative fate of chemically dispersed and untreated oil in the Arctic: Baffin Island Oil Spill studies 1980-1983

Proceedings of the 1985 Oil Spill Conference, pp. 561-569.

ABSTRACT
Two experimental oil spill studies designed to assess the comparative short and long term fates and effects of chemically dispersed and untreated nearshore discharges in the Arctic were undertaken as part of the Baffin Island Oil Spill (BIOS) Project. The fates of oil in the water column, in subtidal and beach sediments, and in five species of filter- and deposit-feeding animals were investigated. Analytical results indicate that the discharge of the chemically dispersed oil caused a large but short-lived chemical impact on the water column (up to 50 ppm), a significant initial bioaccumulation of oil, and little sediment impact. In contrast, the untreated oil, allowed to beach, did not have a significant water column impact, but did result in a large-scale landfall, continual long term erosion of oil off the beach, and increasing oil levels in subtidal sediments and deposit-feeding animals.

Boehm, P.D., D.S. Page, E.S. Gilfillan, W.A. Stubblefield, and E.J. Harner (1995)
Shoreline ecology program for Prince William Sound, Alaska, following the *Exxon Valdez* oil spill: Part 2 - Chemistry and toxicology

In Wells, P.G., J.N. Butler, and J.S. Hughes (eds.), *Exxon Valdez Oil Spill: Fate and Effects in Alaskan Waters*. ASTM STP 1219. Philadelphia: American Society for Testing and Materials, pp. 347-397.

ABSTRACT
Part 2 of a three-part series, this paper describes chemical and toxicological results of a comprehensive shoreline ecology program that was designed to assess recovery in Prince William Sound following the *Exxon Valdez* oil spill on March 24, 1989. The program is an application of the "sediment quality triad" approach, combining chemical, toxicological, and biological measurements. Other parts of the program are described in Part 1: Study Design and Methods (Page et al. 1995) and Part 3: Biology (Gilfillan et al. 1995b). The study was designed so that the results could be extrapolated to the entire spill zone in the sound, and projected forward in time. It combined one-time stratified sampling of 64 randomly chosen study sites representing four major habitats and four oiling levels (including unoiled reference sites), with periodic sampling at 12 subjectively chosen "fixed" sites. Sediment samples -- or when conditions required, filter-wipes from rock surfaces -- were collected in each of three intertidal zones and from subtidal stations up to 30 m deep.

Oil removal was generally quite rapid. By 1991, the concentration of oil spilled from the *Exxon Valdez* had been dramatically reduced on the majority of shorelines by both natural processes and cleanup efforts. Moderate concentrations of petroleum residues remain only in limited, localized areas; however, most of these residues are highly asphaltic, not readily bioavailable, and not toxic to marine life.

Acute sediment toxicity from oil (as measured by standard toxicity tests) was virtually absent by 1990-91, except at a small number of isolated locations. The petroleum residues had degraded below the threshold of acute toxic effects. Measurable PAH levels are, in general, well below those conservatively associated with adverse effects, and biological recovery has been considerably more rapid than the removal of the last chemical remnants. The remaining residues continue to degrade and are, in general, predicted to become indistinguishable from background hydrocarbon levels by 1993 or 1994. Localized residues of weathered oil will no doubt exist beyond 1994 at certain locations, but their environmental significance will be negligible compared with other ongoing stress factors in the sound.

Samples of nearshore subtidal sediments showed surprisingly low concentrations of oil residue, as an increment to the natural petrogenic hydrocarbon background. Sediment toxicity tests showed that they were essentially non-toxic. It appears that most of the oil leaving the shoreline was swept away and dissipated at sea. These findings indicate that long-term ecological effects due to shoreline oiling or subtidal contamination are highly unlikely.

Bokn, T. (1985)

Effects of diesel oil on commercial benthic algae in Norway

Proceedings of the 1985 Oil Spill Conference, pp. 491-496

ABSTRACT
The kelp *Laminaria digitata* and the fucoid *Ascophyllum nodosum* are being studied to see if low, continuous dosage of diesel oil over a two-year period has any effects on length growth. This project is part of a larger experiment to assess long-term effects of low concentrations of oil on a simulated littoral rock community kept in four 50 m^3 concrete basins equipped with artificially made waves and tide. Over three years, four fucoids planted along with associated flora and fauna have established luxuriant and relatively stable communities. From September 1982 to autumn 1984 the plants were exposed to diesel oil mixed with inlet seawater as a water-accommodated fraction. The

exposure level averaged about 100 µg/l total hydrocarbons in the basin with the highest diesel oil concentration and about 25 µg/l in that with the lowest concentration. The other two basins served as controls. The work on *A. nodosum* started in June 1982. No significant growth difference was observed the first year. However, during 1983 and 1984, the new tips of plants in both oil-exposed basins were significantly shorter than those of the controls. No significant difference in growth of *L. digitata* was noted from March to July 1983. However, during spring 1984, growth of plants in both oil-exposed basins varied significantly from the controls. Studies of recovery will start at the end of the diesel oil exposure and will continue until 1986.

Bonsdorff, E. (1981)
The *Antonio Gramsci* oil spill impact on the littoral and benthic ecosystems

Mar. Pollut. Bull. 12:301-305

ABSTRACT
On February 27, 1979 the tanker *Antonio Gramsci* grounded off Ventspils (USSR) in the Baltic Sea. Some 5,000-6,000 tons of crude oil were spilled, and drifted towards the archipelago of Stockholm (Sweden) and Aaland (Finland). About 500 t of oil was mechanically recovered in the Aaland area. The immediate effects were small in the uppermost littoral (the *Cladophora* belt), but in the lower littoral (the *Fucus* belt) severe effects were recorded. Meiofaunal densities decreased in crustacean and mollusc species, but remained stable for the total community. Macrofaunal long-term changes could not be linked to the oil spill.

Bowman, R.E. and R.W. Langton (1978)
Fish predation on oil-contaminated prey from the region of the *Argo Merchant* oil spill

In the Wake of the Argo Merchant, Proceedings of a Symposium, University of Rhode Island, Kingston, pp. 137-141

ABSTRACT
The stomach contents of 21 species of fish and squid were analyzed to determine the potential impact of *Argo Merchant* oil on the fish stocks in the Northwest Atlantic. Important prey groups found in the stomachs of predators sampled in the region of the oil spill included amphipods, polychaete worms, rock crabs, and American sand lance. The quantities and types of foods eaten by each predator were similar to data previously collected. Amphipods covered with oil were found in the stomachs of Atlantic cod and little skate. Although no oil was found in their stomachs, American sand lance were found to feed on the same genera of copepods previously noted to be contaminated with Argo Merchant oil. Predator-prey relationships showed that 81 percent of the predators that were represented ate amphipods and 43 percent ate American sand lance, thus establishing two potential pathways for the oil to have been passed on to the higher trophic levels.

Breaker, L.C. and A. Bratkovich (1993)
Coastal-ocean processes and their influence on the oil spilled off San Francisco by the *M/V Puerto Rican*

Mar. Environ. Res. 36:153-184.

ABSTRACT

The oil tanker *M/V Puerto Rican* exploded on October 31, 1984 and later broke apart to produce a major oil spill in the coastal waters off San Francisco, California, USA. Oil from this spill initially moved to the south-southwest until November 5, when it abruptly reversed direction and began moving rapidly to the north and then to the north-northwest during the following week. The oceanic processes that most likely contributed to the displacement of the oil spilled by the *Puerto Rican* are examined within the framework of a simple, empirical-hindcasting model. Wind drift, inferred by using a simple linear formulation, was the single most important factor in determining the over-all displacement of the oil. Residuals from the model, however, indicate that the winds alone could not fully account for the sudden and dramatic reversal in oil movement that occurred on November 5, 1984. This reversal was surge-like and coincided with an increase in sea level along the central California coast. Finally, the close agreement between the local and advective changes in sea-surface temperature in the Gulf of the Farallones at the time of the *Puerto Rican* oil spill indicate, although not conclusively, that this reversal could have been related to the onset of the Davidson Current or other larger-scale flow phenomena.

Broman, D. and B. Ganning (1985)
Bivalve molluscs (*Mytilus edulis* and *Macoma balthica*) for monitoring diffuse oil pollution in a northern Baltic archipelago

Ambio 14(1): 23-28

ABSTRACT
Most of the previous research dealing with petroleum hydrocarbons in the marine environment has been focused on the short-term biological effects of acute oil spills, such as intentional and unintentional discharges from tankers. However, this type of oil pollution represents only part of the total. Recent studies have pointed out the importance of investigating the more diffuse, low level, continuous discharges and their impact on the environment. The present work is an attempt to monitor levels of petroleum hydrocarbons in a coastal area under urban influence.

Broman, D. and B. Ganning (1986)
Uptake and release of petroleum hydrocarbons by two brackish water bivalves, *Mytilus edulis* L. and *Macoma balthica* (L.)

Ophelia 25(1): 49-57

ABSTRACT
The uptake and release patterns of petroleum hydrocarbon refinery waste water in low-level concentrations (maximum total petroleum hydrocarbon concentration = 176 $\mu g\ l^{-1}$) by two bivalves *Mytilus edulis* L. and *Macoma balthica* (L.) have been investigated (gas chromatograph and fluorescence spectrophotometric analyses) in an experimental outdoor flow through basin. *Mytilus edulis* showed a short period of fast uptake (maximum total petroleum hydrocarbon concentration = 109 $\mu g\ g^{-1}$ wet weight) and a fast initial release followed by a longer period of slow release. *Macoma balthica* showed a slower and more extended uptake (maximum total petroleum hydrocarbon concentration = 73 $\mu g\ g^{-1}$ wet weight) and release pattern probably due to its feeding behavior, lower respiration rate indicating a slower metabolism and possibly lower petroleum hydrocarbon-metabolizing activity. We conclude that in many situations, especially in brackish water systems, the physiology, behavior and distribution of *Macoma balthica* make it an alternative monitoring organism to the more commonly used *Mytilus edulis*.

Brown, D.W., A.J. Friedman, P.G. Prohaska, and W.D. MacLeod, Jr. (1981)
Investigation of- Petroleum in the Marine Environs of the Strait of Juan de Fuca and Northern Puget Sound. Part 2: Second-Year Continuation

NOAA Technical Memorandum, 43 pp.

ABSTRACT
An investigation begun in February 1977 measured existing levels of petroleum hydrocarbons in the Strait of Juan de Fuca and Northern Puget Sound, and to investigate spatial and temporal trends in occurrence, concentration, and composition of petroleum-related hydrocarbons. Sediment and mussel samples from nineteen stations located along shipping lanes in the Strait of Juan de Fuca and Northern Puget Sound were analyzed for alkanes and aromatic hydrocarbons. Although the sites were relatively free from petroleum contamination, hydrocarbons indicative of petroleum were found at Cherry Point, Sandy Point, March Point, False Bay, Dungeness/Three Crabs, Ediz Hook, Kydaka Point, and Baadah Point. A small oil spill in Port Angeles Harbor on May 13, 1979 afforded an opportunity to evaluate the premise that hydrocarbon concentrations in intertidal sediment and mussels can be used to monitor for spilled oil in this region.

Brown, R.S., R.E. Wolke, C.W. Brown, and S.B. Saila (1979)
Hydrocarbon pollution and the prevalence of neoplasia in New England soft-shell clams (*Mya arenaria*)

Animals As Monitors of Environmental Pollutants. Symposium on Pathobiology of Environmental Pollutants: Animal Models And Wildlife As Monitors, pp. 41-51

ABSTRACT
Ecological, chemical, and pathological analyses were made on soft-shell clams from 10 New England sites of varying types and degrees of hydrocarbon pollution (nominal, oil spill, industrial and domestic sewage, and heavy metal). To date, over 1,300 clams have been histopathologically examined. of these, 162 had neoplastic lesions. Clams from one site had predominately gonadal neoplasms, while the majority were of hematopoietic origin. Cells of both types were markedly anaplastic, invasive, and appeared to have metastasized. The amounts of hydrocarbons found in both clams and sediments were in agreement with the ecological histories of the sites. The amount of hydrocarbons in clams was related to the amount in the associated sediments.

Brown, R.S. and K.R. Cooper (1978)
Histopathological analyses of benthic organisms from the vicinity of the *Argo Merchant* wreck

In the Wake of the Argo Merchant, Proceedings of a Symposium, University of Rhode Island, Kingston, pp. 96-102.

ABSTRACT
An examination of marine life two months after the spill found the following: a dead *Cancer* crab with a thick deposit of *Argo Merchant* oil coating the remnant gut; a moribund hermit crab; 1 *Modiolus* with mantle lesions of round, raised calcified nodules several mm in diameter adjacent to patches of *Argo* oil deposited on the internal shell surface; and 1/250 starfish with tarballs in the buccal cavity. Seven months following the spill, no oil was seen in eight *Cancer* and ten hermit crabs, 44 starfish, and five sea cucumbers, collected alive. One *Modiolus*, also visibly uncontaminated, had extensive calcium nodule formation on an adductor muscle and surrounding mantle. The effect of the *Argo* oil on marine life was minor, within the physiological tolerance limits of the macrobenthos.

Bunch, J.N., R.C. Harland, and J. Laliberte (1981)
Abundance and activity of heterotrophic marine bacteria in selected bays at Cape Hatt, Northwest Territory. 1980. First report to the Baffin Island Oil Spill (BIOS) Project

Can. Manuscr. Rep. Fish. Aquat. Sci., no. 1611, 81 pp.

ABSTRACT
On the basis of bacterial abundance and activity, three bays at Cape Hatt, Northwest Territories, were judged to be similar and therefore suitable for comparative microbiological studies during and after experimental petroleum spills in 1981. Variations in values between the sediments of stations and bays for Vmax (maximum velocity of glutamic acid uptake), total count and total viable heterotrophs were attributed to changes in the areas of sediment sampling and methods of collection. Mean total counts of bacteria appeared to reach a peak early in the open water season and then slowly decline, whereas the means of Vmax increased slowly across the sampling period to mid-September. Glutamic acid uptake at the sediment-water interface was found to be different from uptake in the water immediately above the sediment.

Bunch, J. N. (1987)
Effects of petroleum releases on bacterial numbers and microheterotrophic activity in the water and sediment of an Arctic marine ecosystem

Arctic 40(Suppl. 1):172-183

ABSTRACT
The effects of a petroleum slick and chemically dispersed petroleum on bacteria numbers and microheterotrophic activity (uptake of glutamic acid by heterotrophic microorganism) were monitored in the water column and sediments of selected bays at Cape Hatt, Northwest Territories. Observations were made between 1980 and 1983 as a component study of the Baffin Island [Canada] Oil Spill (BIOS) Project. These data were augmented by measurements of chlorophyll a, particulate and dissolved organic carbon and inorganic nutrients in the water column, while total organic carbon (TOC) was measured in the sediments in some years. Petroleum was released on two occasions in 1981. In the first release. undispersed petroleum moved across the surface of test Bay 11 and adhered to the intertidal sediments at low tide. No significant effects were seen in chemical or microbiological variables measured in 1981 or 1982. During the second release in 1981, dispersed petroleum was carried by the current through the water of test Bays 9 and 10 and into the channel beyond. Measurements of Vmax (maximum velocity) of glutamic acid uptake in water samples taken in these bays during the release showed a transient decrease in Vmax compared with control Bay 7. Bacterial numbers were unaffected, as were variables measured in the sediment of test Bays 9 and 10 during and after the release. In vitro experiments with water samples demonstrated that a combination of petroleum and dispersant alone reduced the Vmax of glutamic acid uptake to a greater extent than petroleum alone. A bay-year analysis of variance between 1981 and 1982 demonstrated that TOC and bacterial numbers increased in the sediments of test Bay 9 over 1981, while the Vmax, of glutamic acid uptake remained constant. In control Bay 7 and test Bay 11, all variables decreased over 1981 except TOC in Bay 11. In 1983, trends in the sediments of Bay 9 were similar to those of Bay 7. In test Bay 11, petroleum beached on the intertidal one in 1981 was observed entering subtidal sediments between 1981 and 1983 and forming a decreasing gradation of petroleum concentrations from nearshore to offshore areas. TOC increased between 1982 and 1983. Microheterotrophic activity remained constant in Bay 11, although it decreased in Bays 9 and

7. Bacterial numbers increased in Bay 11 but decreased in Bays 9 and 7. It was concluded that the changes in Bay 9 in 1982 and in Bay 11 in 1983 were a consequence of perturbations by petroleum. Effects on the benthic macrofauna and flora increased the levels of detritus, and hence TOC, in the sediments. This caused changes in bacterial numbers and microheterotrophic activity.

Burger, J. and M. Gochfeld (1992)
Effects of washing fiddler crabs (*Uca pugnax*) following an oil spill

Environm. Poll. 77:15-22.

ABSTRACT
An oil spill on January 2, 1990 in New Jersey resulted in premature emergence of fiddler crabs *Uca pugnax* from their underground burrows. Live fiddler crabs that emerged on the surface were collected and behavioral changes were compared between those that were washed with freshwater and those that were not washed. Locomotion, aggression, balance, and burrowing behavior were examined. Unwashed crabs improved significantly on only one of twelve behavioral tests, while washed crabs improved in four tests relating to movement, defensive behavior, and burrowing. The washed crabs showed the greater improvement on ten of twelve tests while unwashed crabs showed greater improvement for two tests. Washed crabs also showed greater improvement in their ability to find and to construct their own burrows. These experiments indicate that oil removal improves the behavioral performance of crabs, and suggests that under some circumstances the immediate flushing of salt marsh creeks by uncontaminated tidal waters may decrease behavioral effects on crabs.

Burns, K.A. and J.M. Teal (1979)
The West Falmouth oil spill: hydrocarbons in the salt marsh ecosystem

Estuarine and Coastal Marine Science 8:349-360

ABSTRACT
Marsh surface sediments, cores, and organisms were analyzed for hydrocarbons from one to seven years after the spill in September 1969 of No. 2 fuel oil at West Falmouth, Massachusetts. All organisms analyzed showed contamination initially. *Fundulus* were nearly free of oil after one year but *Uca* remained heavily contaminated for at least four years. Alkanes disappeared in sediments after about 4 years while heavy aromatics and naphthenes persisted throughout the study.

Burns, K.A. and J.L. Smith (1981)
Biological monitoring of ambient water quality: the case for using bivalves as sentinel organisms for monitoring petroleum pollution in coastal waters

Est., Coast. and Shelf Sci. 13:433-443.

ABSTRACT
Concepts of lipid/water equilibrium to explain bioconcentration of hydrocarbons were tested *in situ* and seem to hold for petroleum mixtures commonly encountered in coastal waters. K_{bef} in bivalve lipids was constant at approximately $2x10^5$ when concentrations were between 1 and 400 $\mu g\ l^{-1}$. These and related studies on the factors controlling body burden in bivalves were used to formulate a strategy for monitoring levels of chronic oil pollution necessary for water quality management.

Butler, M.J.A. and F. Berkes (1972)
Biological Aspects of Oil Pollution in the Marine Environment, A Review

Manuscript Report no. 22, Marine Sciences Centre, McGill University Montreal (Quebec) 122 pp.

ABSTRACT
A synthesis of some of the most significant research done on oil pollution and its biological effects is presented. The report includes fairly extensive sections on petroleum hydrocarbons, solvent-emulsifiers, effects of oil pollution on birds, mammals, fish, sediment and marine communities and case studies of oil pollution, including the *Torrey Canyon* disaster, the Santa Barbara oil spill, and the *Arrow* accident. The geography of oil pollution is explored in such areas as the Baltic Sea, North Sea, and Arctic Ocean. The study also aims to analyze the environmental implications of a series of hypothetical incidents that would be associated with activities involving oil exploration, exploitation, export and import, coastal movement and marine transportation activities and facilities.

Cabioch, L., J.C. Dauvin, J. Mora Bermudez, and C. Rodriguez Babio (1980)
Effects of the *Amoco Cadiz* oil spill on the sublittoral benthos, north of Brittany. (in French) original Title: (Effects de la maree noire de 1' *Amoco Cadiz* sur le benthos sublittoral du nord de la Bretagne)

14th European Marine Biological Symposium on Protection Life in the Sea. (O. Kinne and H.P. Bulnheim, eds.) *Helgol. Meer. 33:192-208*

ABSTRACT
Effects of hydrocarbons on the sublittoral macrobenthic communities have been observed through (1) studies of population dynamics of selected communities, conducted prior to the spill by the tanker " *Amoco Cadiz* " in spring 1978 and (2) comparisons between the situation in summer 1978 with that in earlier years, with continuation of the observations in some selected sites. The effect of the spill has been selective, involving a limited number of species, mainly crustaceans, molluscs and the sand urchin *Echinocardium cordatum*. The spill mainly affected communities on fine sediments and, to a lesser degree, those on mixed sediments. Notably, the destruction of the dominant populations of *Ampelisca*, in areas of fine sands in the Bay of Morlaix, has led to a marked decrease of biomass and production. Moreover, repopulation will be difficult because of the isolation of such communities on the southern side of the English Channel.

Cabioch, L. (1980)
Pollution of subtidal sediments and disturbance of benthic animal communities

Ambio 9: 294-296

ABSTRACT
In the sublittoral areas, the organisms most affected by *Amoco Cadiz* oil were living in fine sediments on the bottoms of-bays and estuaries. A few sensitive species were completely wiped out in the polluted area. The author notes that for some species, repopulation is proving to be difficult.

Cabioch, L., J.C. Dauvin, F. Gentil, C. Retiere, and V. Rivain (1981)
Disturbances in the composition and functioning of sublittoral benthic populations with the impact of *Amoco Cadiz* hydrocarbons. (in French) Original Title: (Perturbations Induites Dans La Composition et le Fonctionnement des Peuplements Benthiques Sublittoraux, Sous l'Effet des Hydrocarbures de L' *Amoco Cadiz*)

Amoco Cadiz: Fates and Effects of the oil Spill, Proceedings of the International Symposium, pp. 513-525

ABSTRACT
A quantitative and dynamic study of the populations undertaken one year before the Bay of Morlaix became polluted, provided a guide to bring together the interpretations. An essential part of the project was the study of the communities of fine sediments, most affected by the oil. The results obtained from the study of the first annual cycle after the pollution led to the following conclusions: All areas were impacted by a brief immediate phase of selective mortality, which affected a limited number of species (principally Crustaceans, Molluscs and *Echinocardium*) and which mainly disturbed the communities of the fine sediments. In the moderately disturbed sites, most of the surviving species followed afterwards an apparently normal annual cycle. Nevertheless, we observed some interruptions to the recruitment of some species. A transient proliferation or a more lasting rise in the density of certain Polychaetes (particularly the Cirratulidae and Capitellidae) was observed; at the end of the first annual cycle, recolonization by the most important species that had been eliminated had not yet taken place.

Cairns, J. Jr. and A.L. Buikema, Jr., eds. (1984)
Restoration of Habitats Impacted by Oil Spill. Boston: Butterworth Publishers.

ABSTRACT
Before general strategies for the recovery or restoration of damaged ecosystems can be discussed, a number of problems must be considered when attempting to restore ecosystems to original condition. These problems include the following: (1) Inability to define the original condition of ecosystems long exposed to societal stresses, (2) Inability to define long-term or genetic changes in populations that may preclude restoration to a previously known original condition, (3) Lack of understanding of the natural variability in ecosystems, (4) Lack of knowledge of ecosystem recovery processes, and (5) Need to consider the cost/benefit ratio of restoring an ecosystem to its original condition or the return of selected amenities (e.g., recreation) at a substantial reduction in costs. Case histories of the restoration and recovery of damaged ecosystems illustrate that restoration or rehabilitation of damaged ecosystems is within the biological and technological grasp of society, and alternatives are accepted by a public educated in the problems and cost/benefit ratios. The ability of an ecosystem to respond to perturbation depends on three characteristics: inertia (ability to resist change), elasticity (ability to recover), and resiliency (ability to recover after successive perturbations). These characteristics will vary from site to site. Consequently, management strategies will also vary on a site-specific basis. Unfortunately, we do not have the data base to quantify and qualify these characteristics adequately. From reports on investigations with oil spills, we were able to rank habitats as to their vulnerability to oil spills and cleanup operations. Most marine habitats are highly vulnerable because their ability to resist change (inertia) is low; the same is true for the tundra and taiga. Many of these habitats are simple, with low species diversity and/or a high degree of specialized life strategies. For a similar reason, we considered fast-flowing freshwater systems to be vulnerable. Ponds were classed vulnerable because of their small size. In most instances, the recovery process for these systems is expected to be quite long. The second crucial characteristic in ecosystem recovery and restoration is elasticity, or the ability to recover.

The potential for recovery depends on at least five factors: (1) existence and proximity of biological epicenters; (2) dissemination potential of propagules; (3) habitat condition following stress; (4) presence of residual toxicants; and (5) the physical-chemical quality of the environment. The implementation of a management strategy should emphasize methods to enhance elasticity in the recovery process. The last crucial characteristic is ecosystem resilience. Few data are available on the ability of an ecosystem to recover from frequent perturbation, especially with oils. Until data are generated, we must assume that the resiliency of many aquatic ecosystems is low. The first concern of an oil-related industry should be to inventory the aquatic ecosystems in the vicinity of drilling operations, shipping lanes, transport and refining facilities, etc. This inventory should also identify ecosystems some distance away that could also be affected during a spill because of prevailing winds, currents, or any factor capable of inducing oil transport. once these ecosystems have been identified, they should be cataloged according to (l) size, (2) degree of shelter or wave energy; (3) proximity to similar ecosystems; (4) ecologically and/or economically important species that live in, or rely on, that ecosystem; (5) species that have long life cycles; (6) species that may be sensitive or tolerant to potential toxicants; (7) role of that habitat, i.e., erosion control or secondary productivity; and (8) estimate of the current ecological state of the ecosystem, i.e., is it stressed or how does it compare to similar sites nearby? This latter instance may be very difficult to estimate because little is known about the natural variability of healthy ecosystems. Once this inventory has been completed, those ecosystems that are of little ecological value should be identified. Small ecosystems not near biological epicenters are more susceptible to perturbation effects, and recovery is expected to be slow because invasion by new organisms will be slow. These may not be worth restoring to their original condition.

Ecosystems under long-term chronic stress may have changed so drastically that recovery to an original condition is impossible or not cost-effective. In any event, alternative plans should be established for these habitats so that cost-effective rehabilitation strategies can be established. The intent here is to return some amenities that are acceptable to society. This may include development of fishery reefs, recreation areas, etc. The next concern should be to determine if mechanical, physical, or chemical means of preventing oil contamination are possible to protect the remaining ecosystems. This is most important for ecologically important ecosystems such as marshes, mangrove swamps, seagrass beds, coral reefs, and soft-bottom subtidal areas. In most instances, cleanup activities should not be used because the potential damage may be greater than if the system is allowed to recover naturally. If protection of these ecosystems by mechanical, physical, or chemical means is not possible, then management strategies must be directed to facilitating the recovery process of damaged ecosystems. This can occur by a combination of restoration of habitat and/or organisms. one requirement for close, but discontinuous, ecosystems or for a large ecosystem is the establishment of appropriate biological epicenters so that reinvasion of existing flora and fauna can occur rapidly. This may require the establishment and maintenance during a spill of ecological preserves within the ecosystem in question. This may simply be an area that can be fenced off. If ecological preserves within ecosystems are not possible, a more expensive alternative would be the establishment of ecological preserves, zoos, gardens, and nurseries where important species could be cultivated for the express purpose of restocking damaged areas. This concept could require only the culture of important indigenous species. However, the cultivation of early successional or pioneer species (especially plants) would be most important. These species could be used rapidly to stabilize a damaged area for subsequent recolonization by indigenous or climax species. Whenever ecological preserves, gardens, or nurseries are established, emphasis must be placed on those species that can be easily transplanted and the life stage that can be most easily disseminated. For various similar plants and animals, the propagule may be different. This information, if known, must be inventoried so that cultivation methods are employed to guarantee an abundance of propagules in a timely manner.

Strategies for restoration must include an analysis of the habitat condition and methods for stabilizing these habitats. Most important is the prevention of erosion in those habitats that recover slowly. other mechanisms for restoring habitat condition are also important, e.g., aeration may be necessary to prevent lethal effects due to a high biological oxygen demand. Lastly, the most important factor in regulating recovery and restoration is the residual toxicity factor. Sediment particles readily pick up oils and, in the anaerobic environment of marshes, oxidation of oils is severely retarded. Many information gaps were identified in this workshop, and the ubiquitous call for more research was not taken lightly. Information on recovery clearly is lacking because many post-spill studies were not carried out for long periods of time, and these studies were not adequately designed to address the issues of quantification and qualification of impact. Most notable was the lack of studies on freshwater systems. While a number of attempts have been made to facilitate restoration and recovery of damaged ecosystems, the success rate has been variable because of the multitude of unknown or poorly understood factors affecting growth and reproduction of transplanted species. Research and our lack of information on ecosystem structure and function needs on the ecological requirements of critical species have been identified. Development of oil resistant strains of plants and animals would also enhance ecosystem recovery.

Capuzzo, J.M. (1990)
Biological effects of petroleum hydrocarbons: predictions of long-term effects and recovery

Northwest Sci. 64(5): 247-249.

ABSTRACT
Biological effects of petroleum hydrocarbons on marine organisms and ecosystems are dependent on the persistence and bioavailability of specific hydrocarbons, the ability of organisms to accumulate and metabolize various hydrocarbons, the fate of metabolized products, and the interference of specific hydrocarbons with normal metabolic processes that may alter an organism's chances for survival and reproduction in the environment. The responses of organisms to petroleum hydrocarbons can be manifested at four levels of biological organization: (1) biochemical and cellular; (2) organismal, including the integration of physiological, biochemical and behavioral responses; (3) population, including alterations in population dynamics; and (4) community, resulting in alterations in community structure and dynamics. Impairment of behavioral, developmental and physiological processes may occur at concentrations significantly lower than acutely toxic levels; such responses may alter the long-term survival of affected populations. Thus, the integration of physiological and behavioral disturbances may result in alterations at the population and community levels.

Carney, D. and R. Kvitek (1990)
Shallow subtidal survey of the Washington outer coast and Olympic National Park to determine the distribution, fate, and effects of spilled Bunker C fuel oil

Final Report for Olympic National Park, U.S. Department of the Interior/Minerals Management Service and Battelle/Marine Science Laboratory. OCS Study MMS 90-0073; 20 pp.

ABSTRACT
In December 1988, a barge ruptured and spilled 230,000 gallons of Bunker C fuel oil off the mouth of Grays Harbor, Washington. Subtidal benthic surveys were conducted by divers in oiled and unoiled sites in and around Grays Harbor and the Olympic National Park. Divers established benthic

transects and visually inspected the sea floor as well as probed the sediment with PVC stakes looking for signs of oil deposition and incorporation into the sediments. Sediment and faunal tissue samples were collected for laboratory analyses to determine what, if any, contamination of the benthos had occurred. Infaunal samples were collected, preserved and archived for future analysis in the event that contamination of sediments or fauna became evident from sediment and faunal tissue analyses results. No evidence of subtidal oil deposits was found. No sediment samples contained oil or grease concentrations above detection limits. Saturates and aromatics concentrations were low and percent aromatic hydrocarbons were considerably below background levels for all tissue samples. Because neither sediments nor tissues contained contaminants above background levels, phase II of this project was not implemented, and infaunal samples were not evaluated as to species distribution and abundance.

Chan, G.L. (1975)
A study of the effects of the San Francisco oil spill on marine life, Part II: Recruitment

Proceedings of the 1975 Conference on Prevention and Control of Oil Pollution, pp. 457-461

ABSTRACT
A study of marine organisms on intertidal transects was made to observe the effects of the San Francisco Bunker C oil spill of January 18, 1971. From a comparison of pre-oil and post-oil transect data, it was estimated that 4.2 to 7.5 million marine invertebrates, chiefly barnacles (*Balanus glandula, Chthamalus dalli,* and *Pollicipes polymerus*) were smothered by the oil. Other invertebrates included sea anemone, crabs, chiton, sea mussel and boring clam. In subsequent observations from 1972 to 1974, the sample counts of invertebrates had returned to , and in some cases surpassed pre-oil transect levels. No lingering effects of the oil spill were noted in any of the marine species.

Chan, G.L. (1977)
The five-year recruitment of marine life after the 1971 San Francisco oil spill

Proceedings of the 1977 Oil Spill Conference, pp. 543-545

ABSTRACT
On January 18, 1971, two Standard Oil tankers collided beneath the Golden Gate Bridge, releasing about 840,000 gallons of Bunker C fuel. An estimated 4.2 million to 7.5 million intertidal invertebrates, chiefly barnacles, were smothered by the oil. Five-year observations of marine life recruitment following the spill indicate that population densities of some marine species have significantly increased in the San Francisco Bay area intertidal zones at Sausalito and Duxbury Reef. With some fluctuations, the barnacles *Balanus glandula* and *Chthamalus dalli* have increased from July 1971 to May 1976 from 93 to 189 barnacles per square decimeter (dm^2) at Sausalito and from nine to 34 per dm^2 at Duxbury Reef. The large bed of mussels, *Mytilus californianus*, showed a steady rise from 5.9 dm^{-2} in April 1971 to 14.0 dm^{-2} in July 1976. The density of mobile organisms such as limpets, snails and crabs all show cyclical variations: some show an overall increase. The limpet, *Collisella spp.* which suffered high mortality during the spill have increased threefold over pre-oil counts. In 1975, some significantly low sample means were recorded for barnacles in Sausalito and for 18 composite species at Duxbury Reef, probably due to natural ecological forces. The five year recruitment (1971-76), however, shows no evidence of lasting detrimental effects of Bunker C oil on the populations of marine life within the transect sites.

Chasse, C. (1978)
The ecological impact on and near shores by the *Amoco Cadiz* oil spill

Mar. Poll. Bull. 9:298-301

ABSTRACT
By comparison with previous pollution accidents and taking into account the enormous quantity of oil spilled at Portsall, the provisional balance sheet indicates rather less damage to the marine environment than might have been expected. There is now evidence that intertidally and close inshore direct mortalities have been localized, seldom heavy, and always selective and partial. Contamination of organisms and products of commercial fisheries at sea have been transitory. Oyster culture alone has been badly damaged. The algal crop is not exploitable for industrial use. The general cover of macro-algae has survived the incident.

Clark, R.B. (1982)
The long-term effect of oil pollution on marine populations, communities and ecosystems: some questions

Phil. Trans. R. Soc. Lond. B 297:185-192.

ABSTRACT
An evaluation of the consequences of environmental contamination requires an understanding of the extent to which it is responsible for changes in populations of organisms in the affected area. Population change is not solely related to mortality which may be observed, but depends also on the population dynamics, stock size and survival strategy of the species affected. Population changes affecting species of commercial or sentimental importance or whose diminution is followed by major community adjustment, are regarded more seriously than those of other species. Community adjustment to stress by contaminants may be subtle, difficult to detect and still more so to evaluate. In some instances it is possible to unravel the causative agents, but studies of community response to stress have lagged behind those at lower organizational levels of the individual, tissue or cell. The succeeding papers address questions arising from these considerations.

Clark, R.C., Jr., J.S. Finley, B.G. Patten, D.F. Stefani, and E.E. DeNike (1973)
Interagency investigations of a persistent oil spill on the Washington Coast

Prevention and Control of Oil Spills, Proceedings of Joint Conference, pp. 793-808.

ABSTRACT
An interagency team of biologists, chemists, oceanographers and engineers investigated the long-term effects of oil spilled when the troopship *General M.C. Meigs* ran aground on January 6, 1972 on an ocean coast intertidal community of plants and animals. Oil was released from the 440,000 liters of Navy Special Fuel oil carried by the vessel. A series of sites, forming a vertical profile of the rocky shelf area from the upper intertidal zone to the lowest low tide level in Wreck Cove was studied. This report describes the preliminary findings of the first ten months (January-October, 1972) of the investigation. Abnormal and dead urchins indicated that this species was affected. Loss of fronds and bleached thalli not evident in control areas were observed in the plant community in the immediate vicinity of the hulk. Petroleum hydrocarbons were taken up in the intertidal community. The normal paraffin hydrocarbon patterns and content over the range n-$C_{14}H_{30}$ to n-$C_{37}H_{76}$ of

healthy-appearing barnacles, crabs and alga display the same basic characteristics as the released fuel oil.

Clark, R.C., J.S. Finley, B.G. Patten, and E. DeNike. (1975)
Long-term chemical and biological effects of a persistent oil spill following the grounding of the *General M.C. Meigs*

Proceedings of the 1975 Conference on Prevention and Control of Oil Pollution

ABSTRACT
Petroleum hydrocarbon uptake patterns and observations of plant and animal populations of an intertidal community exposed continually since January 1972 to small quantities of a Navy Special Fuel oil residue from the grounded unmanned troopship *General M.C. Meigs* were obtained by an interagency team of oceanographers, biologists, chemists, and engineers. Although the tar-ball-like character of the released oil served to limit its coverage, specific members of the intertidal community showed effects of the persistence of the spill. This report describes the long-term observations and analyses made since the grounding of the 622-foot military transport on a rich and productive intertidal regime

Clark, R.C., B.G. Patten, and E.E. DeNike. (1978)
Observations of a cold-water intertidal community after five years of a low-level, persistent oil spill from the *General M.C. Meigs*

J. Fish Res. Bd. Can. 35:754-765.

ABSTRACT
A rich and productive intertidal community was exposed continually for over five years to small quantities of a Navy Special fuel oil from the unmanned troopship *General M.C. Meigs* that came aground on the Washington coast in January 1972. Observations of animal and plant populations and their petroleum hydrocarbon uptake patterns showed early evidence of contamination and the persistence of the oil spill throughout the study period. Abnormal and dead urchins, and loss of algal fronds and pigment were observed in localized areas near the wreck for at least one year. Within two months of the accident, paraffinic hydrocarbons had been taken up by prominent members of the community and continued to appear in certain species even after five years. Although changes were seen in certain species during the early days of this persistent low-level pollution incident, the community balance in this rocky intertidal ecosystem does not appear to have been markedly altered.

Conan, G. (1982)
The long-term effects of the *Amoco Cadiz* oil spill

Phil. Trans. Roy. Soc. Lond., Ser. B. 297:323-333; 1982

ABSTRACT
The supertanker *Amoco Cadiz* wrecked on the coast of northern Brittany in March 1978. The resulting spill of 223,000 t of crude oil polluted some 360 km of rocky or sandy shores, salt marshes and estuaries. Three to six generations may be necessary before populations retrieve their stable age distribution. Delayed effects on mortality, growth and recruitment were still observed up

to three years after the spill. Estuarine flatfishes and mullets had reduced growth, fecundity and recruitment and were affected by fin rot disease. Populations of clams and nematodes in the meiofauna declined one year after the spill. Weathered oil is still present in low-energy areas. Species with short life cycles tend to replace long-lived species. A fauna of cirratulid and capitellid polychaete worms now prevails in sandy to muddy areas. For several clam populations, recruitment remains unstable. Three years after the spill it is still premature to decide how long it will take before populations and ecosystems reach their former or new equilibria.

Courtot, P. (1985)
Hydrocarbons evolution after the *Amoco Cadiz* oil spill. Observations and modelization. (in French) original Title: (Evolution des hydrocarbures apres l'echouage de l' *Amoco Cadiz*)

Strategies and Advanced Techniques for Marine Pollution Studies in the Mediterranean Sea (Giam C.S. and Doll H., eds.) p. 8

ABSTRACT
After the crash of the super-tanker *Amoco Cadiz* on March 17, 1978, on the reefs of the North Coast of Finistere (Portsall, Brittany, France), a three-year program was established to follow the evolution of petroleum hydrocarbons at sea first and then in the sediments of a highly polluted river, Aber-Benoit. Infrared for total hydrocarbons and capillary column gas chromatography for individual compounds were used, necessitating two-liter seawater samples and 50 grams of sediment. Water and sediment of Aber Benoit were found to contain both petroleum and recent biogenic hydrocarbons. Resuspension of particles play an important role in redissolution of hydrocarbons in water and a study was undertaken of the influence of different parameters on physico-chemical absorption conditions (porosity, size and type of clays and sands, salinity, and temperature). The main results of this study were given.

Cox, G.A., A. Barnett, J.R. Gould, R.G. Hay, J. Hirota, C.D. McAuliffe, and A.D. Michael, eds. (1979)
Oil spill studies: strategies and techniques

Journal of Environmental Pathology and Toxicology 3, 146 pp.

ABSTRACT
An Oil Spill Studies: Strategies and Techniques Workshop was convened to organize and summarize current techniques and suggest sampling strategies to study the effects of oil spills on marine and estuarine biota. The workshop was designed to provide marine scientists with the collective field and analytical experience of researchers in this field. Massive petroleum releases to the marine environment, not continual, chronic spillage was addressed. Workshop participants strongly endorsed the concept of a few comprehensive studies of oil spills rather than many inconclusive studies which are the current norm. The following research areas were covered information management, chemistry, plankton, benthos, and fish, birds, marine mammals and sea turtles. Individual study recommendations are given for each study area.

Cretney, W.J., C.S. Wong, D.R. Green, and C.A. Bawden (1978)
Long-term fate of a heavy fuel oil in a spill-contaminated British Columbia coastal bay

J. Fish. Res. Bd. Can. 35:521-527.

ABSTRACT
The fate of accidentally spilled No. 5 fuel oil in a small coastal bay in British Columbia was observed six times during four years. The oil composition was first changed by loss of the lower molecular weight components by evaporation and dissolution. Biodegradation accounted for almost complete removal on n-alkanes in the first year. Pristane and phytane were biodegraded more slowly, but were almost completely gone in four years. The non-n-alkane components in the nC_{28-36} range seem to be the most resistant to degradation of all the components resolved in the gas chromatograms. The resistance to degradation of these components indicates their potential for long-term studies of oil spills.

Cretney, W.J., D.R. Green, B.R. Fowler, B. Humphrey, F.R. Engelhardt, R.J. Norstrom, M. Simon, D.L. Fiest, and P.D. Boehm (1987)
Hydrocarbon biogeochemical setting of the Baffin Island oil spill experimental sites. 3. Biota

Arctic 40:71-79

ABSTRACT
A baseline for petroleum residues in the Cape Hatt region of Baffin Island in Arctic Canada was obtained in anticipation of controlled oil releases of the Baffin Island Oil Spill (BIOS) Project. Tissue hydrocarbons in a variety of Arctic marine species were dominated by biogenic hydrocarbons. W/F analysis of tissues indicated an upper limit of petroleum residues in the low to sub microgram concentration range. PAHs were detected in samples in the low ng concentration range and revealed a distribution of the combustion type. The hydrocarbon baseline in the BIOS study area was found to be as low as might be found anywhere on each and therefore ideally suited to the BIOS study.

Cross, W.E., and D.H. Thomson (1987)
Effects of experimental releases of oil and dispersed oil on Arctic nearshore macrobenthos. I. Infauna

Arctic 40(Suppl. 1): 184-200.

ABSTRACT
An experimental subsurface release of chemically dispersed oil at Cape Hatt, northern Baffin Island, resulted in short-term, relatively high oil concentrations in the waters of two adjacent bays, whereas untreated oil released onto the surface of a third bay could not be detected in the water below a depth of 1 m. Diver observations revealed no apparent short-term effects of untreated oil on shallow water infauna, whereas marked acute effects on infauna, including emergence from the substrate and narcosis, were apparent in the dispersed oil bays within 24 hours of the release. Analysis of systematic airlift samples at two depths (3 and 7 m) in the three test bays and a fourth (reference) bay during the open water seasons of 1980-83 (two pre-spill and four post-spill sampling periods) showed that most affected animals recovered. Neither type of oil release caused any large-scale mortality of benthic infauna. Multivariate analyses showed no significant change in infaunal community structure, and effects attributable to oil were found in only three of 72 univariate analyses of density, biomass or size data for individual taxa. A progressive decrease in the condition

of the filter-feeding bivalve *Serripes groenlandicus* in the reference bay (several km distant from the dispersed oil release) was apparently the result of exposure to dilute dispersed oil for several days. A similar effect on condition in the surface deposit-feeding bivalve *Macoma calcarea* was apparently caused by relatively low oil concentrations in the sediments of the dispersed and surface oil release bays There were no apparent effects on recruitment in bivalve species with planktonic larvae, but density changes in the polychaete *Spio* spp. indicated that oil in the sediments of the surface oil release and dispersed oil release bays affected reproductive processes. Effects on the condition of the bivalves and on *Spio* spp. were still evident two years post-spill in 1983, the last year of sampling.

Cross, W.E., C.M. Martin, and D.H. Thomson (1987a)
Effects of experimental releases of oil and dispersed oil on Arctic nearshore macrobenthos. II. Epibenthos

Arctic 40(Suppl. 1): 201-210.

ABSTRACT
An experimental subsurface release of chemically dispersed oil at Cape Hatt, northern Baffin Island, resulted in short-term, relatively high oil concentrations in the waters of two adjacent bays, whereas untreated oil released onto the surface of a third bay could not be detected in the water below a depth of 1 m. The only immediate response in epibenthos observed by divers was narcosis in urchins and starfish following the dispersed oil release. Analysis of data from *in situ* counts in the three test bays and a fourth (reference) bay during the open water seasons of 1980-83 showed that densities of the starfish *Leptasterias polaris* were not affected by either oil release and that effects on urchin densities were minor or transitory: *Strongylocentrotus droebachiensis* apparently made immediate and transitory attempts to avoid dispersed oil in the water and possibly tried to avoid untreated and dispersed oil in sediments two years after oiling. Analysis of airlift samples collected at 3 and 7 m depths in the four bays during 1980-83 showed no major effects of either oil release on densities of epibenthic crustaceans; taxa examined included all crustaceans, all cumaceans, one species of cumacean, all amphipods and eight individual amphipod taxa. The overall trend was toward increases in epibenthic crustacean densities over the study period. Effects that may have been attributable to oil were found in only two of 22 analyses of density data for individual taxa. In those cases, effects were minor: untreated oil in sediments apparently altered the depth distribution of *Anonyx* juveniles and dispersed oil in the water column apparently had a delayed adverse effect on reproduction in the amphipod family Stenothoidae. Densities of *Pontoporeia femorata* were not affected by oil, but inspection of size-frequency data indicated a possible delayed adverse effect on its reproduction.

Cross, W.E., R.T. Wilce, and M.F. Fabijan (1987b)
Effects of experimental releases of oil and dispersed oil on Arctic nearshore macrobenthos. III. Macroalgae

Arctic 40(Suppl. 1): 211-219.

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

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

Crothers, J.H. (1983)
Field experiments on the effects of crude oil and dispersant on the common animals and plants of rocky sea shores

Mar. Environm. Res. 8:215-239.

ABSTRACT
In experiments on the Somerset coast, Forties crude oil and BP 1100WD dispersant were sprayed on to small areas of the rocky shore over a period of several days to stimulate conditions following an oil spill. Detailed observations were made at monthly intervals of marked 0.1 m^2 quadrats within (and without) the treated areas. Some areas received oil only, others dispersant only, and the third set received oil followed by dispersant. The experiments were in two parts, the one to simulate a July incident and the other a January incident. Limpets and the small winkles living in and between empty barnacle shells were the most obviously affected organisms. The sites that received both oil and dispersant were most seriously upset, but the oil areas came next. The effect of BP 1100WD on its own as applied in this experiment was relatively slight.

Crutchfield, J.A. Jr. (1979)
Oil interactions with fisheries

Proceedings of Marine Sciences and Ocean Policy Symposium; A Definition of the Issues and a Search for a Consensus on Multiple Uses, pp. 235-242

ABSTRACT
Fish and shellfish feeding on oil-tainted materials gradually build up hydrocarbons in the tissues, especially in the liver and gut. Though taste effects may be detectable for only a relatively short time, the marketing of contaminated products could cause a severe reaction among fish consumers. Since much of the actual or potential damage to fisheries from oil operations involves inshore waters, there is a real likelihood that recreational fishing may suffer. A number of reasonable firm policy conclusions emerge. First, for identifiable and quantifiable damages, full liability of the responsible party seems the appropriate remedy. Second, for specific, quantifiable damages for which no responsibility can be established, both equity and incentive would appear to favor a cooperative indemnification scheme with oil companies providing a repayment pool and with well-defined procedures for arbitration of claims. Third, there is urgent need for fast response capability in areas subject to high risk of oil spill, including immediate availability of biological assessment procedures and of personnel; activation of cleanup techniques; and advisory services to the fishing industry as to the limits within which the fishing must be curtailed. Finally, the need for national and

international authority is emphasized to influence investment choices in the production, transportation, and transfer of oil at sea.

Dambo, W.B. (1993)
Tolerance of the periwinkles *Pachymelania aurita* (Muller) and *Tympanotonus fuscatus* (Linne) to refined oils

Environm. Poll. 79:293-296.

ABSTRACT
Tolerance of *Pachymelania aurita* (Muller) and *Tympanotonus fuscatus* (Linne) to kerosene, diesel, and gasoline was studied. Emulsions of these refined oils were observed to be more harmful when compared with such oil films on the water surface. *T. fuscatus* was observed to be less susceptible to such exposures. After 48-hour exposure to kerosene, diesel, and gasoline, as an oil film on the water surface, there was no significant difference in the mean survival values obtained for *T. fuscatus* and *P. aurita*, respectively. However, the differences in the mean survival values obtained for *P. auria* in emulsions of these three refined oils were statistically significant, following a trend of kerosene>diesel>gasoline in order of toxic effects. The values for *T. fuscatus* showed no significant differences.

Dauvin, J-C. (1982)
Impact of *Amoco Cadiz* oil spill on the muddy fine sand *Abra alba* and *Melinna palmata* community from the Bay of Morlaix

Estuar. Coast. Shelf Sci. 14:517-531

ABSTRACT
Thirteen quantitative quarterly samples of the *Abra alba - Melinna palmata* community from the Bay of Morlaix (France) were taken from August 1977 to August 1980. The quantitative and qualitative changes in the community subsequent to the *Amoco Cadiz* oil pollution (April 1978) could thus be studied. Hydrocarbons were present in the sediments in exceptionally high quantities for more than a year after the oil spill, and then they decreased sharply. The numbers of species in the community increased as a whole during the three years' observation. Some species that disappeared after April 1978 have not yet reappeared. Density and biomass showed important seasonal variations, with summer maxima and winter minima and with a net dominance by the polychaete populations. During the first annual cycle after the pollution, there was a sharp increase in the density of some species which were present in very low or very high numbers before the pollution.

Dauvin, Jean-Claude. (1987)
Evolution a Long Terme ~1978-1986) des Populations d'Amphipodes des Sables Fins de la Pierre Noire (Baie de Morlaix, Manche occidentale) Apres la Catastrophe de l'*Amoco Cadiz*

Mar. Environ. Res. 21:247-273

ABSTRACT
Greatly reduced in 1978 by the *Amoco Cadiz* oil spill, the amphipod populations of the fine sand community of Pierre Noire in the Bay of Morlaix, have not yet fully recovered eight years after the pollution. The sublittoral sandy-mud benthic communities in the western part of the English Channel

show a discontinuous distribution, occurring in isolated zones which are localized in estuaries and bays. The amphipods, which are characteristic of these communities and lack a pelagic larva, form insular populations. This insular distribution delays their re-introduction to the fine sand community of Pierre Noire. Moreover, the biological and demographic characteristics of the species entail limited periods of recolonization and increase in population.

Dauvin, J.C. and F. Gentil (1990)
Conditions of the peracarid populations of subtidal communities in northern Brittany ten years after the *Amoco Cadiz* oil spill.

Mar. Poll. Bull. 21:123-130

ABSTRACT
Peracarid populations were greatly reduced in 1978 by oil from the *Amoco Cadiz*. Ten years after the spill, a benthic survey was conducted in the soft-bottom infralittoral communities of the bays of Morlaix and Lannion and the Aber Wrac'h channel to study the state of recovery of peracarid populations. Living in isolated populations in fine sand and muddy sand communities with low potential for immigration, the recolonization and the reconstitution of these perturbed populations was expected to be slow. The amphipod populations from the subtidal channel of Aber Wrac'h, which were initially the most affected by the oil spill, were in the least advanced state of recovery. Some species present in abundance before the oil spill were not rediscovered. Nevertheless, ten years after the oil spill, most of the populations had completely recovered.

Davies, W.P., G.L. Scott, C.D. Getter, M.O. Hayes, and E.R. Gundlach (1980)
Methodology for environmental assessments of oil and hazardous substance spills

Proceedings 14th European Marine Biological Symposium on Protection of Life in the Sea (Kinne O. and H.P. Bulnheim, eds.). Helgol. Meer. 33:246-256

ABSTRACT
Ecological assessment of oil and hazardous material spills has been divided into three distinct phases: (1) First-order response studies conducted at the time of the initial spill event, (2) Second-order response studies conducted two months to one year post-spill, which document any delayed mortality and attempt to identify potential sublethal impacts in sensitive species, and (3) Third-order response studies conducted one to three years post-spill, to document chronic impacts (both lethal and sublethal) to specific indicator species. The need for contingency planning before a spill is discussed along with the use of the Vulnerability Index, a method in which coastal environments are classified on a scale of 1-10, based upon their potential susceptibility to oiling. A study of the lower Cook Inlet section of the Alaskan coast illustrates the practical application of this method.

Davies, W.P., D.E. Hoss, G.I. Scott, and P.F. Sheridan (1984)
Fisheries resource impacts from spills of oil or hazardous substance

Restoration of Habitats Impacted by Oil Spills (J. Cairns Jr. and A.L. Buikema, eds.) Boston: Butterworth Publishers, pp. 157-172

ABSTRACT
Oil pollution is a potential impact to fisheries resources for three reasons: a direct (lethal or sublethal) effect to fisheries stocks may occur, oil may render the fisheries products unacceptable to the consumer, and fishing operations may be directly affected by the presence of oil. These reasons may be extended to other hazardous or toxic materials. Examples have been documented for each of these reasons. High mortalities occurred among oysters in the estuaries of Brittany, France during the 1978 *Amoco Cadiz* spill. oysters and other fisheries resources elsewhere have acquired hydrocarbon taint from spills or seepages. The vast areas covered by oil released from the IXTOC I well blowout near Campeche, Gulf of Mexico in 1979 caused shrimpers and other fishermen to change location of their operations.

Davis, P.H. and R.B. Spies (1980)
Infaunal benthos of a natural petroleum seep: study of community structure

Mar. Biol. 59:31-41.

ABSTRACT
At eight-week intervals from December 1975 through March 1978, we took a census of the infaunal benthic invertebrates at a natural petroleum seep near Santa Barbara, California, and at an area nearby where no fresh petroleum occurred in the sediments. Both sites had in common 72 percent of the populations, representing over 90 percent of the individuals, strongly suggesting that the two sites are part of the same community. At the petroleum seep there were higher densities of individuals in many populations (~60 percent), but no dramatic difference in diversity (Shannon-Wiener or dominance diversity). The seep populations tended to be more variable from one sampling period to the next, possibly due, at least in part, to large larval settlements there. The most abundant populations at the seep site were dominated by deposit feeders (14 of the 15 species considered), especially oligochaetes which are extremely rare at the comparison site. The discussion includes a hypothesis of trophic enrichment of the seep populations by bacterial growth stimulated by fresh petroleum.

Dean, T.A. and S. Jewett (1993)
The effects of the *Exxon Valdez* oil spill on epibenthic invertebrates in the shallow subtidal

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska, pp. 91-93

ABSTRACT
Studies were conducted in 1990 and 1991 to examine the effects of the *Exxon Valdez* oil spill on the shallow subtidal community in Prince William Sound. Here we will present results from a stratified random sampling program that compared population densities of numerically dominant species of large epibenthic invertebrates at oiled and control sites. Sampling in 1990 was conducted within four different habitats within the Sound: eelgrass habitats in shallow protected bays, *Laminaria/Agarum* habitats in sheltered bays (hereafter referred to as bays), *Laminaria/Agarum* habitats on exposed points (hereafter referred to as points), and in *Nereocystis* habitats on

exposed coastlines. Within each habitat we sampled at two to four pairs of oiled and control sites. The oiled sites were selected from areas that had adjacent shorelines that were moderately to heavily oiled during the fall of 1989. Control sites were selected that matched the oiled site with respect to physiographic factors (e.g., exposure, slope, substrate type) but that did not have oil present on adjacent shorelines in Fall 1989. We sampled within one depth stratum in eelgrass and *Nereocystis* habitats, and within two depth strata at bay and point habitats. Divers counted the number of large benthic invertebrates along three randomly placed 30 m by 2 m transects within each site and depth stratum. In 1991, we sampled only in eelgrass beds and within the shallower depth stratum of bays. The sites sampled within these habitats were the same sites sampled in 1990, except that one additional pair of sites was sampled within the eelgrass habitat.

Dean, T.A., M. Stekoll, and S. Jewett (1993)
The effects of the *Exxon Valdez* oil spill on eelgrass and subtidal algae

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska, pp. 94-96

ABSTRACT
Studies were conducted in 1990 and 1991 to examine the effects of the *Exxon Valdez* oil spill on eelgrass (*Zostera marina*) and dominant subtidal algae in shallow subtidal habitats in Prince William Sound. Sampling in 1990 was conducted within four different habitats within the Sound: eelgrass habitats in shallow protected bays, *Laminaria/Agarum* habitats in sheltered bays (hereafter referred to as bays), *Laminaria/Agarum* habitats on exposed points (hereafter referred to as points), and in *Nereocystis* habitats on exposed coastlines. Within each habitat we sampled at two to four pairs of oiled and control sites per habitat. The oiled sites were selected from areas that had adjacent shorelines that were moderately to heavily oiled during the fall of 1989. Control sites were selected that matched the oiled site with respect to physiographic factors (e.g. exposure, slope, substrate type) but that did not have oil present on adjacent shorelines in Fall 1989. We sampled within one depth stratum in eelgrass and Nereocystis habitats, and within two depth strata at bay and point habitats. For eelgrass, we examined a variety of population parameters including percent cover, the density of turions (uprights protruding from the substrate) and the density of flowers. Divers counted the number of turions and estimated percent cover in each of 4 - 0.25 m^2 quadrats along each of three randomly placed 30 m by 2 m transects within each site.

den Hartog, C. and R.P.W.M. Jacobs (1980)
Effects of the *Amoco Cadiz* oil spill on an eelgrass community at Roscoff (France) with special reference to the mobile benthic fauna

14th European Marine Biological Symposium on Protection of Life in the Sea (O. Kinne and H.P. Bulnheim, eds.) Helgol. Meer. 33:182-191

ABSTRACT
In October 1977 an investigation was initiated of the qualitative and quantitative composition of the fauna of the eelgrass (*Zostera marina*) beds at Roscoff. Samples were taken in 2 seagrass beds at different tidal levels in order to follow numerical changes in the course of the year. In March 1978 the area of study was struck by the oil slick of the tanker *Amoco Cadiz*. For this reason, sampling has been continued at the same frequency. The tabulated results show clearly that the oil slick had a profound but selective influence on the various animal groups; some of them disappeared while others were apparently unaffected. Rapid recovery of some species has taken place, but re-establishment of other species, particularly the filter feeders has not been observed. The very

diverse amphipod fauna has disappeared, and has been replaced by a population of *Pherusa fucicola* and *Gammarus locusta*; the latter was absent in the year before the oil disaster took place.

DeVogalaere, A.P. and M.S. Foster (1994)
Damage and recovery in intertidal *Fucus gardneri* assemblages following the *Exxon Valdez* oil spill

Mar. Ecol. Progr. Ser. 106:263-271.

ABSTRACT
In March 1989, the *Exxon Valdez* spilled over ten million gallons of crude oil into Prince William Sound, Alaska. The spill was followed by massive cleanup using hot seawater at high pressure as well as other mechanical and chemical techniques. We studied initial damage and subsequent recovery in the upper margin of the *Fucus gardneri* assemblage on protected shores by comparing sites that were unoiled, oiled and cleaned with hot water at high pressure, and oiled but less intensely cleaned. *F. gardneri* cover averaged 80 percent on unoiled sites but greater than one percent on all oiled and cleaned sites 18 months after the spill. The abundances of barnacles, littorine snails, and limpets varied among sites and species, and this variation was associated in part with differences in their life histories. *F. gardneri* cover was still extremely low on oiled and cleaned sites 2.5 years after the spill. Holdfasts that persisted after cleaning did not resprout. *F. gardneri* recruitment was lowest at intensely cleaned sites, and most recruits occurred in cracks near adults. Recruits were less abundant under adult canopies but placing canopies over recruits did not decrease their survivorship over five months. Natural weathering of tar was rapid, with most marked patches gone in less than one year. We conclude that intense mechanical cleaning following this oil spill increased damage and slowed recovery. Such methods should be avoided if reduction of environmental damage is the primary objective of post-spill management decisions. The recovery of *F. gardneri* at its upper margin might be enhanced by devices that retain moisture and increase substratum rugosity.

Diaz, R.J., L.J. Hansson, R. Rosenberg, P.C. Gapcynski, and M.A. Unger (1993)
Rapid sedimentological and biological assessment of hydrocarbon contaminated sediments

Water, Air, and Soil Poll. 66:251-266.

ABSTRACT
It is possible to rapidly detect the presence of high concentrations of sediment associated with hydrocarbons using a sediment profile camera and simultaneously evaluate the general sedimentological and biological character of a contaminated area. In sediments that were heavily contaminated with hydrocarbons from spills and chronic long-term additions the presence of hydrocarbons was seen about 50 percent of the time in the sediment profile images as unique features, "H spots." The presence of these features was related to the concentration of hydrocarbons in the sediment. In highly contaminated muddy sediments "H spots" were found in images collected at stations that had from 270 to 610 ppt total hydrocarbons. Sedimentological and biological information obtained from the sediment profile images confirmed the impacted nature of Elizabeth River sediments. Sediment profile imaging provide a means of obtaining an overall evaluation of the quality of a habitat and impacts on that habitat from pollution related environmental disturbances. While qualitative, an advantage of sediment profile image data is that they can be evaluated in less than a day and used to quickly locate inclusions of hydrocarbons in the sediments for further quantitative chemical or biological sampling, or mapping of heavily contaminated areas.

Dicks, B., and R. Iball (1981)
Ten years of salt marsh monitoring- The case history of a Southampton water salt marsh and changing refinery effluent discharge

Proceedings of the 1981 Oil Spill Conference, pp. 361-374.

ABSTRACT
One of the largest refinery and petrochemical plants in the U.K. has been discharging its effluents into the creek system of a *Spartina anglica*-dominated salt marsh in Southampton water since 1953. This resulted in extensive damage to the marsh system up to 1971. At that time, a program of effluent quality improvement commenced that has resulted first in recolonization of small areas of damaged marsh followed by extensive recovery. Changes in the marsh vegetation have been studied first by transect surveys in 1969 and 1970 (to assess damage) and subsequently by twice-yearly vegetation mapping resurveys from 1972 to the present. This paper summarizes the data from the ten-year survey. The recovery/recolonization has continued progressively to the present day, with improvements in several annual and perennial marine species that have been successful colonizers; the original dominant *Spartina anglica* has recolonized only poorly. In addition to vegetation mapping, several series of *Spartina* transplantation experiments have been carried out to precisely define areas of continued effluent impact. These have formed a nucleus for *Spartina* recolonization in some parts of the marsh and may well speed up the return of this species in these areas. Using these relatively simple techniques it has been possible to identify differences in toxicity between different outfalls. This has been taken into account in site effluent management policy. Research programs have recently been extended to include recolonization of the marsh by intertidal animals and detailed analyses of hydrocarbon contents of sediments over the marsh. Preliminary results from these programs are described. These additional techniques improve monitoring sensitivity and provide valuable information for interpreting long-term continued effluent improvements being undertaken by the refinery.

Dixon, I.M.T. (1987)
Experimental application of oil-based muds and cuttings to seabed sediments

In: J. Kuiper and W.J. Van den Brink (eds.). *Fate and Effects of Oil in Marine Ecosystems*. Dordrecht, Netherlands: Martinus Nijhoff Publishers.

ABSTRACT
Between September 1984 and July 1985, a field experiment was carried out in Milford Haven to follow the macrofaunal effects and subsequent recovery from a single application of used diesel and "low-toxicity" oil-based muds (OBM). Six treatments, including two levels of cuttings addition, were investigated and each was replicated three times in a randomized block experimental design. The cuttings' treatments were designed to give surficial sediment hydrocarbon concentrations of about 5,000 ppm (high dose) and 400 ppm (low dose). Treatments were applied by divers to marked seabed plots (2 m by 2 m). Core samples were taken for hydrocarbon, sedimentological and macrofaunal analysis prior to treatment and then subsequently at two weeks, one month, and then two monthly intervals for a total period of ten months. Prior to treatment no hydrocarbon or biological gradients across the experimental site were discernible. Following treatment, sediment hydrocarbon concentrations tended to fall rapidly within the first month, followed by a period of slower removal. Evidence of OBM contamination had disappeared from the low-dose plots after four to six months. In the high-dose plots hydrocarbon levels had all fallen almost to within the background range of values by ten months, but slight contamination was still evident on all gas-liquid chromatography traces. Faunal disturbance was minor and significant effects were mainly recorded from the high-dose plots where the initial effect of oiled cuttings addition was to depress

faunal density, species richness and diversity relative to controls. Population reductions were observed in a number of species but no expansion of opportunists occurred. In the high-dose plots, total faunal density and the abundance of certain species remained depressed for the duration of the experiment. Faunal disturbance occurred more rapidly following diesel treatment than with low-tox treatment; reflecting the greater acute toxicity of the former. After one or two months, however, the longer-term effects of low-tox OBMs became indistinguishable from those of the diesel treatment.

Dow, R.L. (1975)
Reduced growth and survival of clams transplanted to an oil spill site

Mar. Poll. Bull. 6:124-125.

ABSTRACT
Production of soft clams fell 20 percent in two years following oil pollution although in adjacent mudflats production increased by 250 percent. Transplanting uncontaminated clams into this area confirmed poorer survival and slower growth in polluted mud.

Dow, R.L. and J.W. Hurst, Jr. (1975)
The ecological, chemical and histopathological evaluation of an oil spill site, Part I: ecological studies

Mar. Poll. Bull. 16:164-166.

ABSTRACT
An oil spill into Long Cove, Searsport, Maine, began on March 16 and lasted until at least June 30, 1971. It resulted in immediate and continuing soft clam mortalities which, based on before and after biological surveys, had by August 1974 exceeded 85 percent of the estimated 50 million market-size clams occupying the area.

Dow, R. L. (1978)
Size-selective mortalities of clams in an oil spill site

Mar. Poll. Bull. 9:45-48

ABSTRACT
Mixed No. 2 fuel oil and JP 5 jet fuel, following an oil spill into Long Cove, Searsport, Maine in March 1971 was concentrated locally at levels up to more than 250 ppm in intertidal sediments from 15 to 25 cm below the surface and continued until 1976 to kill successive year class juvenile clams as in normal growth behavior they burrowed down through redistributed overlying clean sediments into the oil concentration beneath.

Driskell, W.B., A.K. Fukuyama, J. Houghton, D.C. Lees, G. Shigenaka, and A.J. Mearns (1993)
Impacts on intertidal infauna: *Exxon Valdez* spill and subsequent cleanup

Proceedings of the 1993 Oil Spill Conference, pp. 355-361.

ABSTRACT
Field surveys were conducted throughout Prince William Sound in the summers of 1990 through 1992 to evaluate recovery of infauna from the effects of oiling and shoreline cleaning treatments following the *Exxon Valdez* oil spill. Infauna were quantitatively sampled at mixed, sand/gravel/cobble beaches categorized into treatment groups according to their general degree of disturbance: (1) Category 1: unoiled reference sites; (2) Category 2: oiled sites, not hot-water washed; (3) Category 3: oiled sites, "cleaned" with hot-water flushes. Shoreline treatments applied in 1989 and 1990 had varied effects on intertidal infauna including organism displacement and burial, thermal stress, oil dispersion, and transformed beach morphology. These treatments resulted in significant reductions in infauna (total abundance and diversity, as well as densities of polychaetes, bivalves, and some crustaceans) at Category 3 beaches. In contrast, Category 2 beaches had a richer and more varied infauna than Category 3 beaches. Multivariate analyses indicate some trends in recovery; namely a convergence by certain Category 2 sites toward the Outside Bay, Category 1 control site. PAH concentrations in 1990 also suggest that treatments acted to move some hydrocarbons downslope from the upper beach into the shallow subtidal. By 1991, PAH concentrations in the shallow subtidal were no longer at the high levels seen in 1990, but PAH levels at other elevations of Category 3 sites remained at about the same levels as in 1990.

Duncan, P.B., A.J. Hooten, and R.C. Highsmith (1993)
Influence of the *Exxon Valdez* oil spill on intertidal algae: tests of the effect of residual oil on algal colonization

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska, pp. 179-181.

ABSTRACT
Following the *Exxon Valdez* oil spill in 1989, we began to study the effects of stranded oil on algal colonization in rocky intertidal communities in Prince William Sound. This knowledge is critical because (1) algae are extremely important structurally and functionally to intertidal communities; (2) there appears to be a predictable succession of organisms following a spill, and enhancement of the early phases could reduce the time to recovery; (3) there is evidence that oil inhibits algal growth (Straughan 1971); and (4) there is evidence that cleanup measures on rocky shores might even delay recovery, if their biotic effects are as harmful as those of the oil (Thomas 1978; Foster et al. 1990). As part of recovery from a spill, succession on oiled substrates can differ from natural succession, due to residual toxicity of the oil, large scale mortality that reduces available propagules, and loss of herbivores (Southward and Southward 1978). We were particularly interested in whether normal mechanisms of colonization were affected by the stranded Exxon Valdez oil, so we examined the initial stages of a succession, the settlement, growth, and early survivorship of algae. Rocks or tiles were used as substrates for colonization. In 1989, oiled rocks of a similar size were collected from beaches on Knight and Eleanor islands. In 1990, oiled rocks were collected from the western arm of Herring Bay. In addition, clean rocks were collected from the supratidal zone in southeast Herring Bay, coated with fresh Prudhoe Bay oil, and allowed to weather for a month until the oil was a tarred consistency. Ceramic tiles were similarly prepared with Prudhoe Bay crude oil.

Dutrieux, E. (1992)
Experimental study of the impact of hydrocarbons on the intertidal benthic community: the Mahakam Delta (East Kalimantan, Indonesia)

Oceanol. Acta 15(2):197-209

ABSTRACT
Two simulated oil spills in the Mahakam Delta revealed the consequences of this type of pollution on the site's main benthic populations. The results of these trials differentiated between short-term (high toxicity similar to chemical pollution) and long-term effects (similar to organic pollution) of hydrocarbons. Two factors affected the distribution of the main macrofaunal species: intertidal height and degree of pollution. The latter was measured either by the initial quantity of oil spilled or by concentrations measured at each sampling. These trials also showed that dispersants were inefficient and that dredging treatments did not yield positive results. Often no treatment was preferable to these treatment. A global statistical analysis was generated to define the role of the different environmental variables, both natural or pollution-related, in the spatial distribution of the different species.

Duval, W., S. Hopkinson, R. Olmsted, and R. Kashino (1989)
The *Nestucca* oil spill: preliminary evaluation of impacts on the west coast of Vancouver Island

Report for Environment Canada and BC Ministry of Environment by ESL Environmental Sciences, Ltd.; Vancouver, B.C., Canada

ABSTRACT
On December 23, 1988, a collision occurred between the fuel barge *Nestucca* and its tender tug *Ocean Service* off the mouth of Grays Harbor in the state of Washington. The barge had a cargo capacity of 11.2 million liters and was transporting heavy Bunker C oil. An estimated 875 000 L of this volume was reported to be spilled near Grays Harbor, which is located 175 km from the US-Canada border. An unknown proportion of this oil moved north and eventually stranded on shorelines along the west coast of Vancouver Island in British Columbia.

Several projects and activities were initiated to determine the immediate or short-term impacts of the *Nestucca* oil spill on the biophysical environment of the west coast of Vancouver Island. The results of many of these studies are described in this report, while other investigations are only identified here and will be discussed in more detailed reports to be prepared by various federal and provincial government agencies. Longer-term research programs are in progress or are being planned on the fate of oil in key environmental compartments and the effects of Bunker C from the *Nestucca* on Valued Ecosystem Components. The overall objective of such investigations would be to assess the impact of the *Nestucca* oil spill on the Canadian marine environment.

Oil from the *Nestucca* was observed in a variety of different forms in marine environments along the coast of Vancouver Island. Types of oil varied from thin sheens to heavy encrustations on rocks and logs, "patties" of varying size and density, oil fouled in eelgrass and algal growth, and heavy black sticky oil adhering to crab traps and on the carapaces of Dungeness crabs. Bunker C from the *Nestucca* was at sea from 1-3 weeks before stranding in coastal areas of Vancouver Island and underwent substantial "weathering" during this period, despite the low air and water temperatures in January. Nevertheless, strong odors and visible sheens persisting through March indicated that some volatile fractions remained during this period.

The *Nestucca* spill resulted in some mortality and damage to plants within the intertidal zone. Much of the oil-contaminated debris removed by clean-up crews during shoreline restoration programs was storm-blown kelp and eelgrass. Losses of intertidal algae occurred in rocky and sandy habitats, particularly in those areas where either the entire intertidal zone was coated with oil or oil stranded in upper intertidal areas over successive tidal cycles (i.e., where re-oiling occurred).

Salt-marsh habitat in a lagoon at Friendly Cove on Nootka Island was extensively contaminated with Bunker C and required an intensive clean-up effort. Marsh grasses can be severely affected by oil contamination and can require many years to recover. This is because of the tendency of oil to penetrate and persist in the sediments, thereby resulting in long-term toxic effects as a result of the uptake of petroleum hydrocarbons through the root systems of these plants. Salt-marsh habitats are very sensitive to oil spills. Despite efforts to remove most of the oil-contaminated marsh vegetation from Friendly Cove, it is probable that at least some oil penetrated the sediments and that additional oil remains on uncropped grasses.

There were no observations of the effects of the *Nestucca* spill on benthic infauna (invertebrates living within the upper layer of sediments on the seafloor). Mortality of infauna has only been documented infrequently following bunker fuel spills.

Observations of dead gammarid amphipods on oil mats indicate that some losses of intertidal fauna occurred in areas where oil stranded. The most common cause of mortality among intertidal species is smothering by thick layers of stranded oil. There is often complete elimination of intertidal fauna in heavily-oiled areas. This may have occurred in the relatively localized areas that were heavily oiled.

Ebert, T., D. Lees, and H. Cumberland (1993)
Growth and survival of the predatory snail *Nucella lamellosa* in areas exposed to the *Exxon Valdez* oil spill

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska, pp. 73-74

ABSTRACT
Populations of the predatory snail *Nucella lamellosa* (frilled dogwinkle or drill) were studied in Prince William Sound to determine growth and survival at oiled, oiled and cleaned, and unoiled sites. In 1991, individual tags were used to mark animals in resident stocks where possible, or, at sites where populations had been decimated, to tag animals imported from a reference population (Hogg Bay) Tagging was done during April/May and July 1991. Samples of animals tagged in May were measured in July 1991 and samples from most sites were again measured in September 1991 and July 1992. Size changes over periods of up to 14 months were used to evaluate growth differences among treatments and recapture rates were used to estimate survival. This study provides insights regarding the efficacy of treatment following an oil spill and complications associated with possible restoration efforts for species with direct development following a major environmental perturbation.

Elkaim, B. (1981)
Amoco Cadiz oil spill effects on sublittoral populations of the Penze Estuary (in French). Original Title: (Effects de la Maree Noire de 1' *Amoco Cadiz* sur le Peuplement Sublittoral de l'Estuaire de la Penze)

Amoco Cadiz: Fates and Effects of the Oil Spill. Proceedings of the International Symposium. pp. 527-537

ABSTRACT
The effects of *Amoco Cadiz* hydrocarbons on the subtidal fauna of Penze (North Brittany) have been studied from samples collected before (1976, 1977) and after pollution (1978). The following conclusions can be drawn: A selective effect on the crustaceans notably peracarids (*Ampelisca, Anseudes, Bathynoreia, Urothoe*) and at the dominance level of zoological groups: A reduction in the populations and density of several marine species (*Gibbula, Nassa, Eunaaurus*). These effects of the oil spill limited to the outer six kilometers of the estuary did not bring about a profound modification of the fauna pattern: the subtidal population presents a greater tendency for a mosaic distribution of facies: The effects observed appear to be reversible, with the possible exception of repopulation by some species (*Anseudes, Urothoe*), which have no pelagic larval stage whose recolonization may be delayed. At the estuary level, the stress effect though limited in space has evolved rapidly with time.

Elmgren, R., S. Hansson, U. Larsson, B. Sundelin, and P.D. Boehm (1983)
The *Tsesis* oil spill: acute and long-term impact on the benthos

Mar. Biol. 73:51-65

ABSTRACT
The *Tsesis* oil spill in October 1977 resulted in the release of over 1,000 tons of medium grade fuel oil in an Archipelago in the brackish Baltic Sea. Considerable oil quantities reached the benthos by sedimentation. Within 6 d benthic amphipods of the genus *Pontoporeia*, as well as the polychaete *Harmothoe sarsi* Kinberg, showed reduction to less than 5 percent of pre-spill biomasses at the most impacted station. The clam *Macoma balthica* (L.) was more resistant, and showed little or no mortality, but was heavily contaminated by oil (about 2,000 ug/g dry wt total hydrocarbons). Not until the second summer after the spill were the first signs of recovery noted at the most heavily impacted station. Three years after the spill *Pontoporeia* spp. biomass was still depressed in the most affected area, while *H. sarsi* showed normal biomass, and *M. balthica* abundance was inflated. Recovery was thus underway, but the lifespan of *M. balthica* implies that the disturbed community composition may persist for many years at this station. Full recovery is likely to require more than five years and may take a decade or more.

Farrington, J.W., A.C. Davis, N.M. Frew, and K.S. Rabin (1982)
No. 2 fuel oil compounds in *Mytilus edulis* : Retention and release after an oil spill

Mar. Biol. 66:15-26

ABSTRACT
M. edulis contaminated by a two-day exposure to a slick from a No. 2 fuel oil spill in the Cape Cod Canal, Massachusetts, USA were sampled six times during an 86-day post-spill period to study the rate of release of fuel oil compounds under field conditions. Typical half-lives were n-alkanes, 0.2-

0.8 days; pristane, 1.5 days; C-2 (dimethyl or ethyl) naphthalenes, 0.9 days; methyl phenanthrenes, 1.7 days. Changes in relative ratios of C-2 phenanthrenes during the release period were observed. The evidence available to date strongly supports the role of molecular weight and accompanying properties of water solubility as the main controlling factors in the rate of release of fuel oil compounds by *M. edulis*. However, the data for the rapid release of n-alkanes and C-2 phenanthrenes also indicate molecular type and molecular configuration as additional key factors.

Feder, H.M., L. M. Cheek, P. Flanagan, S.C. Jewett, M.H. Johnston, A.S. Naidu, S.A. Norrell, A.J. Paul, A. Scarborough, and D. Shaw (1976)
The sediment environment of Port Valdez, Alaska: the effect of oil on this ecosystem

EPA-600/3-76-086; July 1976; Corvallis Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency; Corvallis, Oregon 97330

ABSTRACT
The tidal flat sediments of Port Valdez, Alaska display significant variations in lithological, chemical, and biological subfacies. These variations are attributed to lateral changes in tidal energies and distances from rock outcrops. The tidal flat deposits are poorly sorted, vary from gravels to plastic clays with various admixtures of sand and silt, have low intercalated organic matter, and are constituted chiefly of physically weathered glacial flour. Simulated crude oil spills resulted in no changes in the sediment load, nickel, vanadium and organic carbon content. Only under chronic oil dosages did copper and zinc concentrations increase. The general lack of chemical change in oiled sediments is attributed to (1) inability of glacial sediments to immobilize crude oil and its degradable products, and (2) the swift tidal removal of the oil from tidal flat surfaces. Sediment samples from three intertidal sites in Port Valdez were processed and numbers of filamentous fungi, bacteria and yeasts occurring at various depths in the sediment profile tabulated. Numbers of fungi were low and there was a general decrease in numbers with increased depth. Bacterial numbers varied from site to site but also exhibited a decrease in numbers with depth. Bacterial forms were largely gram negative rods. Fungi were found to be common terrestrial forms of types often isolated from Alaskan soils. Monthly meiofaunal counts were made at a mid-tide station on three beaches in Port Valdez over a two-year period from 1972 through 1974. Additional beaches within Port Valdez and in Galena Bay were sampled when time and logistics permitted. The meiofauna consisted primarily of nematodes and harpacticoid copepods with representatives of the Protozoa, Cnidaria, Platyhelminthes, Nemertinea, Annelida, Tardigrada, and Arthropoda (ostracods, cumaceans and arachnids) present. Several small macrofaunal species were also sampled with representatives of Annelida, Mollusca, and Arthropoda found. Most of the meiofaunal species were restricted to the upper three centimeters of sediment. No seasonal differences in vertical distribution were noted. Distinct seasonal patterns of abundance of meiofauna were observed with densities tending to be highest in the summer and lowest in the winter. High winter meiofaunal densities were recorded in the winter of 1972 through 1973. Total meiofauna population values reached a maximum of 4,682 individuals per ten square centimeters (cm^2) in August 1973. Limited information is presented on the reproductive biology of several harpacticoid copepods with only one species, *Halectinosoma gothiceps*, apparently reproducing throughout the year. A macrofaunal clam species, *Macoma balthica*, was most abundant in July and early August with many recently settled young present. The biology of the harpacticoid copepod *Harpacticus uniremis* Kroyer was studied for three years on an intertidal beach in Port Valdez, Alaska. The species shows a relatively distinct reproductive period with a single brood of eggs produced approximately 9 to 10 months after insemination. The harsh environmental conditions typical of sediment beaches in Port Valdez and the resultant selective pressures acting on *H. uniremis* there have resulted in high fecundity. Males do not live longer than six months while the longevity of females is at least ten months.

The properties of the silt sediment ecosystem at Port Valdez have important biological consequences that affect the ability of bacterial population to degrade additional organic material. The bacterial populations were unaffected by single applications of up to 2,000 ppm of oil, or by chronic applications applied for several consecutive days during several low tide series. However, when the sediment was enriched in situ by algal growth and oil seepage and in in-vitro model systems, the bacteria responded with an increase in biomass, an increase in respiratory activity, and the formation of a sulfide system in sediment columns. Except for heterotrophic H_2S-producing bacteria, the sulfur cycle bacteria were present in very low numbers. It is concluded that oil and other organic matter are removed by tidal action, leaving an organically poor and relatively biologically inactive ecosystem. Three species of copepods (*Harpacticus uniremis, Heterolaophonte sp., Halectinosoma gothiceps*) exposed to various levels of oil (200, 500, 1,000, and 2000 ppm) in the field significantly increased in density within a variable number of oiled plots. Two of the species, *H. gothiceps* and *Heterolaophonte sp.*, also demonstrated an increase in reproductive activity in some of the oiled plots. The statistically significant increase in numbers of individuals in conjunction with the increase in reproductive activity for these species suggest that density increments are primarily a reflection of heightened reproductive activity. On the other hand, the slight increase in numbers of *H. uniremis* in some of the oiled plots could be the result of an attraction of the copepod to oil since this species was not reproducing during the experimental period. The responses of the copepods to oil in Port Valdez are in contrast to observations made in the laboratory elsewhere in which crude oil fractions were found to be toxic to various species of pelagic copepods. Further experimental work is recommended to fully comprehend the results of our experiments. The uptake and release of added Prudhoe Bay crude oil by intertidal sediments and by *Macoma balthica*, a resident of those sediments, has been studied at Port Valdez, Alaska. Under the experimental conditions used, petroleum was no longer detectable two months after a five day oiling procedure designed to simulate the stranding of a light oil slick. During the experimental period a significant increase in mortality was noted for *M. balthica* exposed to oil as compared to the clams in the unoiled control plots.

Feder, H.M., A.S. Naidu, and A.J. Paul (1990)
Trace element and biotic changes following a simulated oil spill on a mudflat in Port Valdez, Alaska

Mar. Pollut. Bull. 21:131-137

ABSTRACT
A mudflat in Port Valdez, Alaska, was examined to determine effects of experimental additions of Prudhoe Bay crude oil on metal chemistry and harpacticoid copepod abundance. Hydrocarbon concentrations were at background levels 30 days after final addition of oil. The short residence time of oil added to sediments is attributable to physical removal of oil by tides, low sediment permeability, and low affinity of hydrocarbons for periglacial clay surfaces. Elemental concentrations, except Si, were lower in oiled than in unoiled sediments. Elemental depletion in oil-impacted sediments is attributable to mobilization of metals from oxide/hydroxide sediment phases or to desorption from clay due to lowering of Eh-pH of sediments subsequent to oil addition. In oiled sediments, abundance of harpacticoid copepods was similar to or higher than values within unoiled plots. The reasons for lack of deleterious effects of oil on copepods in Port Valdez are not yet understood.

Fleeger, J.W., M.A. Todaro, T.C. Shirley, and M. Carls (1993)
Meiofaunal Recolonization Experiment with Oiled Sediments; The Harpacticoid Copepod Assemblage

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska, pp. 176-178.

ABSTRACT
To gain insight into the effects of the *Exxon Valdez* oil spill on the meiobenthos (small organisms living on the ocean floor) of Prince William Sound, Prudhoe Bay crude oil was used in a colonization study initiated in 1990. Sediment, collected near Juneau, Alaska, was repeatedly frozen and thawed, washed with freshwater and sieved through 2 and 0.417 mm screens to kill and remove meiofauna. Prudhoe Bay crude oil was added and mixed into this azoic sediment to reach concentrations of 0.5 and 1.7 percent crude oil. The resulting mixture was added to replicated colonization trays (13 by 28 by 33 cm). Non-oiled azoic sediments were added to additional trays. Triplicate trays of all treatments were placed flush with the sediment surface on beach transects in a randomized block design near mean low water (-0.6 m) in Herring Bay (a cove that was heavily oiled from the *Exxon Valdez* spill), Prince William Sound. Trays were sampled by coring on days 0, 1, 2, and 29. Cores were also collected from nearby undisturbed ambient sediments on each collection date, including Day 0, to quantify the colonizing source pool. Here, we report on an analysis of the harpacticoid copepod species from these collections.

Flower, R.J. (1983)
Some effects of a small oil spill on the littoral community at Rathlin Island, Co. Antrim

Irish Naturalists' Journal 21:117-120

ABSTRACT
The trawler, *Ella Hewirt*, sank in Church Bay, Rathlin Island, during November 1962. Small quantities of bunker oil leaked from the trawler until 21 September 1978 when the Royal Navy destroyed the wreck with controlled explosions. This caused about 170 tons of oil to be washed onto the shores of Church Bay. Attempts were made to remove the stranded oil from the rocky shores (chemical dispersants) and sandy beach (mechanical methods). In order to determine the long-term effects of the oil on the rocky shores, observations were made during May 1979 and November 1980. During May 1979, one transect was run on an oiled shore and one was run on a similar unoiled shore, approximately 120 m away. The abundances of invertebrates and algae were similar along the two transects, however the sea anemone, *Actinia equina*, was abundant at the unoiled site and rare at the oiled site. During November 1980 the abundances of the sea anemone were similar along the two transects. Therefore I conclude that the rocky shore organisms had recovered from the effects of the oil spill within two years.

Foster, M.S., A.C. Charters, and M. Neushul (1971)
The Santa Barbara oil spill Part 1: initial quantities and distribution of pollutant crude oil

Environ. Pollut. 2:97-113.

ABSTRACT
The quantity of oil which came ashore during the early stages of the Santa Barbara oil spill has been estimated from intertidal oil samples and aerial photographs. These methods indicate that 4,500 metric tons of crude oil were deposited on nearly 90 km of coast by February 8, 1969, eleven days after the spill began. Dosages in the intertidal zone varied from 2.7 to 118.1 metric tons/km. These

dosage estimates suggest that the flow rate at the well was around 5,000 barrels (726 metric tons) per day during the early stages of the spill. A large quantity of oil was held for varying periods of time in the surface canopies of offshore kelp beds. The interaction of wind, wave action, tides, and substrate determined the pattern of oil distribution within the intertidal zone.

Foster, M.S., M. Neushul, and R. Zingmark (1971)
The Santa Barbara oil spill Part 2: initial effects on intertidal and kelp bed organisms

Environ. Pollut. 2:115-134.

ABSTRACT
The initial effects of the Santa Barbara oil spill on intertidal and kelp bed organisms were studied. Based on earlier surveys, the greatest negative biological change at a sample station after the spill was the loss of 16 plant species. However, losses in species were correlated in most cases with sand movement, and may have been related to the severe storms which occurred before and during the oil spill. Although gross species changes were not correlated with oil dosage, severe damage occurred in intertidal surf grass and barnacle populations as a result of the oil pollution. Potential long-term biological effects of the continuing pollution are discussed.

Foster, M.S. and R.W. Holmes (1977)
The Santa Barbara oil spill: an ecological disaster?

pp. 166-190 In: J. Cairns Jr., K.L. Kickson, and E.E. Herricks (eds.) *Recovery and Restoration of Damaged Ecosystems.* University Press of Virginia, Charlottesville.

ABSTRACT
In its initial stages, the 1969 Santa Barbara oil spill released over 70,000 barrels of crude oil into the Santa Barbara Channel. This oil eventually polluted the entire channel and over 230 km of mainland and Channel Island shore. The greatest known damage occurred in surfgrass communities and barnacle and bird populations; an estimated nine million barnacles and 9000 birds were killed, and over fourteen tons of surfgrass blades and associated organisms were lost. The oil also affected other populations, but, in general total damage cannot be determined. Cleanup procedures resulted in additional damage on both rocky shores and sandy beaches. Although some populations have recovered, the lack of prespill and postspill information makes it impossible to determine adequately the long-term effects. In addition, the size of the spill, diversity of habitats affected, and lack of ecological information combine to make an overall "disaster" assessment impossible. The inherent difficulties in assessing biological damage and recovery resulting from such a pollution incident suggest that every effort must be made to prevent and contain future spills.

Foster, M.S., J.A. Tarpley, and S.L. Dearn (1990)
To clean or not to clean: the rationale, methods, and consequences of removing oil from temperate shores

The Northwest Environ. Journal 6:105-120.

ABSTRACT
Oil spilled on the shore is aesthetically offensive, disrupts recreational and commercial uses of the polluted area, and damages organisms and habitats. Except for chronically polluted areas, such as natural oil seeps and harbors, oil eventually degrades and ecosystems recover. This may, however,

take months to years, depending on the amount and kind of oil spilled, the size of area polluted, and types of habitats and organisms affected. Therefore, a large effort usually is made to remove or disperse stranded oil as quickly as possible. Although often not explicitly stated, the traditional rationale for most cleanup activities has been political and economic.

Ganning, B., D.J. Reish, and D. Straughan (1984)
Recovery and restoration of rocky shores, sandy beaches, tidal flats, and shallow subtidal bottoms impacted by oil spills

In: Cairns, J. Jr. and A.L. Buikema (eds.) *Restoration of Habitats Impacted by Oil Spills.* Boston: Butterworth Publishers. pp. 7-36.

ABSTRACT
The authors use a modified definition where recovery comprises the return of the ecosystem to within the limits of natural variability. Natural variability may include alternative components of the ecosystem or even a modified one, but it is a natural and functional ecosystem for the area. Restoration in this context is the return of the ecosystem to within limits of natural variability by natural and/or artificial means. Discussion of the ecological effects of oil and possible cleanup actions in different types of habitats necessitates defining the types of oil. This discussion deals with three different main types of petroleum: (1) heavy black oil that includes most crude oils and heavy fuel oils, (2) light refined products such as diesel and light fuel oils, gasoline, etc., and (3) the water-in-oil emulsion called mousse. This division is based largely on physical characteristics because these tend to dictate the methods of cleanup and/or restoration.

Getter, C.D., G. Cintron, B. Dicks, R.R. Lewis III, and E.D. Seneca (1984)
The recovery and restoration of salt marshes and mangroves following an oil spill

In: Cairns, J. Jr. and A.L. Buikema (eds.) *Restoration of Habitats Impacted by Oil Spills.* Boston: Butterworth Publishers, pp. 65-114.

ABSTRACT
This chapter reviews briefly those portions of these studies that are relevant to determining the effects of oil on marine wetlands. Also, the literature is synthesized to allow an evaluation of methods of protection, cleanup, and restoration attempts that have been carried out in marine wetlands. This chapter accomplishes these two objectives by: providing a brief review of the effects of oil spills and related cleanup activities on salt marshes and mangrove ecosystems; reviewing methods of protecting marine wetlands from being oiled; reviewing successful means of cleaning marine wetlands following oil spills; reviewing and presenting techniques that have proven successful in restoring marine wetlands damaged by oil spills and/or cleanup operations; establishing a set of criteria and discussing guidelines for decisions on means of protecting susceptible areas, and for cleaning and restoring oiled marine wetlands.

Gilfillan, E.S., and J.H. Vandermeulen (1978)
Alterations in growth and physiology of soft-shell clams, *Mya arenaria*, chronically oiled with Bunker C from Chedabucto Bay, Nova Scotia, 1970-76

J. Fish. Res. Bd. Can. 35:630-636

ABSTRACT
Two populations of soft-shell clam, *Mya arenaria*, one from a chronically oiled lagoon (since the *Arrow* oil spill in 1970) and the other from an unoiled lagoon, were compared as to population structure, growth, and metabolism. The oiled lagoon sediments contained up to 3,800 µg/g oil (W determination), and clams up to 200 µg/g hydrocarbon in their tissues (fluorescence). The oiled population of clams differed from the unoiled population in lower total numbers with fewer mature adults, a one to two-year lag in tissue growth, a lower shell growth rate, and a reduced carbon flux with a lower assimilation rate. Results are interpreted to indicate that the recovery potential of *M. arenaria* in these oiled sediments is low and that these oiled populations remain under continued stress six years after the *Arrow* spill.

Gilfillan, E.S., S.A. Hanson, D. Vallas, R. Gerber, D.S. Page, J. Foster, J. Hotham, and S.D. Pratt (1983)
Effect of spills of dispersed and non-dispersed oil on intertidal infaunal community structure

Proceedings of the 1983 Oil Spill Conference, pp. 457-463.

ABSTRACT
The effect of two nearshore discharges of Murban crude oil on community structure in intertidal benthic communities was studied. One discharge consisted of 250 gallons of Murban crude only. Following the discharge, no measurable amount of Murban crude could be found in sediments exposed to the cloud of dispersed oil. Significant amounts were found in the test plot exposed to untreated oil. In the area exposed to untreated oil, more oil was found in the upper intertidal zone than lower down. Effects on infaunal communities mirrored the analytical results. There was no evidence of adverse effects on infaunal community structure from exposure to dispersed oil. There is clear evidence that exposure to untreated oil did adversely affect community structure. Some indigenous species were reduced in number or eliminated; there were blooms of opportunistic polychaetes. The changes in community structure brought about by the untreated oil are consistent with results observed at real-world oil spill sites.

Gilfillan, E.S., D.S. Page, S.A. Hanson, J. Foster, J. Hotham, D. Vallas, E. Pendergast, S. Hebert, S.D. Pratt, and R. Gerber (1985)
Tidal area dispersant experiment, Searsport Maine: an overview

Proceedings of the 1985 Oil Spill Conference, pp. 553-559.

ABSTRACT
On August 19, 1981 two test spills of Murban crude oil were carried out in Long Cove, Searsport, Maine. One spill was chemically dispersed; the other was not. Measurements were made to make quantitative comparisons of the chemical fates and biological effects of the two spills. Hydrocarbon analyses were carried out on water samples, animal tissue samples, intertidal sediment samples, and subtidal sediment samples. Biological measurements were carried out at the community level, whole animal level, and biochemical level of organization. No significant biological

effects attributable to the dispersed oil spill were observed. This lack of effects is, in part, a result of changes in the physical and chemical properties of dispersed oil which help limit its availability and toxicity. The chemical fate and biological effects of the undispersed oil were typical of those reported from actual oil spill sites. Oil was incorporated into sediments and animal tissues. On the community level of organization, reduced diversity and evenness, increased population density, and increased dominance by opportunists were all observed immediately after the spill, and up to one year later. On the whole animal level of organization, no effects on scope-for-growth were observed in two filter-feeding bivalves. On the biochemical level of organization, activities of two sensitive enzyme systems were elevated.

Gilfillan, E.S., D.S. Page, B. Griffin, S.A. Hanson, and J. Foster (1987)
The importance of using appropriate experimental designs in oil spill impact studies: an example from the *Amoço Cadiz* oil spill impact zone

Proceedings of the 1987 Oil Spill Conference, pp. 503-507

ABSTRACT
On March 16, 1978 the tanker *Amoco Cadiz* ran aground off the coast of North Brittany. Her cargo of 221,000 tons of light crude oil was released into the sea. More than 126 miles of coastline were oiled, including a number of oyster (*Crassotrea gigas*) growing establishments. The North Brittany coastline already was stressed by earlier additions of oil and metals. In December 1979, 21 months after the oil spill, measurements of glucose-6-phosphate dehydrogenase activity, aspartate aminotransferase activity, and condition index were made in fourteen populations of *C. gigas*. Five of the populations were outside of the oil spill impact zone; nine populations were within it. At the same time the body burden of chromium, silver, zinc, copper, cadmium, palladium, and mercury, as well as the body burden of aliphatic and aromatic hydrocarbons, was determined. Also at the same time, the numbers of total and fecal coliform bacteria in the ambient water were determined. Results of stepwise multiple regression have shown that 21 months after the *Amoco Cadiz* oil spill, aromatic hydrocarbons were only one of three factors adversely affecting *C. gigas* populations in North Brittany. Multiple regression techniques can be extremely useful in identifying those stressors associated with physiological effects in populations of animals.

Gilfillan, E.S., T.H. Suchanek, T.H. Boehm, E.J. Harner, D.S. Page, and A.N. Sloan (1995a)
Shoreline impacts in the Gulf of Alaska region following the *Exxon Valdez* oil spill

In Wells, P.G., J.N. Butler, and J.S. Hughes (eds.), *Exxon Valdez Oil Spill: Fate and Effects in Alaskan Waters*. ASTM STP 1219. Philadelphia: American Society for Testing and Materials, pp. 444-481.

ABSTRACT
Forty-eight sites in the Gulf of Alaska region (Kodiak Island, Kenai Peninsula, and Alaska Peninsula) were sampled in July/August 1989 to assess the impact of the March 24, 1989 *Exxon Valdez* oil spill on shoreline chemistry and biological communities hundreds of miles from the spill origin. In a 1990 companion study, 5 of the Kenai sites and 13 of the Kodiak and Alaska Peninsula sites were sampled 16 months after the spill. Oiling levels at each site were estimated visually and/or quantified by chemical analysis. The chemical analyses were performed on sediment and/or rock wipe samples collected with the biological samples. Additional sediment samples were collected for laboratory amphipod toxicity tests. Mussels were also collected and analyzed for hydrocarbon content to assess hydrocarbon bioavailability. Biological investigations at these Gulf of Alaska sites focused on intertidal infauna, epifauna, and macroalgae by means of a variety of common ecological

techniques. For rocky sites the percentage of hard substratum covered by biota was quantified. At each site, up to five biological samples (scrapes of rock surfaces or sediment cores) were collected intertidally along each of three transects, spanning tide levels from the high intertidal to mean-lowest-low-water (zero tidal datum). Organisms (down to 1.0 mm in size) from these samples were sorted and identified. Community parameters including organism abundance, species richness, and Shannon diversity were calculated for each sample. As might be expected for shores so far from the spill origin, oiling levels were substantially lower, and beached oil was more highly weathered than in Prince William Sound. Samples of oiled Gulf of Alaska shoreline sediment were not statistically more toxic in bioassay tests than sediment from unoiled reference sites. As a consequence of the lower oil impact, the biological communities were not as affected as those in the sound. Biological impacts, although present in 1989 in the Gulf of Alaska, were localized, which is consistent with the patchy and discontinuous nature of much of the oiling in the Gulf of Alaska. Some organisms were locally reduced or eliminated in oiled patches but survived in unoiled patches nearby. In areas where oiling occurred, impacts were generally limited to middle and upper intertidal zones. Analyses of mussel samples indicate that by 1990 little of the shoreline oil remained bioavailable to epifauna. Quantifiable measures of the overall health and vitality of shoreline biological communities, such as organism abundance, species richness, and Shannon diversity for sediment infauna, show few significant differences between oiled and reference sites in 1990.

Gilfillan, E.S., D.S. Page, E.J. Harner, E.J., and P.D. Boehm (1995b)
Shoreline ecology program for Prince William Sound, Alaska, following the *Exxon Valdez* oil spill: Part 3 - Biology

In Wells, P.G., J.N. Butler, and J.S. Hughes (eds.), *Exxon Valdez Oil Spill: Fate and Effects in Alaskan Waters.* ASTM STP 1219. Philadelphia: American Society for Testing and Materials, pp. 398-443.

ABSTRACT
Part 3 of a three-part series, this paper describes the biological results of a comprehensive shoreline ecology program that was designed to assess recovery in Prince William Sound following the *Exxon Valdez* oil spill on March 24, 1989. The program is an application of the "Sediment Quality Triad" approach, combining chemical, toxicological, and biological measurements. Other aspects of the program are described in Part 1: Study Design and Methods (Page et al., this symposium) and Part 2: Chemistry and Toxicology (Boehm et al. 1993). The study was designed so that the results could be extrapolated to the entire spill zone in Prince William Sound.

The spill affected four major shoreline habitat types in Prince William Sound: pebble/gravel, boulder/cobble, sheltered bedrock, and exposed bedrock. The study design had two components: (1) one-time stratified random sampling at 64 sites representing these four habitats and four oiling levels (including unoiled reference sites) and (2) periodic sampling at 12 non-randomly chosen sites that included some of the most heavily oiled locations in the sound. Biological communities on rock surfaces and in intertidal and shallow subtidal sediments were analyzed to detect differences due to oiling in each of 16 habitat/tide zone combinations. Statistical methods included univariate analyses of individual species abundances and community parameter variables (total abundance, species richness, and Shannon diversity), and multivariate analysis of community structure.

The communities of animals and plants inhabiting the bedrock and coarse sediments on Prince William Sound shorelines responded much differently to oiling than the communities in soft-sediment environments that were the subject of a majority of shoreline studies conducted after other oil spills.

Sedimentary environments in Prince William Sound did not become anaerobic but showed evidence of increased biological activity as the oil residue became a source of organic carbon -- without the usual succession of opportunistic invaders. Similarly, some bedrock sites showed increases in abundance, species richness, and diversity, as the spaces created by oiling were recolonized. This was to be expected in a high-energy environment dominated by "patch dynamics": the rock surfaces support a mosaic of species that are adapted to rapidly colonize new spaces created by wave action and other physical factors.

Two measures of shoreline recovery are reported: an upper-limit estimate based on univariate analysis of community parameters and a lower-limit estimate based on multivariate correspondence analysis of community structure. Overall, the results indicate that between 73 percent and 91 percent of the oiled shoreline in Prince William Sound was recovered (indistinguishable from reference) in the summer of 1990. These results reflect rapid recovery of the biological communities and are consistent with chemical and toxicological studies (discussed in Part 2), which found that hydrocarbon-related toxicity was virtually absent in the shoreline sediments by 1990-1991.

Glemarec, M. (1986)
Ecological impact of an oil spill: utilization of biological indicators

Water Sci. and Tech. 18:203- 211

ABSTRACT
The effects of the *Amoco Cadiz* oil spill on the fine sand ecosystem are evaluated by means of macrofauna which represent medium hydrodynamic conditions. Different species were classified in ecological groups according to their sensitivity to hydrocarbons and to organic matter overload. The two parameters, specific richness and abundance per square meter, indicate the structure of the macrofauna population, while a third parameter, the biomass, can also be used. The study of these factors and their evolution in time, as well as the ecological groups, enables definition of the degradation, recolonization and restructuring conditions. Finally, predators such as fish juveniles, regulate these communities. Six years after the *Amoco Cadiz* oil spill, even if this fine sand ecosystem reaches a new equilibrium, it is still too early for the regulation processes by predators to take place.

Glemarec, M. and E. Hussenot (1982)
A three-year ecological survey in Benoit and Wrac'h Abers following the *Amoco Cadiz* oil spill

Neth. J. of Sea Res. 16:483-490.

ABSTRACT
The succession in time of different ecological groups along a gradient of organic enrichment was studied for three years after the *Amoco Cadiz* oil spill in two adjacent tidal inlets or abers. From the results, time patterns are established, through which the ecosystem evolves towards a new equilibrium or back to a former one. In a first stage both pollution sensitive and tolerant species were wiped out as a result of the high toxicity of the kind of oil involved. Once the level of contamination was somewhat stabilized, an opportunistic fauna developed that eventually was overtaken by a community of pollution tolerant species. The latter exhibited an excessive development before a new equilibrium was reached. Differences in the rate of this temporal succession were found between the abers, dependent on the intensity of hydrodynamic processes. Nearly three years after the oil spill, most communities had still not reached equilibrium.

Glemarec, M., E. Hussenot, and Y.E. Moal (1982)
Utilization of biological indications in hypertrophic sedimentary areas to describe dynamic process after the *Amoco Cadiz* oil spill

Atlantica 5:48

ABSTRACT
An ecological survey was conducted for four years in the area that is the most affected by the *Amoco Cadiz* oil-spill (Abers Wrac'h and Benoit) to define chronological processes that were confirmed by another oil spill two years later. The approach taken was to recognize taxonomic groups. These groups were used as biological indicators. The successive appearance of these various groups, their relative importance, and their disappearance, are the key features of this dynamic approach. This temporal succession is studied along two different gradients of decreasing hydrodynamism, the Abers, where the chemical decontamination and the biological process are not synchronized. Patterns of temporal evolution and succession are discussed. This type of analysis indicates that biological perturbations can persist within the ecosystem well beyond the time when most physical and chemical factors have apparently returned to normal.

Gordon, D.C. Jr., J. Dale, and P.D. Keizer (1978)
Importance of sediment working by the deposit-feeding polychaete *Arenicola marina* on the weathering rate of sediment-bound oil

J. Fish. Res. Bd. Can. 35:591-603.

ABSTRACT
The interactions between the polychaete *Arenicola marina*, a common deposit feeder in sandy intertidal areas, and sediment contaminated with the fresh American Petroleum Institute reference oils and weathered Bunker C oil remaining from the 1970 *Arrow* spill were investigated in laboratory experiments. Worms can tolerate low concentrations of sediment-bound oil, although the sediment working rate is reduced depending upon oil type, concentration, and degree of weathering. Hydrocarbon concentrations, measured gravimetrically and by gas chromatography and fluorescence spectroscopy, were substantially lower (17 to 72 percent) in worm casts than initial sediment. This loss can be accounted for by microbial degradation, which is stimulated by the worms' activity, uptake of hydrocarbons into worms, and perhaps dissolution. A large population (10 to 25 m^2) of *Arenicola* is present at Black Duck Cove, Nova Scotia, living in sediment contaminated with weathered Bunker C oil remaining from the *Arrow* spill. These worms, which have spent their entire lives in oil-polluted sediment, do not have markedly elevated hydrocarbon concentrations and behaved no differently in experiments than worms collected from a clean environment. Calculations suggest that they are capable of removing the oil present in a square meter of sediment in two to four years. After any oil spill, when concentrations reach tolerable levels, activities of deposit-feeding animals such as *Arenicola* can apparently accelerate the weathering rate of sediment-bound oil.

Gourbault, N.E. (1987)
Long-term monitoring of marine nematode assemblages in the Morlaix Estuary (France) following the *Amoco Cadiz* oil spill

Estuar., Coast Shelf Sci. 24:657-670

ABSTRACT
In March 1978 the coast of Brittany was heavily polluted with oil from the *Amoco Cadiz*. Marine nematode assemblages from the Morlaix estuary were regularly monitored at three sites from October 1978 to November 1984. Differences among the assemblages and indications of the effects of oil contamination were detected by diversity, correspondence analysis, and fits to empirical models. Clearest-evidenced effects were seen at the shallowest upstream site, and were detectable four years after the spill. By 1984, it was concluded that the fauna had recovered at all sites to situations similar to that existing in October 1978.

Grahl-Nielsen, O., J.T. Staveland, and S. Wilhelmsen (1978)
Aromatic hydrocarbons in benthic organisms from coastal areas polluted by Iranian crude oil.

J. Fish. Res. Bd. Can. 35:615-623.

ABSTRACT
This investigation was begun one month after a spill of 2,000 tons of Iranian crude oil polluted shores along the west coast of Norway in February 1976. It is based on mass-fragmentographic analysis of naphthalene, methyl-, dimethyl-, and trimethylnaphthalenes, phenanthrene, methyl- and dimethylphenanthrenes, dibenzothiophene, methyl-, dimethyl-, and trimethyldibenzothiophenes. Samples of stranded oil, water, and seven species of benthic organisms were collected periodically during the following year. During the first month of weathering the total amount of these aromatic compounds had decreased 1.22 percent in the original oil to 0.76 percent, with a further decrease to 0.2-0.3 percent during the next three to four months. In the water the concentration of these compounds was approximately 2 ug/l (parts per billion; ppb) at the start of the sampling. At one of the investigated locations a chemical dispersant was used in cleaning the shores. This resulted in higher concentrations of the aromatic compounds in the water, up to 12 ug/l. The organisms studied had accumulated aromatic hydrocarbons up to an excess of 20 ug/g wet weight, one month after the spill. Although seasonal and individual differences were large, the dibenzothiophenes appeared to be retained to a larger extent relative to the naphthalenes and phenanthrenes.

Gray, J.S., K.R. Clarke, R.M. Warwick, and G. Hobbs (1990)
Detection of initial effects of pollution on marine benthos: an example from the Ekofisk and Eldfisk oil fields, North Sea

Mar. Ecol. Progr. Ser. 66:285-299.

ABSTRACT
Reductions in number of species and diversity and increased dominance of opportunistic species occurred late in the sequence of response to oil as a stress factor (within 500 to 1,000 m of discharge sources). However, multivariate analyses (classification analysis using the Bray-Curtis dissimilarity index) and ordination (multi-dimensional scaling) clearly distinguished site groupings related to oil activities at distances of up to two to three kilometers from the Ekofisk pollution source and up to 1.5 km from the Eldfisk source. The first recorded changes in benthic communities

in response to oil were increased abundance patterns of some species and changes in the presence and absence patterns of rare species, with species being mostly present in one site group and mostly absent in another site group. Only under severe pollution did the opportunistic species, which have often been suggested as universal indicators of pollution, dominate. The major site groupings could still be distinguished after aggregation to higher taxa (families and even phyla) when using multivariate analyses. If this finding proves to be a general one then great savings in time and effort, with little or no loss of precision, will be possible in environmental monitoring.

Griffiths, R.P. and R.Y. Morita (1981)
Study of microbial activity and crude oil-microbial interactions in the waters and sediments of Cook Inlet and the Beaufort Sea

Environmental Assessment of the Alaskan Continental Shelf. Final Reports of Principal Investigators. Volume 10-Biological Studies, NOAA/OMPA, Boulder, Colorado, pp. 417-784

ABSTRACT
It has been found that crude oil alters microbial function in marine sediments. This altered function will have three major impacts on normal biological activity. (1) It will reduce overall productivity by interfering with the normal flow of food through the detrital food chain. Recent estimates show that 50-80 percent of food available to all animals present is ultimately derived from this source. (2) Crude oil will interfere with the processes that convert the nitrogen and phosphorous in organic material into inorganic forms which are required for plant growth. Without these inorganic nutrients, plants can not produce the new organic material required to feed the animals present. (3) Crude oil changes microbial activity in the sediments so that the chemical environment of the sediment surface is changed. It seems quite likely that these changes will remain long after the initial crude oil toxicity has abated and could greatly alter the normal recruitment of animals back into the impacted area. It is believed the most vulnerable environment in Alaskan marine systems is the soft-fine grained sediments such as those found in the St. Georges Basin in the southern Bering Sea, Shelikof Strait, and the major bays of Cool Inlet. These are the regions predicted to have the greatest long-term perturbation in the case of a large scale oil spill.

Gulliksen, B. and J.P. Taasen (1982)
Effect of an oil spill in Spitzbergen in 1978

Mar. Poll. Bull. 13:96-98

ABSTRACT
The oil content in the sediment and the marine life along the Arctic shores of Van Mijenfjord, Spitzbergen were investigated about two years after a spill from diesel storage tanks. High concentrations of oil were recorded in the sediment along the shore near the tanks. The shore fauna is generally poor in these areas and the only biological effect detected was the disappearance of the amphipod *Gammarus setosus* from the surface layers.

Gundlach, E.R., I.A. Fischer, and R.J. Stein (1977)
The black tide of La Coruña

Oceans 10:56-60

ABSTRACT
The supertanker *Urquiola*, carrying 107,000 tons of crude oil and 3,000 tons of Bunker C fuel oil, struck bottom while entering La Coruña Harbor, the major port of Galicia, May 12, 1976. Spain was not prepared for a spill of this magnitude and an estimated 25,000-30,000 tons of oil washed ashore the following weeks. Oil was spread over 215 km of coastline, with 60 km having moderate to heavy oil coverage. Shellfish fatalities on a sandy tidal flat at the Playa de Santa Cristina were dramatic. There were high mortalities of bivalves and snails in the top 15 cm of fine sediment. Nearly 70 percent of the edible cockle (*Cerastoderma edule*) population, the dominant species of the area, was killed. Other species of clams, such as *Scrobicularia plano, Tellina tenuis*, and *Venerupis decussata*, were reduced 10 to 30 percent. Evidence of behavioral impairment was obvious in many still living. Mortality at the marsh behind Santa Cristina was not as immediately evident as on the sand flat. The benthic invertebrates most sensitive to this spill were the edible, commercially valuable cockle and the sandworm. However, the oil soaked cordgrass (*Spartina*) and local shore crabs (*Carcinus maenas*) did not seem to suffer great damage.

Gundlach, E.R., S. Berne, L. D'Ozouville, and J.A. Topinka. (1981)
Shoreline oil two years after *Amoco Cadiz*: new complications from *Tanio*

Proceedings of the 1981 Oil Spill Conference, pp. 525-534.

ABSTRACT
The latest in a series of joint Franco-American surveys of the *Amoco Cadiz* (233,000 tons; March 17, 1978) spill site was conducted during May and June 1980. The purposes of this survey were to determine remaining surface oil, buried oiled sediment, oil incorporation in interstitial water, and recovery of attached macroalgae. Oil was found to persist primarily as tar blotches and black staining along exposed rocky shores and as oil-contaminated (indicated by surface sheen), interstitial water in previously heavily oiled, sheltered tidal flats. Less commonly, oil was present as asphalted sediment and oil-coated rocks in sheltered embayments. The cleaned marsh at Ile Grande remained significantly damaged from the oil; however, both upper and lower recovery occurred in uncleaned, heavily oiled areas. On sheltered rocky shoes, heavily oiled algae showed rapid recolonization by *Fucus*; however *Ascophyllum nodosum*-dominated areas showed less recovery. The *Tanio* oil spill on March 7, 1980 (7,000 tons lost) impacted 45 percent of the *Amoco Cadiz* spill site and severely complicated further differentiation of *Amoco Cadiz* oil in many areas. In total, 197 km of shoreline were impacted; 45 km were heavily oiled. Nine weeks after initial impact, *Tanio* oil occurred as patches of heavy oil along sheltered and exposed, rocky shores. Sand beaches and tidal flats were generally free of oil. Several hundred soldiers continued to pressure spray dispersants and water to clean up oiled areas, even in high wave energy and isolated localities.

Guzman, L. and I. Campodonico (1981)
Studies after the *Metula* oil spill in the Straits of Magellan, Chile

Proceedings of the Petromar 1980 Conference, pp. 363-376.

ABSTRACT
The *Metula* ran aground during August 1974, releasing approximately 40,000 tons of oil. Much of the oil was washed ashore and approximately 250 km of shoreline was oiled. This paper summarizes many observations made at the oiled sites and many papers published on the oil spill.

Hampson, G.R. and E.T. Moul (1978)
No. 2 fuel oil spill in Bourne, Massachusetts: Immediate assessment of the effects on marine invertebrates and a 3-year study of growth and recovery of a salt marsh

J. Fish. Res. Bd. Can. 35:731-744.

ABSTRACT
On October 9, 1974 the oil barge *Bouchard 65* loaded with 73,000 barrels of oil spilled what was initially thought by the Coast Guard to be a few barrels and later raised to an undetermined amount of No. 2 fuel oil off the west entrance of the Cape Cod Canal in Buzzards Bay, Massachusetts. Within the following two-week period, oil from the barge was found contained along the west side of Bassets Island and inner Red Brook Harbor, a distance of 5.0 km from the site of the spillage. Qualitative samples of dead and moribund marine invertebrates were collected in tide pools and slight depression along the beaches. A collection consisting of 4,360 invertebrates comprising 105 species, plus two species of fish were found in eight samples. Noticeable effects of the oil on the salt-marsh plant community were also observed. A detailed quantitative examination was begun to determine the effects of the oil on various components of the affected salt marsh community in Winsor Cove compared to a selected control site. From data collected in September 1977, the marsh grass in the lower intertidal zone in Winsor Cove has shown an inability to reestablish itself by either reseeding or rhizome growth. The associated sediments show a correspondingly high concentration of petroleum hydrocarbons impregnated in the peat substrate. Erosion rates measured in the affected area, as a result of the three-year period of marsh degeneration, were 24 times greater than the control site. Microscopic algae were considered least sensitive to environmental changes. Examination of the interstitial fauna found in the study area in the summer of 1977 showed an extremely reduced number of individuals and species.

Harger, J.R.E. and D. Straughan (1972)
Biology of sea mussels (*Mytilus californianus* (Conrad) and *M. edulis* (Linn.) before and after the Santa Barbara oil spill (1969)

Water, Air , and Soil Pollution 1:381-388

ABSTRACT
Effects of the 1969 Santa Barbara oil spill on sea mussels were investigated by comparing biomass characteristics of mussel populations in polluted and clean areas before, during, and after the discharge. The following null hypotheses were tested: (a) mussels collected in August 1969 from areas experiencing oil pollution were not lighter in body weight than those collected from the same locations in previous years. (b) mussels collected from areas experiencing oil pollution in August 1969 were not lighter in body weight than those collected in subsequent years from the same

locations. Animals in exposed areas were not significantly lighter in body weight than those in clean areas. Likewise no deleterious effect in the form of lowered body weights could be detected in mussels from polluted areas in three successive years subsequent to the oil spill. Mussels were not sampled until seven months after the initial spill so that any immediate deleterious effect generated by the oil could have been compensated for by the time of examination. It is noted that the spill in question occurred at a time of minimal growth response might have resulted if the oil had washed ashore during a period of heightened growth.

Hartley, J.P. and J. Ferbrache (1983)
Biological monitoring of the Forties Oil Field (North Sea)

Proceedings of the 1983 Oil Spill Conference, pp. 407-414.

ABSTRACT
The Forties Oil Field (the largest in the United Kingdom sector of the North Sea) has been in production since September 1975. In June 1975, a quantitative survey of the benthic sediments and fauna over the area was made at the start of an environmental monitoring program for the field. The results of a repeat survey carried out after three years of production have been reported by Hartley. This paper presents data from a third similar survey in June 1981 and compares findings with those of the earlier surveys. The benthic fauna of the Forties Field is rich and diverse and qualitatively corresponded well in 1981 to previous descriptions. Naturally occurring gradients in both the sediment type and fauna are a feature of this area. Changes in densities of certain species were noted at some sites in 1981, including increases in certain opportunistic forms. Although no areas of biological effect could be delineated around the four production platforms, the industrial activity in the field may be implicated in the changes found at several stations. The hydrocarbon content of the sediments was low, and with one possible exception, did not appear related to the biological changes noted. The results to date suggest that offshore oil fields in deep water, developed using water-based drill fluids, present relatively few biological problems in the short term. Since no major biological effects have been found after six years of drilling and production, a reduced program of monitoring is recommended to maintain biological surveillance during the life of the field.

den Hartog, C. and Jacobs, R.P.W.M. (1980)

Effects

Hellou, J., C. Upshall, J.F. Payne, S. Naidu, and M.A. Paranjape (1993)

Total unsaturated compounds and polycyclic aromatic hydrocarbons in molluscs collected from waters around Newfoundland

Arch. Environ. Contam. Toxicol. 24:249-257

ABSTRACT
Baseline concentrations of total unsaturated compounds extracted from six species of molluscs, collected from waters around Newfoundland and Labrador were determined by ultraviolet/ fluorescence spectroscopy (uv/f, chrysene equivalents, IOC recommendation). Extracts of muscle tissue from scallops, *Placopecten magellanicus*, clams, *Mya arenaria*, whelks, *Buccinum undatum* and propeller clams, *Cyrtodaria siliqua* had negligible hydrocarbon concentrations compared to the

corresponding visceral mass. The pattern of concentration (GC-MS) of the sixteen polynuclear aromatic hydrocarbon (PAH) priority pollutants (EPA recommendation) was similar in the visceral mass of these species and in whole mussels (*Mytilus edulis*) and periwinkles (*Nucella lapillus*). When the sixteen PAH were detected (less than 5 ng/g, dry weight), fluoranthene dominated (greater than 200 ng/g), followed by phenanthrene-anthracene (greater than 50 ng/g). Extracts of the visceral mass of scallops appeared to contain a relatively larger amount of uv/f absorbing hydrocarbons; therefore, a further investigation was undertaken. A C-25 unsaturated hydrocarbon of molecular weight 346 was identified as the major component of the extraction mixture. Overall, hydrocarbon levels were very low in comparison to other geographical regions.

Highsmith, R.C., S.M. Saupe, K.O. Coyle, T. Rucker, and W. Erickson (1993)
Impact of the *Exxon Valdez* oil spill on intertidal invertebrates throughout the oil spill region

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska, pp. 166-168.

ABSTRACT
The Coastal Habitat Injury Assessment Study was initiated to document and quantify injury to biological resources in shallow subtidal, intertidal and supratidal (immediately above the high tide level) habitats impacted by the *Exxon Valdez* oil spill. The coast was divided into three major regions: Prince William Sound, Cook Inlet-Kenai Peninsula, and Kodiak Island-Alaska Peninsula. This report deals with some of the impacts documented by the intertidal invertebrate component. Results for intertidal algae are presented separately. The coastline in the above three regions was surveyed by the Alaska Department of Environmental Conservation to determine the degree of oiling relative to a map of shoreline habitat types. The sites were classified as heavily, moderately, lightly or non-oiled; habitat classifications included sheltered rocky, coarse textured, exposed rocky, fine textured and estuarine. Oiled sites were randomly selected from each habitat type. A list of potential control sites for each oiled site was randomly generated and, through a ground truthing (verification) process, a control site was selected from the list as a matched site for each oiled site. Control sites included lightly oiled and non-oiled locations. Experimental sites included heavily and moderately oiled locations. This presentation deals only with sheltered rocky and coarse textured habitats.

Hiyama, Y. (1979)
Survey of the effects of the Seto Inland Sea oil spill in 1974

Proceedings of the 1979 Oil Spill Conference, pp. 699-707.

ABSTRACT
On December 18, 1974, a fuel oil tank in Mizushima Refinery of Mitsubishi Oil Co. ruptured. About 50,000 barrels of fuel oil spilled and spread in the Seto Inland Sea, where there were intensive fisheries and heavy marine traffic among various industrial settlements. Coastal fisheries and fish culture fell into confusion, but, according to this survey, marine life quickly recovered by the summer of 1975 and the effect of the oil on the natural environment was not so large as suspected, the reason being mainly the quick and energetic work to recover the spilled oil. This paper is a report of the outline of the accident and a survey of its influence on the marine environment.

Hooten, A.J. and R.C. Highsmith (1993a)
Impacts to intertidal invertebrates in Herring Bay, Prince William Sound, following the *Exxon Valdez* oil spill

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska, pp. 192-194

ABSTRACT
Intertidal monitoring and experimental studies were carried out in Herring Bay, Knight Island, Prince William Sound as part of the Coastal Habitat Injury Assessment program. Population densities for several species of invertebrates were compared between matched oiled and control sites from 1990 to 1992. Limpets were included because they are important intertidal grazers. The periwinkle, *Littorina sitkana*, the dog whelk, *Nucella* spp., and the six-armed starfish, *Leptasterias hexactis*, were studied because they lack a free-swimming larval stage, and may recover slowly after a large reduction in population over a large area. The initial study design in Herring Bay was to select a range of sites with different oiling histories, including a non-oiled control site, and oiled sites that were mechanically treated (washed) and bioremediated. Ideally, this combination of sites would have been replicated several times to achieve statistical rigor. However, after surveys in May 1990, review of data from the Exxon/Federal/state spring shoreline assessments, and detailed discussion with Alaska Department of Environmental Conservation monitors working in Herring Bay, treatment history of specific sites could not be determined with certainty. Therefore, the matched pair design of oiled and non-oiled study sites was adopted and treatment was not included as a variable. Sites were matched for substrate composition, direction and solar aspect, wave exposure, and common biological communities. Control sites were restricted to the southeast corner of Herring Bay, where ice had prevented oil from entering in the spring of 1989. Most matched oiled sites were located in the lower-mid and western portion of Herring Bay.

Hooten, A.J. and R.C. Highsmith (1993b)
Exxon Valdez oil spill: recruitment on oiled and non-oiled substrate

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska, pp. 195-197

ABSTRACT
As part of the Coastal Habitat Injury Assessment program, intertidal experiments were established in Herring Bay, Knight Island, Prince William Sound in 1990. Two separate studies, continued through 1992, examined the effect of north slope crude oil on recruitment of barnacles, *Fucus* germlings and filamentous algae. The effects of oil on algal recruitment are reported in a separate abstract in this symposium. In 1990 two oiled sites and two control sites of similar character were selected to study recruitment on tarred and clean vertical rock faces. At each site, paired 10 by 10-cm plots were randomly established. One member of each pair was scraped and brushed to remove all visible tar and/or barnacles. The sites were periodically visited and numbers of barnacles and *Fucus* germlings were noted. In 1991 the study was expanded to include a total of five site pairs and grazing-exclusion cages were added to half of the study plots. The 1990 data show that barnacle recruitment was initially retarded on the oiled plots at oiled sites, compared to the scraped ones ($p<0.05$, paired t-test), but these differences began to fade at several sites over time ($p=>0.2$, paired t-test). This trend is most evident with the caged plots. The control sites have had consistently greater densities on the control plots compared to the scraped ones. *Fucus* germlings began to emerge at control sites in 1990, and only in low density at the oiled sites in 1991. In 1992 *Fucus* was in greater abundance at oiled sites, and were greater on the unscraped plots (both control and oiled sites) compared to the scraped ones ($0.2>p<0.8$, paired t-test). Densities of

grazers (limpets, *Littorina sitkana*, and *L. scutulata*), were significantly greater at control sites compared to oiled sites in 1991 ($p<0.05$, ANOVA for four of five site pairs).

Houghton, J.A., A.K. Fukuyama, D.C. Lees, H. Teas, H.L. Cumberland, S. Landino, W.B. Driskell, and T.A. Ebert (1991a)
Evaluation and condition of intertidal and shallow subtidal biota in Prince William Sound following the *Exxon Valdez* oil spill and subsequent shoreline treatment

HMRAD Report 91-1, NOAA Hazardous Materials Response and Assessment Division, Seattle.

ABSTRACT
The effect and extent of shoreline treatment in areas affected by the *Exxon Valdez* oil spill will greatly complicate assessment of the long-term impacts of treatment and the oil alone. Because much of the heavily oiled shoreline was washed with high-pressure hot water at least once, and because so little of the oiled shoreline was left untreated, only a limited number of areas remain where comparisons may be made to distinguish between effects of oiling and the effects oiling plus treatment. Lack of specificity in the available treatment information (e.g., equipment, temperature, duration, bioremediation application rates, and repetitions) also complicates separation of effects of individual treatment approaches. Nevertheless, the results from this study to date provide a strong basis to argue that conditions spanning a broad spectrum of biological properties reflect both the influences of hydrocarbon contamination and the intrusive shoreline treatment. The high number of cases in which the null hypothesis of no impact from oiling and/or treatment was rejected is impressive. It is clear, based on the number of rejections and the high levels of significance observed in many cases, that the data provided by this study strongly support the conclusion that hydrocarbon contamination and high pressure, hot-water treatment each caused major adverse impacts to the intertidal biota of western Prince William Sound, but that the effects of the treatment predominated. Moreover, it appears likely that the treatment, while removing oil from the upper and mid-littoral zones, where its effects were somewhat restricted to relatively tolerant organisms such a barnacles, rockweed, and mussels, transported the remobilized oil into the lower intertidal and shallow subtidal zones, where the oil was placed into contact with relatively more sensitive and productive organisms such as hardshelled clams and crustaceans.

Houghton, J.A., D.C. Lees, W.B. Driskell, and A.J. Mearns (1991b)
Impacts of the *Exxon Valdez* spill and subsequent cleanup on intertidal biota--1 year later

Proceedings of the 1991 International Oil Spill Conference, pp. 467-475

ABSTRACT
A substantial amount of the crude oil which spilled from the tanker *Exxon Valdez* on March 24, 1989, was deposited on beaches in Prince William Sound. Major beach cleanup activities began in May and continued throughout the summer of 1989. Additional cleanup activities occurred during the summer of 1990. A study was conducted in 1989 to document the short-term impact to biota of hot water wash treatments. Additional field surveys were conducted in the summer of 1990 to evaluate recovery of littoral habitats from the effects of oiling and shoreline treatment. Stratified random sampling was used to assess epibiota and infauna at 27 sites, representing several habitats and degrees of disturbance. Preliminary data evaluations indicate that treatment methodologies applied in 1989 had varied effects on intertidal assemblages. Some treated rocky beaches were stripped of flora and fauna at mid- and upper intertidal elevations and showed relatively little colonization by mid summer 1990. On other oiled rocky beaches that received less

severe or no treatment, the majority of the community dominants remained in place and significant recolonization was underway. Protected sand and gravel beaches subjected to hydraulic treatments displayed greatly altered beach morphology. Finer sands and gravels were flushed from upper intertidal elevations, often burying the lower beach in several centimeters of sediment, resulting in major reductions in infauna in 1990. Oiled but untreated sand and gravel beaches had a rich and varied infauna. The effects of 1989 shoreline treatment activities on intertidal flora and fauna were significant and widespread and will greatly complicate assessment of the long-term impacts of the oil itself.

Houghton, J.A., A.K. Fukuyama, W.B. Driskell, D.C. Lees, G. Shigenaka, and A.J. Mearns (1993a)
Recovery of Prince William Sound intertidal infauna from *Exxon Valdez* spill and treatment ~1990-1992

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska, pp. 75-78.

ABSTRACT
Much of the crude oil spilled from the tanker *Exxon Valdez* on March 24, 1989, was deposited on beaches in Prince William Sound. Major beach cleanup activities began in May and continued throughout the summer of 1989. About 400 km of shoreline were treated in the sound 1989 using various hydraulic wash and bioremediation (fertilization) techniques; additional mechanical cleanup and bioremediation occurred during the summers of 1990 and 1991. High pressure, hot-water washes used on mixed gravel/sand/silt beaches in 1989 altered the nature of habitat available to infauna. Hydraulic washing of heavily oiled upper beach areas transported large quantities of silts, sands (to 4 mm diameter), and even pebbles (4 to 64 mm) down the face of the beach to the water's edge. Coarser materials were deposited on the lower beach, while suspended oils and silts were carried from the area by currents in both surface and water column plumes. Presumably many organisms, along with a large proportion of the organic matter in the sediment column, were similarly displaced.

Houghton, J.A., A.K. Fukuyama, D.C. Lees, W.B. Driskell, A.J. Mearns, and G. Shigenaka (1993b)
Recovery of Prince William Sound intertidal epibiota from the *Exxon Valdez* spill and treatment ~1990-1992

Exxon Valdez Oil Spill Symposium Abstracts; February 2-5, 1993, Anchorage, Alaska; pp. 79-82

ABSTRACT
Following the 1989 *Exxon Valdez* oil spill, significant concerns were raised regarding the potential effects on intertidal habitats and biota of high pressure, hot-water washes used to remove oil from the shorelines of Prince William Sound. The objectives of this study were to evaluate recovery of important intertidal and shallow subtidal habitats and resources from the effects of oiling and shoreline treatment and to assess the influence of high pressure, hot-water treatments on the nature and rates of recovery. This study also was designed to extrapolate persistence of effects of 1989 hot-water washes over the broader area where hot-water treatments had been applied. Primary variables isolated in the sampling design were habitat type, tidal elevation, degree of oiling, and use of high pressure, hot-water shoreline treatments. The status of recovery of intertidal assemblages from the oil spill and subsequent shoreline treatments was examined by repeated sampling of a suite of rocky intertidal sites during 1990,1991, and 1992.

Houghton, J.A., A.K. Fukuyama, D.C. Lees, W.B. Driskell, G. Shigenaka, and A.J. Mearns (1993c)
Impacts on intertidal epibiota: *Exxon Valdez* spill and subsequent cleanup

Proceedings of the 1993 Oil Spill Conference, pp. 293-300

ABSTRACT
Following the *Exxon Valdez* spill, several approaches were used to remove crude oil from beaches of Prince William Sound. Pre- and post-treatment monitoring in 1989 documented the severe short-term impacts to intertidal epibiota of high pressure, hot-water treatments widely used to remove stranded oil. Quantitative field surveys were conducted in 1990 and 1991 to evaluate recovery of littoral habitats from the effects of oiling and hot water washing. Stratified random sampling was used to assess epibiota at sites representing several habitats and degrees of disturbance. Effects of hot-water treatments applied in 1989 remained visible in intertidal assemblages through 1991. Some hot water-treated rocky beaches that had been stripped of biota at middle and upper intertidal elevations showed little colonization by 1990. In 1990, statistically significant differences were noted between variables measured on unoiled beaches and those same variables on hot water-treated beaches. On other oiled rocky beaches that received less severe or no treatment, the majority of the community dominants, including rockweed, mussels, barnacles, limpets, drills, and littorines, survived the oiling. While these populations were still depressed below abundance levels on unoiled in May 1991, by July recovery of most species had raised abundances to levels seen on unoiled beaches. In summer 1991, few statistically significant differences remained between the biota of unoiled rocky shores and those of hot water-washed shores, but full recovery is still several years away in many areas.

Howard, S. and D.I. Little (1987a)
Effect of infaunal burrow structure on oil penetration into sediments

Proceedings of the 1987 Oil Spill Conference, pp. 427-431

ABSTRACT
The presence of an infaunal burrow structure facilitated the penetration of a medium fuel oil mousse into subsurface sediments to a greater depth than similar sediments lacking a burrow structure (destroyed by digging). The increased penetration of oil appeared to be related to better drainage characteristics resulting from the burrow structure. Oil was found to penetrate burrows of all sizes down to at least 1 mm diameter. Penetration of oil into the burrows occurred within 24 hours and was accompanied by a decrease in feeding rate of the lugworm *Arenicola marina*, although there were no detectable toxic effects of the oil on the small-sized infaunal community during the one-month experiment. Depending on the toxic properties of the oil, reworking of oiled sediments by the infauna may return oil to the surface, thus promoting degradation.

Howard, S. and D.I. Little (1987b)
Biological effects of low-pressure seawater flushing of oiled sediments

Proceedings of the 1987 Oil Spill Conference, pp. 439-443.

ABSTRACT
The objectives of this study were to assess the field effectiveness and biological effects of low-pressure saltwater flushing of a thin (less than 4 mm) oil layer applied to a very fine intertidal sand.

On average approximately 85 percent of the applied medium fuel oil mousse was found to be recoverable. Hydrocarbon analyses indicated negligible oil incorporation into flushed plots. The technique is believed to have been effective partly because the water table was successfully raised (by up to 20 cm), and also because the surface 3 to 4 cm was sufficiently disturbed to liberate oil that had penetrated the surface layer during the two hours between oil application and flushing. Counts of *Arenicola marina* casts in "oiled" plots were significantly lower ($p=0.02$) than in the "oiled and then flushed" plots. The technique is likely to work with viscous oils deposited in 10 mm thick strandlines on accessible sloping shores, where the sediment is greater than 4 cm thick and reasonably firm. The technique is likely to be unsuccessful on very coarse sands and gravels, fluid muds, and low shear strength sands, because of erosion and mixing of sediments and oil.

Humphrey, B., P.D. Boehm, M.C. Hamilton, and R.J. Norstrom (1987)
The fate of chemically dispersed and untreated crude oil in Arctic benthic biota

Arctic 40:149-161.

ABSTRACT
Subtidal benthic biota were monitored for petroleum hydrocarbons following two experimental oil spills at Cape Hart, North West Territories, Canada. In one spill, oil was chemically dispersed into the water column, and in the other oil was released onto the water surface and allowed to land on the shoreline. In addition to baseline samples, samples were collected immediately after the oil releases, two to three weeks after and one and two years after. Initial observations did not distinguish between effects of the surface and dispersed releases. Total oil content and hydrocarbon compositional analyses were conducted to investigate patterns of uptake and depuration for five different Arctic species: *Astarte borealis, Macoma calcarea, Mya truncata, Serripes groenlandicus* and *Strongylocentrotus droebachiensis*. Filter-feeding species took up oil rapidly from the water column, while deposit-feeding species took up oil less rapidly from the sediments. All species depurated most of the oil after one year, but after two years the deposit feeders appeared to be taking up more oil from sediments contaminated by stranded oil from the surface oil release.

Jacobs, R. (1980)
Effects of the *Amoco Cadiz* oil spill on the seagrass community at Roscoff with special reference to the benthic infauna

Mar. Ecol. Prog. Ser. 2:207-212

ABSTRACT
The benthic fauna of an eelgrass (*Zostera marina* L.) community was investigated at Roscoff (France) from October 1977 to April 1979. The impact of the *Amoco Cadiz* oil spill of March 1978 on the community was studied. Direct effects on the eelgrass itself were only local during the first weeks after the spill, when many plants had black, "burnt" leaves. This was, however, a temporary phenomenon, for the production of new leaf tissue continued normally. Effects on the benthic fauna were observed directly after the arrival of the oil at Roscoff. A sharp decrease in numbers of both individuals and species occurred—mainly caused by an almost total disappearance of the smaller Crustacea and Echinodermata, and a serious numerical decrease in other groups. Recovery took place relatively rapidly. In the beginning of 1979 all numbers were at the same level as the year before, the filter feeding Amphipoda being the only exception: on May 1, 1979 they were still absent.

Jewett, S.C. and T.A. Dean (1993)
The effects of the *Exxon Valdez* oil spill on infaunal invertebrates in the eelgrass habitat of Prince William Sound

Exxon Valdez Oil Spill Symposium Abstracts; February 2-5, 1993, Anchorage, Alaska; pp. 97-99.

ABSTRACT
Sampling was conducted in 1990 and 1991 to assess the impacts of the *Exxon Valdez* oil spill on infaunal invertebrates within and adjacent to shallow (less than 20 m) subtidal eelgrass (*Zostera*) beds in western Prince William Sound. We present results from a stratified random sampling program that compared measures of diversity, abundance and biomass of mainly infaunal invertebrates at paired oiled and control (unoiled) sites. The oiled and unoiled site pairs for both years were Bay of Isles-Drier Bay, Herring Bay-Lower Herring Bay, Sleepy Bay-Moose Lips Bay, and Clammy Bay- Puffin Bay, respectively. The oiled sites were selected from areas that had adjacent shorelines moderately to heavily oiled during the fall of 1989. Control sites were selected that matched the oiled sites with respect to physiographic factors (e.g., exposure, slope, substrate type), but that did not have oil present on adjacent shorelines in fall 1989. Two depth strata (6 to 20 m and within the eelgrass bed [less than 3 m]) were sampled at each site. Three stations were established within each depth stratum and two 0.1 m^2 benthic samples were collected from each station with a diver-operated suction dredge. Sediment samples were concurrently collected for grain size and hydrocarbon analyses. We tested for differences among oiled and unoiled sites using a randomization procedure (Manley 1991).

Jewett, S.C., T.A. Dean, and D.R. Laur (1993)
The effects of the *Exxon Valdez* oil spill on benthic invertebrates in silled fjords in Prince William Sound

Exxon Valdez Oil Spill Symposium Abstracts; February 2-5, 1993, Anchorage, Alaska; pp. 87-90.

ABSTRACT
During October 1989, when examining the effects of the *Exxon Valdez* oil spill on several shallow subtidal habitats in western Prince William Sound, high mortality of invertebrates and fishes was observed in a heavily oiled silled fjord. Here we present the results from the initial observations and sampling of this fjord in 1989, and subsequently in 1990 and 1991. Other silled fjords were examined in 1990. We consider the effects of the spill versus natural benthic hypoxia or anoxia. The main silled fjord studied is a small embayment in northeastern Herring Bay, which is located along the northwestern side of Knight Island. It has an area of approximately 600 km^2 with the greatest depth within the basin approximately 35 m; the sill depth at the entrance of the fjord is only 4 m. At depths greater than 10 m the substrate was mainly composed of fine, flocculant silt. This fjord was considered as "heavily oiled" after two shoreline surveys were conducted during the summer and fall of 1989. The dead and moribund animals observed in 1989 were primarily in the deeper portions (greater than 13 m) of the fjord. In one area extensively surveyed (approximately 70 m^2), we observed over 40 dead animals laying on the bottom, including 23 large polychaete worms, eleven starfish (all *Pycnopodia helianthodes*), and miscellaneous clams. Also encountered were dead mobile organisms, such as shrimp, squid, and Pacific cod. In addition to the observed dead organisms, the substrate had a patchy, cobweb-like layer of the bacteria, *Beggiatoa*. This colorless, sulfur-dependent, hemolithotrophic bacteria is associated with decaying vegetation and low dissolved oxygen.

Juday, G.P. and N.R. Foster (1990)
A preliminary look at effects of the *Exxon Valdez* oil spill on Green Island research natural area

Agroborealis 22(1): 10-17.

ABSTRACT
Observations were made on three beaches on Green Island from July 20-22, 1989. Extensive notes were taken on intertidal zonation and plant and animal taxa, and voucher specimens of intertidal and beach organisms were collected for later identification. A total of 96 animals were identified along with 39 plants.

Karinen, J.F. (1980)
Petroleum in the deep sea environment: potential for damage to biota

Environmental International 3:135-144.

ABSTRACT
Information on the fate, persistence and biological impact of petroleum hydrocarbons in shallow marine environments, coupled with recent data on hydrocarbons in offshore sediments and the biology of deep sea organisms, have provided new perspectives on the potential impact of oil on the deep sea environment. A review of literature on petroleum hydrocarbons in deep sea sediments, mechanisms for transport of petroleum to the deep sea floor, interaction of petroleum hydrocarbons and particulate matter, and the physiology and metabolism of deep sea fish and crustaceans has resulted in the following conclusions: (1) Hydrocarbons of apparent anthropogenic origin are accumulating in bottom sediments of coastal margins and in deeper offshore waters at unknown rates, (2) Several mechanisms exist for the rapid transport of petroleum hydrocarbons to the deep sea floor, (3) Petroleum hydrocarbons are intimately associated with particulate matter in the sea, behaving much the same as natural biogenic material and having the potential to modify or interrupt natural processes, (4) The unique physiology of deep water life forms increases the potential for adverse impact of petroleum hydrocarbons on the deep sea environment, and (5) There is a need to determine trends of temporal and spatial deposition of hydrocarbons in deep sea sediments and evaluate the biological impact of this introduction of xenobiotic compounds on the largest environment on earth.

Keizer, P.D., T.P. Ahern, J. Dale, and J.H. Vandermeulen (1978)
Residues of Bunker C oil in Chedabucto Bay, Nova Scotia, 6 years after the *Arrow* spill

J. Fish. Res. Bd. Can. 35:528-535.

ABSTRACT
The *Arrow* spill in February 1970 heavily oiled approximately one half of the 600 km shoreline of Chedabucto Bay, Nova Scotia. An extensive field survey and chemical analysis of sediment samples for aliphatic and polycyclic aromatic hydrocarbons identified only a few locations where *Arrow* Bunker C remained in the intertidal and sublittoral sediments. The upper intertidal zones of Rabbit, Crichton, and Durell islands remain covered with an oil and sediment mixture of a "pavement-like" consistency. Several areas showed visual and chemical evidence of recent spills during the survey period. All sublittoral sediment samples contained hydrocarbons of petroleum origin. The distribution of the most highly contaminated sublittoral sediments suggests either reentry of stranded oil into the water column and into the sublittoral sediments or contamination from

shipping and fishing vessels. Concentrations in the sublittoral sediments are below those found toxic to benthic organisms. An estimation of the amount of Bunker C remaining in Chedabucto Bay is impossible due to the patchy distribution, contributions of more recent spills, and the absence of adequate control sites.

Kemp, P.F., R.C. Swartz, and J.O. Lamberson (1986)
Response of the phoxocephalid amphipod, *Rhepoxynius abronius*, to a small oil spill in Yaquina Bay, Oregon

Estuaries 9:340-347

ABSTRACT
A spill of approximately 284,000 liters of Bunker C and diesel fuel oils occurred at the entrance of Yaquina Bay, Oregon, following the wreck of the freighter *Blue Magpie* on November 19, 1983. A portion of this oil entered the lower estuary and was deposited on subtidal benthic habitats occupied by the phoxocephalid amphipod *Rhepoxynius abronius*. Bioassays with *Rhepoxynius abronius* showed that the oil globules were not acutely toxic unless mixed into the sediment at concentrations of 1.0 parts ppt or greater. A series of ten-day bioassays before and after the spill showed that sediment collected from oiled subtidal sites did not become acutely toxic to this species. Although the density of the *R. abronius* population declined by 75 percent after the spill, similar declines of the same population were observed at this site in Fall 1980. Although mean fecundity was greater in 1984 than in 1981, recruitment following the spill was lower than in the 1980-1981 study. Thus, there is limited evidence for a small impact of the oil spill on this sensitive amphipod.

Kennicutt, M.C., T.J. McDonald, G.J. Denoux, and S.J. McDonald (1992a)
Hydrocarbon contamination on the Antarctic Peninsula I. Arthur Harbor - subtidal sediments

Mar. Poll. Bull. 24(10): 409-506.

ABSTRACT
Near-field contamination in Arthur Harbor can be traced to spills, ship and boating activities, and runoff. Soil samples from Palmer Station and Old Palmer Station contain hydrocarbons derived from diesel fuel, lubrication oil, and hydraulic fluid. The majority of contamination in subtidal sediments around Palmer Station is due to diesel fuel spills. Subtidal sediments below an abandoned open incineration site also contain combustion-derived PAHs. Soils collected at Old Palmer Station were also contaminated with diesel fuel residues and combustion-derived PAH. High concentrations of these contaminants were detected in nearby subtidal sediments. Small amounts of diesel fuel contamination are detectable throughout Arthur Harbor. Despite being abandoned for years, soils in the vicinity of Old Palmer Station and Base N represent the most concentrated source of contaminants in Arthur Harbor. Environmentally sound practices at Palmer Station have helped to minimize localized contamination.

Kennicutt, M.C., T.J. McDonald, G.J. Denoux, and S.J. McDonald (1992b)
Hydrocarbon contamination on the Antarctic Peninsula II. Arthur Harbor - Inter- and subtidal limpets (*Nacella concinna*)

Mar. Poll. Bull. 24(10):506-511.

ABSTRACT
Accidental and operational releases of hydrocarbons during activities in support of scientific bases in the Antarctic can contaminate organisms in close proximity to these locations. Intertidal and subtidal limpets in Arthur Harbor were found to contain elevated levels of polynuclear aromatic hydrocarbons near Palmer and Old Palmer stations. Contamination was highest in the intertidal and decreased with increasing water depth in the subtidal. The highest concentrations of tissue contamination were found in intertidal areas associated with high levels of onshore soil contamination. Limpets (*Nacella concinna*) preferentially incorporated the more water soluble aromatic compounds suggesting exposure to dissolved contaminants in run-off rather than particulates or slicks. This was in contrast to subtidal sediments that were primarily contaminated with freshly spilled diesel fuel. While contamination was present near stations, the concentrations observed are one to two orders of magnitude lower than the initial contamination caused by the *Bahia Paraiso* diesel fuel spill in 1989.

Kingston, P.F. (1992)
Impact of offshore oil production installations on the benthos of the North Sea

ICES J. Mar. Sci. 49:45-53.

ABSTRACT
Input of contaminants into the sea associated with offshore oil drilling and production include accidental spillage, discharge of cuttings and discharge of production water. Of these, oil discharged on drilling cuttings is by far the greatest source of oil pollution in the North Sea from these operations, having peaked in 1985 at 25,800 tons. The response to the seabed fauna to these inputs has been shown to follow established patterns in which there may be high individual abundance of a few species close to the source of contamination (organic enrichment effect) or a reduced number of individuals with few species close to the installation (smothering or toxic effect). Diversity shows a similar pattern to species richness, both are low in the immediate vicinity of the installation and in most cases, attaining pre-operational levels within 2000. High levels of hydrocarbon contamination have also been shown to be concentrated around installations. There are indications that a fall in diversity can be expected when total hydrocarbon concentrations in the sediment reach 50-60 ppm. There is also increasing evidence to suggest that for some areas where there has been intensive drilling/production activity (e.g., Shetland Basin), there has been a significant rise in hydrocarbon levels in the sediment at distances between 5 and 10 km from installations.

Kittredge, J.S. (1975)
Effects of Crude Oil on Marine Invertebrates

Final Report to Office of Naval Research, Publication AD-A017 921 from the National Technical Information Service, Springfield, Virginia 22161

ABSTRACT
A brief summary of research on the effects of crude oil on the behavior of marine invertebrates, principally crustaceans. Behavior patterns examined was the feeding response. Polyaromatic hydrocarbons were probably the potentially dangerous component of oil pollution.

Koons, C.B. and Wheeler, R.B. (1978)
Oil spill has minimal effect on environment

Northern Offshore 7:24-25

ABSTRACT
The estimated annual petroleum input into the North Sea and northeastern Atlantic is 400,000 tons. The estimated standing crop of dispersed hydrocarbons in the North Sea alone is 1.6 million tons on this basis, the 12,000-20,000 tons of petroleum spilled in the Ekofisk Bravo blowout is rather insignificant compared to this total. There are many physical, chemical, and biological processes acting on spilled petroleum at any given time following an incident. Some processes are more important immediately following the spill: others have more long-range effects. Evaporation and biodegradation, both important processes for hydrocarbon removal, are discussed, as well as the impact of marine animals on hydrocarbon uptake. The effect of oil pollution on birds, fish, and benthic organisms is discussed.

Koons, C.B. and H.O. Jahns (1992)

The fate of oil from the *Exxon Valdez*--a perspective

MTS Journal 26(3): 61-69.

ABSTRACT
On March 24, 1989, the *Exxon Valdez* struck Bligh Reef in Prince William Sound, Alaska, and released about 260,000 barrels of crude oil into the sea. Currents and wind spread the oil throughout the southwestern part of the Sound, along the coast of the Gulf of Alaska and, finally, into the open Pacific Ocean. More than three years after the spill, the shorelines of Prince William Sound and the northern Gulf of Alaska contained only a few isolated patches of weathered oil residue. The waters were essentially free of *Valdez* oil much earlier. However, questions still persist regarding the fate and ultimate disposition of the oil. Is it still lurking in the environment? Has it sunk to the bottom of Prince William Sound or the Gulf of Alaska? We address these questions by reviewing the environmental factors that determine the fate of spilled oil. Several powerful natural processes are at work in the sea to degrade oil and to dissipate it to naturally background levels. Were it not for these processes, hydrocarbons from many sources would accumulate indefinitely in the oceans. The intent of this article is to provide perspective regarding the fate of spilled oil. The *Valdez* spill itself was a regrettable accident and the fact that hydrocarbons are assimilated by the environment is not intended to trivialize the acute effects of the spill. However, we take issue with the notion that any oil that was not recovered in the cleanup continues to exert harmful effects in the environment.

Krebs, C.T. and K.A. Burns (1977)
Long-term effects of an oil spill on populations of the salt-marsh crab *Uca pugnax*

Science 197:484-487

ABSTRACT
A spill of fuel oil at West Falmouth, Massachusetts, in 1969, contaminated contiguous salt marshes with up to 6,000 µg/g (ppm) of wet mud and affected local populations of *Uca pugnax*. Directly related to high-sediment oil content were reduced ratio of females to males, reduced juvenile settlement, heavy overwinter mortality, incorporation of oil into body tissues, behavioral disorders such as locomotion impairment, and abnormal burrow construction. Concentrations of weathered fuel oil greater than 1,000 ppm were directly toxic to adults, while those of 100 to 200 ppm were toxic to juveniles. Cumulative effects occurred at lower concentrations. Recovery of the marsh from this relatively small oil spill is still incomplete after seven years.

Kvenvolden, K.A., F.D. Hostettler, J.B. Rapp, and P.R. Carlson (1993)
Hydrocarbons in oil residues on beaches of islands of Prince William Sound, Alaska

Mar. Poll. Bull. 26(1): 24-29.

ABSTRACT
Aliphatic and aromatic hydrocarbons were measured on oil residues from beaches on six islands in Prince William Sound, Alaska. In addition to altered products from the *Exxon Valdez* oil spill of 1989, we also found, at two widely separated locations, residues that are similar to each other but chemically distinct from the spilled oil. Terpanes, steranes, monoaromatic steranes, and carbon isotopic compositions of total extracts were most useful in correlating the altered products of the spilled oil. These same parameters revealed that the two non-Valdez samples are likely residues of oil originally produced in California. The results indicate that oil residues currently on the beaches of this estuary have at least two quite different origins.

Laubier, L. (1980)
The *Amoco Cadiz* oil spill: an ecological impact study

Ambio 9:268-276

ABSTRACT
On the night of March 16-17, 1978, the supertanker *Amoco Cadiz* ran aground, spilling into the sea almost 223,000 tons of oil with a volatile fraction of 30 to 40 percent. A program to assess the ecological impact of the spill was begun immediately, to run for three years. It includes: chemical monitoring of the water, the sediments and the marine organisms; study of ecological effects on flora and fauna, including acute mortality and re-establishment of heavily damaged communities; studies of microbial degradation of the oil. Major results of these studies have been presented at a special symposium and are reviewed here. The recovery of areas exposed to waves, currents and wind energy is almost complete, but there is still oil in areas more protected from the physical energy of the sea. The ecological impact was extremely complex; in addition to the direct loss in biomass (acute mortality) and the corresponding loss in production, there are sublethal long-term effects especially on reproduction.

Laughlin, R.B. Jr, J. Ng, and H.E. Guard (1981)
Hormesis: a response to low environmental concentrations of petroleum hydrocarbons.

Science 211:705-707

ABSTRACT
Possible lasting harmful effects resulting from short-term exposures to pollutants were investigated using the zoeal larvae of the mud crab, exposed to water soluble fractions of jet fuel for either the first five days of the stage or for the duration of zoeal development, which is 11 to 14 days. The salinity of the water, concentration of the fuel, and length of exposure each affected the survival of the zoeae. Short-term exposure or continuous exposure to low concentrations of petroleum hydrocarbons caused no increase in mortality or changes in the development rate, and increased megalopal weight was characteristic of such groups. This phenomenon is termed hormesis and has seldom been reported as a generalized aspect of environmental stress etiology. These experiments suggest an organismic resilience to episodic oil-spill incidents. It is felt that many marine organisms have compensatory physiological strategies that enable them to tolerate low concentrations of pollutants or short term exposures.

Lee, R. F. (1977)
Accumulation and turnover of petroleum hydrocarbons in marine organisms

Fate and Effects of Petroleum Hydrocarbons in Marine Organisms and Ecosystems (D.A. Wolfe, ed.), Pergamon Press, pp. 60-70

ABSTRACT
This review deals with the uptake, storage and discharge of petroleum hydrocarbons by marine organisms under laboratory and field conditions. organisms collected from oil spill and chronically polluted areas were analyzed. Special attention was directed toward the ability of animals to depurate their hydrocarbons accumulated after exposure to oil. organisms studied were: benthic algae; zooplankton; benthic crustaceans; benthic worms; bivalves; and fish. Bivalves received emphasis because of the extensive amount of laboratory and field studies on their accumulation of petroleum.

Lee, W.Y. and J.A.C. Nichol (1980)
Study of the recovery of a marine isopod (*Sphaeroma quadridentatum*) from petroleum-induced sensitivity

Biological Monitoring of Marine Pollutants, Proceedings of a Symposium on Pollution and Physiology of Marine Organisms, Academic Press, New York pp. 467-482

ABSTRACT
Experiments were designed to determine (a) whether offspring of water soluble fractions (WSF) of a No. 2 fuel oil-exposed isopods become less resistant to WSF in terms of rates of development, reproduction, and survival, and (b) the number of generations it would take to recover from such exposure. Chronic exposure of juvenile isopods to low levels of WSF resulted in a less resistant F1 generation. Petroleum-induced susceptibility lasted for about one to two generations when progeny of exposed isopods were grown in WSF-free sea water. Based on the life cycle of *Sphaeroma quadridentatum* observed in the laboratory, treated isopods required only one-half to one year to recover in WSF-free sea water. This short time interval was related to published data on the rates of

accumulation and depuration of petroleum compounds by marine invertebrates. The rapid loss of accumulated hydrocarbons in clean sea water was probably the main reason why petroleum-induced sensitivity did not persist over a long period of time. Isopods in this study recovered more rapidly than the fauna in an oil-spill site. Since recovery of isopods took place in WSF-free sea water, the estimated time interval should be considered only as the minimum time period for a population to recover following an oil spill. However, when applying laboratory results to a field study, the authors suggest that other factors such as the chemical characteristics of oil and its persistence in the environment must be also taken into account.

Lees, D., W. Driskell, and J. Houghton (1993)
Short-term biological effects of shoreline treatment on intertidal biota exposed to the *Exxon Valdez* oil spill

Exxon Valdez Oil Spill Symposium Abstracts; February 2-5, 1993, Anchorage, Alaska, pp. 69-72.

ABSTRACT
A substantial amount of the 11.6 million gallons of Alaska North Slope crude oil spilled from the *T/V Exxon Valdez* on March 24, 1989, was deposited on beaches in Prince William Sound. Following the spill, biological studies were conducted on the biota of the intertidal and shallow subtidal habitats in the Sound to determine short-term effects of several shoreline treatment techniques considered for beach cleanup. Four treatment methodologies examined were high-pressure hot-water (HP-HW) and low-pressure warm-water (LP-WW) wash, and applications of a dispersant (Corexit 7664) and a beach cleaner (Corexit 9580 M2). These methods were designed to remobilize oil that coated the substrate and facilitate its removal from the beaches. Only LP-WW and HP-HW treatments were employed on a routine basis in the Sound. The basic objective of these studies was to assess and compare the short-term biological impacts of several alternative treatment methodologies. The major elements of these studies, con ducted on three islands at the north end of the Knight Island Archipelago in protected boulder/cobble habitat, were pre- and post-treatment measurements of abundance, cover, and community composition of the biota at specific levels in the test areas. These studies employed a stratified-random design with replicate quadrat sampling before and after implementation of the specific shoreline treatment methodologies. Each program compared two treatment alternatives; the programs were independent and not compared at the time.

Leppakoski, E.J. and L.S. Lindstrom (1978)
Recovery of benthic macrofauna from chronic pollution in the sea area off a refinery plant, Southwest Finland

J. Fish. Res. Bd. Can. 35:766-775

ABSTRACT
Quantitative field studies (density, wet biomass, Shannon diversity, species richness, evenness of distribution) on benthic sublittoral macrofauna were made in the vicinity of an oil refinery in southwest Finland before and after the installation of a new wastewater treatment plant that reduced the amount of oil and liquid effluents by about 90 to 95 percent. The number of species and species diversity increased during the first and second year after pollution abatement at the stations close to the former outflows. The amphipods *Pontoporeia affinis, Corophium volutator,* and *C. lacustre,* midge larvae of the *Chironomus plumosus*-group, the oligochaete *Tubifex costatus,* the polychaetes *Harmothoe sarsi* and *Polydora redeki,* and the bivalve *Cardium* sp. were the most successful recolonizers of the 23 taxa sampled. The strong lethal effect of oil-contaminated

sediments upon *Chironomus plumosus* larvae decreased markedly in laboratory experiments (LTs were estimated at seven days in 1973 and at 28 days in 1974; in 1975, 80 to 90 percent of the larvae survived for 28 d. Details of post-abatement succession are discussed. The results demonstrate not only the recovery from chronic oil pollution but also the degree of ecological damage caused by previous continuous discharge of oil.

Levasseur, J., M-A. Durand, and M-L. Jory (1981)
Biomorphologic and floristic aspects of the reconstitution of a phanerogamic vegetal cover, altered by the *Amoco Cadiz* oil spill and the following clean-up operations. Special study of the Ile Grande salt marshes (Cotes du Nord) (in French)

Amoco Cadiz Fates and Effects of the Oil Spill. Proceedings of the International Symposium, pp. 455-473

ABSTRACT
Oiling and subsequent cleaning of coastal marshes of the Ile Grande have drastically reduced vegetation cover. They have also caused profound modifications of habitat types and distribution. Current reestablishment of vegetation involves the two classical processes of (1) primary succession, where dikes have been raised or lower and middle areas of marshes have been bulldozed, (2) secondary succession elsewhere. It seems necessary to consider changes at the level of the site rather than the community and specifically as regards the population. The age and prior extension of certain clones have a decisive influence on the redistribution of species dominance actually under way since the first stage of succession implies reoccupation of the surface. In this respect, rhizomatous geophytes are currently favored. In the middle and upper marsh areas, contrary to what is seen in haute-slikke or bas-schorre, chances of vegetation re-establishment are correlated with degree of species and growth form diversities.

Levasseur, J.E. and M-L. Jory (1982)
Natural recovery of salt-marsh vegetation destroyed by the *Amoco Cadiz* oil spill: Circumstances and tendencies. (in French) Original Title: Retablissement naturel d'une vegetation de marais maritimes alteree par les hydrocarbures de 1' *Amoco Cadiz*: Modalites et tendances

Ecological Study of the Amoco Cadiz Oil Spill: Report of the NOAA-CNEXO Joint Scientific Commission (E.R. Gundlach and M. Marchand, eds.) pp. 329-362

ABSTRACT
Recovery of Ile Grande salt marsh vegetation (*Spartina maritima, Salicornia nerennis, Halimione portulacoides, Pucinella maritima,* and *Juncus maritimus*) partially destroyed by hydrocarbons has been significantly restored since 1980. Ways and timing of recovery are due to the relative dominance, in each point, of two processes, viz. in situ regeneration of perennial individuals and germination of seeds produced near or on the site. Colonization is mainly due to annual species while germination of perennials is a rare event, except in shady places with loose and clean substrate. However, it is impeded either in tide exposed points or in formerly heavily trampled places.

Linden, O., R. Elmgren, and P. Boehm (1979)
The *Tsesis* oil spill: its impact on the coastal ecosystem of the Baltic Sea

Ambio 8:244-253

ABSTRACT
The *Tsesis* oil spill was relatively minor by international standards—roughly 1,000 tons of medium grade fuel oil. However, severe effects were observed, at least locally, in the pelagic, littoral, and benthic ecosystems. Moreover, the speed of recovery varied greatly. The plankton communities were back to normal after about one month, but it took a year before the littoral communities showed considerable recovery and within that time the soft bottom community did not show even the beginning of a recovery.

Lindstedt-Siva, J., D.W. Chamberlain, and E.R. Mancini (1987)
Environmental aspects of the *Arco Anchorage* oil spill, Port Angeles, Washington

Proceedings of the 1987 Oil Spill Conference, pp. 407-410.

ABSTRACT
On December 21, 1985, the tanker *Arco Anchorage* ran aground in Port Angeles Harbor. Approximately 5,960 barrels (239,000 gallons) of Alaska North Slope crude oil were released from two gashes in the ship's hull. Weather conditions permitted the effective operation of containment booms and skimmers. Once the vessel was secured, first priority during the response was protection of environmentally sensitive areas to the east of the spill site, including a National Wildlife Refuge with large populations of marine birds, fishes, and invertebrates. Heaviest shoreline contamination was on Ediz Hook in Port Angeles Harbor, but oil was observed as far east as Dungeness Bay and as far west as Neah Bay. Approximately 2,000 seabirds were known to be oiled during the spill. Removal of oiled debris was a successful cleanup strategy for all beaches except Ediz Hook, and concentrations of oil in the sediments returned to background levels within weeks. Oil penetrated into coarse sediments at the most heavily oiled sites at Ediz Hook. A unique cleanup method incorporating a combination of physical agitation and high-pressure water jets was devised to remove most of the entrained oil. Concentrations of oil in these sediments and biological recruitment are being monitored. Recommendations are made to further reduce the environmental impacts of such incidents.

Mackie, P.R., R. Hardy, and K.J. Whittle (1978)
Preliminary assessment of the presence of oil in the ecosystem at Ekofisk after the blowout, April 22-30, 1977

J. Fish. Res. Bd. Can. 35:544-551.

ABSTRACT
The marine environment in the Ekofisk area was assayed for the presence of oil components after the blowout on Platform Bravo was brought under control. Several methods of assay were used but the results were not always strictly comparable. Relatively high fluorescence values were observed in water samples in the vicinity of the platform. However, gas-liquid chromatography of these samples indicated that although some of the hydrocarbon fractions now resembled crude oil, none had increased markedly in concentration. The presence of oil could be detected in the biota and taste panels were able to identify an oily taint at low level in some fish caught near the platform. A second

survey some two months after the spill indicated that little, if any, oil from the blowout remained in the water column.

Mageau, C., F.R. Engelhardt, E.S. Gilfillan, and P.D. Boehm (1987)
Effects of short-term exposure to dispersed oil in Arctic invertebrates

Arctic 40(Suppl. 1):162-171

ABSTRACT
A series of experimental studies was carried out as part of the Baffin Island [Canada] Oil Spill (BIOS) project to define the behavioral, physiological, and biochemical reactions of three Arctic marine benthic invertebrate species exposed to chemically dispersed crude oil. Behavioral responses and patterns of hydrocarbon accumulation and release observed in the bivalves and the urchin during the 1981 field spill were similar to those observed during the laboratory simulations. Ostial closure, loss of responsiveness to mechanical stimuli and narcosis were characteristic of the bivalves. Exposed urchins displayed a functional loss of the tube foot and spine behavior. Detailed hydrocarbon analysis indicated different uptake dynamics among the species. The effects of dispersed oil were immediate and short lived and resulted in temporary accumulation of hydrocarbons. Depuration of these stored hydrocarbons occurred during the experimental recovery period. In vivo biodegradation of hydrocarbons was indicated in the bivalves. Physiological, parameters measured in bivalves exposed to oil included elements of scope for growth, activity of aspartate aminotransferase and glucose-6-phosphate dehydrogenase. Dose-response relationships between physiological rates and hydrocarbon body burden were apparent.

Maki, A. W. (1991)
Exxon Valdez oil spill: initial environmental impact assessment

Environ. Sci. and Tech. 25:24-29

ABSTRACT
Exxon's response to the *Exxon Valdez* oil spill on Bligh Reef in Prince William Sound in Alaska was unprecedented in scale. The Exxon response included the employment of more than 11,000 people, utilization of essentially the entire world supply of containment booms and skimmers, and an expenditure of more than two billion dollars. Following the spill and cleanup, Exxon mobilized a massive environmental assessment program. Data from these studies indicate that wildlife and habitats are recovering from the impacts of the spill and that commercial catches of herring and salmon in Prince William Sound are at record high levels. Samplings of petroleum aromatic hydrocarbons concentrations in the waters clearly demonstrate that average levels have remained well below exposure levels known to cause acute and chronic effects to sensitive aquatic life. Field counts of plants, fish and mammals from throughout the spill area provide convincing data that wildlife species are surviving and reproducing, thus confirming that biological recovery is rapidly taking place. Ecosystem recovery from spill impacts is due to the combined efforts of the cleanup program as well as natural physical, chemical, and biological processes. From all indications this recovery process can be expected to continue.

Mair, J. McD., I. Matheson, and J.F. Appelbee (1987)
Offshore macrobenthic recovery in the Murchison field following the termination of drill-cuttings discharges

Mar. Poll. Bull. 18:628-634.

ABSTRACT
The effects of discharged drilling cuttings contaminated with oil-based drilling fluids on the macrobenthos surrounding several North Sea oil-production platforms have been well documented. Areas of biological effect ranging from highly modified benthic communities, through transitional zones to undisturbed zones have been identified and characterized. Results are presented from a series of studies at the Murchison oil field which indicate partial recovery of macrofaunal communities around the production platform after cuttings discharges had ceased. Eventual rates of recovery of affected macrobenthic communities around production platforms are discussed in terms of persistence of oil in the drilling cuttings and the rates of degradation of the oil and its toxic components.

Malins, D. C. (1982)
Alternations in the cellular and subcellular structure of marine teleosts and invertebrates exposed to petroleum in the laboratory and field: a critical review

Can J. Fish. Aquat. Sci. 39:877-889

ABSTRACT
Laboratory studies with individual petroleum components, model mixture of hydrocarbons, fractions of petroleum, and whole oil have demonstrated, mostly at high exposure concentrations, an association between petroleum and various cellular/subcellular alterations in marine organisms. Recent evidence, notably from studying the effect of the *Amoco Cadiz* oil spill, suggest that cellular/subcellular alterations also result from exposing marine organisms to petroleum in the field. In marine environments, however, it is still generally not possible to predict the type or degree of impact of petroleum or organisms because little information is available on the influence of myriad natural and human-induced environmental variables on its fate and effects.

Mancini, E.R., J. Lindstedt-Siva, and D.W. Chamberlain (1989)
Environmental impacts of the 1985 Arco Anchorage oil spill: 1988 conclusions

Proceedings of the 1989 Oil Spill Conference, pp. 459-462.

ABSTRACT
The beach of Ediz Hook, Port Angeles, Washington, was heavily oiled by Alaska North Slope crude oil spilled subsequent to the grounding of the tanker *Arco Anchorage* on December 21, 1985. Intertidal crude oil concentrations measured in beach sediments ranged from less than 50 to 20,000 ppm, with an average of 2,240 ppm. Beach reclamation efforts, concluded in April 1986, reduced average crude oil concentrations to 670 ppm. An intertidal and subtidal sediment chemistry and benthic invertebrate monitoring program was initiated at Ediz Hook in 1986 and was concluded in early 1988. Sediment chemistry data indicated a decline in mean intertidal concentrations from 670 to 110 ppm between April 1986 and July 1987. Shallow subtidal concentrations decreased from a mean of 460 to 110 ppm in the same time period. Benthic invertebrate population indices, developed with core and box sampler data, generally demonstrated a negative correlation with

sediment crude oil concentrations. Organism density, taxonomic diversity and biomass increased significantly at numerous stations during the course of the monitoring studies. Successful bivalve population recruitment and growth were evident for several hardshell clam species by the fall of 1987. There was no evidence of petroleum-derived hydrocarbons in the edible tissues of salmonids (rainbow trout and Atlantic salmon) which were gathered for several months after the spill from a net-pen culturing facility in Port Angeles. Despite vigorous bird rehabilitation efforts, approximately 80 percent of the 1,917 oiled birds perished. Pre- and post-spill population census data indicate, however, that population level impacts did not occur. Various reconnaissance, monitoring and damage assessment investigations conducted during and after the spill have documented the environmental value of a rapid and effective spill response and cleanup effort. Significant impacts associated with the spill were short-term and generally limited to the immediate spill area.

Maurer, D., W. Leathem, and C. Menzie (1981)
The impact of drilling fluid and well cuttings on polychaete feeding guilds from the US northeastern continental shelf

Mar. Poll. Bull. 12:342-347

ABSTRACT
The effect of recent drilling operations (fluid and well cuttings) on polychaete feeding guilds from continental shelf off Atlantic City, New Jersey, was examined. Although there were some adverse effects on macrobenthos from 2,160 metric tons of cuttings and mud solids discharged into the marine environment, the composition of polychaete feeding guilds remained essentially unchanged. This key trophic relationship between polychaetes and the changing environment due to the drilling operation was apparently uninterrupted. This relationship remains to be examined in other natural and perturbed habitats.

Mearns, A.J. and G. Shigenaka (1993)
NOAA's long-term ecological recovery monitoring program: overview and implications of recovery trends and treatment effects

Exxon Valdez Oil Spill Symposium Abstracts; February 2-5, 1993, Anchorage, Alaska; pp. 83-86.

ABSTRACT
NOAA's Hazardous Materials Response and Assessment Division is responsible for providing, through the Scientific Support Coordinator, guidance to the Federal On-Scene Coordinator during responses to major oil spills. The aim of that guidance is to maximize protection of marine resources. A major source of guidance comes from experiences gained during previous spill responses. Obviously, the *Exxon Valdez* oil spill provided many opportunities for learning about the success and failures of various containment, removal and shoreline treatment methods. This paper summarizes the rationale and approach of NOAA's shoreline treatment studies in Prince William Sound and suggests some implications for future responses and restoration.

Michael, A.D., C.R. Van Raalte, and L.S. Brown (1975)
Long-term effects of an oil spill West Falmouth, Massachusetts

Proceedings of the 1975 Conference on Prevention and Control of Oil Pollution, pp 573-582

ABSTRACT
A small spill of No. 2 fuel oil occurred near Wild Harbor, Massachusetts in September 1969. The benthic fauna of the Wild Harbor marsh, boat basin, and offshore area was sampled through the fourth and fifth years after the spill (1973, 1974). Sediment samples were analyzed for the presence of petroleum hydrocarbons. Gas chromatography produced evidence of hydrocarbons typical of weathered fuel oil in the sediments of the marsh, boat basin, and two offshore stations. The numbers of benthic species at the offshore stations and the marsh were slightly, but significantly, lower than those found at control stations. Population densities were similar to control areas for the offshore stations but not in the case of the marsh. The boat basin was still heavily affected. Some stations were characterized by the presence of opportunistic species. The recovery process in terms of the total benthos has leveled off, but there was evidence for further recovery during the course of the study.

Michaelis, F.B. (1983)
Effect of *Turoa* oil spill on aquatic insects in the Mangawhero River system

N.Z. Entomol. 7:447-455

ABSTRACT
Oil (17,000 liters) was spilled from Turoa Skifield on Mt. Ruapehu, New Zealand and entered the headwaters of the Mangawhero and Makotuku rivers where it persisted for up to five months. Brown trout, rainbow trout, long-finned eels, and blue duck were not killed. However, in the upper reaches, aquatic insects were disturbed and killed by the oil spill within 2 weeks. The total numbers of aquatic insects were not significantly affected at the lower stations within Tongariro National Park over the following year. Mayflies were significantly reduced in numbers in the Mokotuku River following the oil spill and may be indicator species for oil pollution. Comparisons with overseas studies confirmed a recovery time of at least six months for the sensitive orders of aquatic insects following an oil spill of this magnitude.

Mielke, J.E. (1990)
Oil in the ocean: the short- and long-term impacts of a spill

CRS Report for Congress 90-356 SPR, July 24, 1990. 34 pp.

ABSTRACT
This report describes the short- and long-term impacts of an oil spill. The short-term impact is the incident as generally portrayed immediately following the spill, and the long-term impact is the life cycle of the spilled oil itself. Not surprisingly, the impacts are often different. The media presentation is commonly one of a catastrophic occurrence, and a major oil spill is indeed that. Media coverage also tends to focus on the more emotional aspects of destruction to the local environment, to which irreparable harm is often claimed. Rarely does media coverage convey the fact that oil is a natural substance, and that natural processes, over time, will do much to remove it.

Mothershead, R.F. and R.C. Hale (1992)
Influence of ecdysis on the accumulation of polycyclic aromatic hydrocarbons in field exposed blue crabs (*Callinectes sapidus*)

Mar. Environ. Res. 33:145-156.

ABSTRACT
The effect of molting on xenobiotic accumulation in crustacea was examined. Molting is essential for crustacean growth and is integral to the reproductive process in some species. Molting and intermolt blue crabs (*Callinectes sapidus*) were exposed in the field to high environmental concentrations of unsubstituted PAHs. The PAH concentration in muscle and hepatopancreas was measured for both molt groups. Newly molted blue crabs possessed statistically higher tissue burdens than intermolt crabs of three unsubstituted PAH (cyclopenta(def)phenanthrene, fluoranthene and pyrene) characteristic of the creosote contaminated exposure site. The mean total concentration of these three PAH in hepatopancreas was 9,560 ng/g in newly molted crabs and 3,360 ng/g in intermolt crabs. Mean total PAH concentration in muscle was 1,380 ng/g in new molts and 498 ng/g in intermolts. The elevated tissue burdens may be due t either increased water uptake and shell permeability at ecdysis or decreased metabolism of PAH during the molt process. Newly molted blue crabs are regarded as a seafood delicacy and tissue burdens of xenobiotics, such as PAH, may be of concern to human health.

Neff, J.M., E.H. Owens, S. W. Stoker, and D.X. McCormick (1993)
Condition of shorelines in Prince William Sound following the *Exxon Valdez* oil spill: Part I-- Shoreline oiling

In Wells, P.G., J.N. Butler, and J.S. Hughes (eds.) *Exxon Valdez* Oil Spill: Fate and Effects in Alaskan Waters. ASTM STP 1219. Philadelphia: American Society for Testing and Materials. pp. 312-346.

ABSTRACT
Following the *Exxon Valdez* oil spill of March 24, 1989, in Prince William Sound, Alaska, Exxon conducted comprehensive, systematic shoreline surveys in cooperation with federal and state authorities to obtain information on the distribution and magnitude of shoreline oiling and to identify natural and cultural resources requiring special protection. Similar joint surveys were performed during the springs of 1990, 1991, and 1992 on all Prince William Sound and Gulf of Alaska shorelines that were suspected of having remnants of weathered oil and that could benefit from further cleanup. The extent of oiling declined substantially between 1989 and 1992: in 1989, survey teams found oil on about 16 percent of the 3,000 miles (4,830 km) of shoreline in Prince William Sound; in the spring of 1991, they found oil on about 2 percent; and, in May 1992, on only 0.2 percent. During this period, most of the oil was located in the biologically least productive upper intertidal and supratidal zones. In the springs of 1990, 1991, and 1992, isolated pockets of subsurface oil were found, chiefly in small scattered zones in coarse cobble/boulder sediments in the upper intertidal or supratidal zones. In 1991, 0.3 percent of the intertidal area surveyed in Prince William Sound contained subsurface oil. Survey data for 1992 show that the areal extent of this oil had declined by about 70 percent from 1991 levels. Moreover, where subsurface oil remained in 1992, it was present in lower concentrations. Rates of oil removal were greatest on coastal sections treated early in the spring and summer of 1989. The shoreline treatment program, aimed at bulk oil removal, enabled recovery, recruitment, and recolonization of affected habitats to begin more quickly than if the oil had been left to weather naturally.

Nelson-Smith, A. (1968)
Biological consequences of oil pollution and shore cleansing

Biological Effects of Oil Pollution on Littoral Communities: Supplement to Volume 2 of Field Studies, Field Studies Council, London, pp. 73-80

ABSTRACT
The effects of oil spills in different areas were investigated to provide interesting comparisons. Oil spilled into a small cove yielded extensive shore pollution and mortalities. No emulsifiers were used and in less than a year the animal populations were again normal, gastropod mollusks appeared to be most seriously affected. Marine algae populations were also reduced. Misuse of emulsifiers embedded the oil more firmly and resulted in increased mortalities. Emulsifiers enable the oil to wet the surfaces of shore organisms and to penetrate their systems and also to spread the oil to previously unreached areas. Time of year of oil spill and mobility of organisms regulate the rate at which the members of the shore community are able to recover from oil pollution.

Nelson-Smith, A. (1977)
Recovery of some British rocky seashores from oil spills and cleanup operations

In: J. Cairns Jr., K.L. Kickson, and E.E. Herricks (eds.) *Recovery and Restoration of Damaged Ecosystems.* University Press of Virginia, Charlottesville, Virginia, pp. 191-207

ABSTRACT
The effects of oil spills of varying severity are described. The most striking result is a reduction in the numbers of grazing mollusks, especially limpets, resulting in successive blooms of green and brown algae. The recovery period varied from up to seven years after a major crude-tanker wreck (even longer where toxic cleansers were spilled) to virtually no time after a small spillage of heavier oils. Recovery may be retarded by further spills at the same site, while chronic pollution by an oily refinery effluent has modified the balance of shore populations so that recovery to the previous state can never occur. However, cleanup procedures need not necessarily inhibit a reasonable recovery. Simple transect surveys can reveal both effects on shore life and the progress of its recovery. Serious oil spills cause about as much ecological disturbance as unusually cold winters but, unlike these, are potentially avoidable.

Nelson-Smith, A. (1980)
Biological consequences of oil-spills in Arctic waters

The Arctic Ocean: the Hydrographic Environment and the Fate of Pollutants (L. Rey and B. Stonehouse, eds.) Macmillan, pp. 275-293

ABSTRACT
This is a review of the biological effects of oil spills and blowouts in Arctic waters and on Arctic shorelines, as well as the implications of cleanup techniques.

Notini, M. (1978)
Long-term effects of an oil spill on *Fucus* macrofauna in a small Baltic bay

J. Fish. Res. Bd. Can. 35:745-753.

ABSTRACT
On October 6, 1970, the small tanker *Irini* ran aground in the southern part of the Stockholm archipelago, releasing about 1,000 tons of medium and heavy fuel oil. Approximately 400 tons drifted into a small bay, Gastviken, wiping out nearly the entire littoral fauna. Most of the oil was collected mechanically during the winter, and by May 1971 cleanup operations were completed. The recruitment of the bladder wrack (*Fucus vesiculosus*) community in the bay was observed at intervals over a five-year period. Significantly increased macrofauna population densities were found for a number of species in the 1974 and 1976 samples compared to those of 1971 and 1972. From June to July 1971 to June 1976, the mean numbers of individuals for all species rose from about 280 to 1,000/100 g *Fucus* dry weight. The bivalve *Mytilus edulis* increased in number from 0 to about 45, the gastropod *Theodoxus fluviatilis* from 0 to about 160, the amphipod *Gammarus* spp. from about 40 to 580, the isopods *Idotea* spp. from about 5 to 35, and *Jaera* spp. from almost 0 to about 10/100 g *Fucus*. Larvae of Chironomidae were the only group found with a decreased density between the first and sixth summers after the spill, with 240 and 145 individuals, respectively. The data obtained are discussed in relation to conditions in a nearby unpolluted bay and to normally occurring cyclic variations.

Nounou, P. (1980)
The oil spill age--fate and effects of oil in the marine environment

Ambio 9:297-302

ABSTRACT
This paper presents a summary of the fate and effects of oil pollution in the marine environment and prospects for the future. Although large spills from wrecked ships or blown wells are more spectacular, 90 percent of oil in the ocean comes from rivers, coastal refineries, deballasting by tankers, offshore exploration, and natural seepage. Within a few days after a discharge, oil spreads on the surface, the volatile components evaporate, and the oil disperses according to properties of the oil and the energy in the environment. Emulsification and tar lump formation can occur. Oil may then degrade chemically or biologically or persist in sediment. Literature on effects of petroleum on marine organisms is not very consistent because researchers use different techniques and different oils. Lethal concentrations vary with species and age of the organism, eggs being very sensitive. Sublethal effects are many. Direct coating and ingestion of oil affect immobile species, such as barnacles and algae, as well as sea birds. Edible fish and shellfish can be contaminated. Bioaccumulation of carcinogens in food chains is widespread, as are disturbances in ecosystems. The greatest damage occurs near the shore, but deep-sea contamination of breeding grounds or migration routes can severely damage some species.

Olla, B.L., W.H. Pearson, S.E. Miller, and J.W. Blaylock (1981)
Detection of the water-soluble fraction of crude oil by the blue crab, *Callinectes sapidus*

Mar. Environ. Res. 5:3-11

ABSTRACT
The ability of the blue crab, *Callinectes sapidus*, to detect petroleum hydrocarbons was measured with behavioral techniques. When presented with a water-soluble fraction of Prudhoe Bay crude oil, blue crabs abruptly changed antennule orientation, began rhythmic beating of the maxillipedal flagellae, and increased antennular flicking rate. The threshold concentration at which 50 percent of the crabs detected the water-soluble fraction was 2×10^{-6} mg/litre. The blue crab apparently can readily detect petroleum hydrocarbons at concentrations found in chronically polluted areas as well as oil spill situations.

Olla, B. L., A.J. Bejda, and W.H. Pearson (1983)
Effects of oiled sediment on the burrowing behavior of the hard clam, *Mercenaria mercenaria*

Mar. Environ. Res. 9:183-193

ABSTRACT
The burrowing behavior of juvenile hard clams, *Mercenaria mercenaria*, in oil-contaminated sediment was examined in a series of laboratory experiments. At oil concentrations within the range that might occur after an oil spill, depth and rate of burrowing were altered. The depth to which clams in oiled sediment burrowed after 96 hours was significantly shallower than the depth in the controls, while the time taken to burrow beneath the surface was longer in oil-contaminated sediment. Alterations in burrowing were indicative of avoidance behavior rather than oil-induced debilitation. The results suggest that such alterations may increase the vulnerability of this species to predation.

Oudot, J., P. Fusey, M. Van Praet, J.P. Feral, and F. Gaill (1981)

Hydrocarbon weathering in seashore invertebrates and sediments over a two-year period following the *Amoco Cadiz* oil spill: Influence of microbial metabolism

Environ. Pollut. Ser. A. 26:93-110

ABSTRACT
The weathering of aliphatic and aromatic hydrocarbons from the *Amoco Cadiz* oil was monitored from May 1978 to January 1980 in selected seashore invertebrates and sediments of the polluted area in Brittany, using high temperature high resolution gas liquid chromatography. The major part of the oil was relatively rapidly eliminated but some petroleum constituents, such as long-chain n-alkanes, triterpanes and alkylated phenanthrenes and dibenzothiophenes, appeared to persist for a time. In high energy sites (Roscoff beach), depuration was generally quite complete between 12 and 18 months after the wreck, whereas in sheltered muddy sediments and associated organisms of Aber Benoit and Aber Wrac'h, the presence of neosynthesized very long-chain alkanes up to nC56 was shown. These compounds are believed to result from bacterial metabolism and were still clearly visible 22 months after the accident. Microbial degradation was the main weathering factor and bacterial counts in the Aber Benoit muds showed that almost all the bacteria present were adapted to hydrocarbon utilization.

Page, D.S., J. Foster, J. Hotham, S.H. Pendergast, L. Gonzalez, E.S. Gilfillan, S.A. Hanson, R. Gerber, and D. Vallas (1983)

Long-term fate of dispersed and non-dispersed crude oil in two nearshore test spills

Proceedings of the 1983 Oil Spill Conference, pp. 465-471.

ABSTRACT
The fate and effects of two nearshore discharges of Murban crude oil at Long Cove, Searsport, Maine in August 1981 were studied following a one-year, pre-spill baseline study of the test areas. An upper and lower intertidal sampling area within a 60 by 100 m test plot were exposed to dispersed oil in water resulting from the discharge of 250 gallons of oil pre-mixed with 25 gallons of Corexit 9527 dispersant. Release of treated oil was around high-water slack tide on the surface of the water, with added mixing energy provided by mixing gates deployed by small boats. The maximum water depth over the test areas was 3.5 m. Untreated crude oil (250 gallons) was released on an ebbing tide within a separate, boomed-off 60 by 100-m test plot. A third test plot served as an oil-free reference plot. Water samples taken near the surface and near the bottom during and after discharge showed that chemically dispersed oil loses lower boiling hydrocarbons in both the aliphatic and aromatic fractions below n-C_{17} as the droplets diffuse downward. Data are given for sediment samples taken from the test plots eleven months pre-spill and ten months post-spill. Hydrocarbon analyses of the sediment samples show little incorporation of dispersed oil into the sediments of the treated oil plot relative to the sediments exposed to undispersed oil.

Page, D.S., E.S. Gilfillan, P.D. Boehm, and E.J. Harner (1995)
Shoreline ecology program for Prince William Sound, Alaska, following the *Exxon Valdez* oil spill: Part 1 - Study design and methods

In Wells, P.G., J.N. Butler, and J.S. Hughes (eds.). *Exxon Valdez Oil Spill: Fate and Effects in Alaskan Waters*. ASTM STP 1219. Philadelphia: American Society for Testing and Materials, pp. 263-295.

ABSTRACT
Part 1 of a three-part series, this paper describes the design and analysis of a large field and laboratory program to assess shoreline recovery in Prince William Sound following the *Exxon Valdez* oil spill. The study was designed so that the results could be extrapolated area-wide and projected forward in time. It made use of the "sediment quality triad" approach, combining chemical, toxicological, and biological measurements to assess shoreline recovery. Key aspects of the study include:
- Coordinated field sampling for chemical, toxicological, and biological studies;
- Rigorous stratified random sampling (SRS) as a basis for spatial extrapolations;
- Periodic sampling to assess trends, including sites with worse-case conditions;
- Analysis of oil-spill effects on hundreds of species;
- Statistical methods based on normal and non-normal theory, consistent with the structure of the data, including generalized linear models and multivariate correspondence analysis.

Prince William Sound shorelines were stratified into four types of habitat (exposed bedrock/rubble, sheltered bedrock/rubble, boulder/cobble, and pebble/gravel) and four different levels of oiling (unoiled [or reference], light, moderate, and heavy). Sixty-four SRS sites were randomly selected with an average of four replicates in each combination of habitat type and oiling level. The SRS sites were sampled in 1990 to assess the state of recovery in the sound as a whole. Twelve additional non-

random sites, including some of the most heavily oiled locations in the sound, were monitored annually to assess time trends from 1989 to 1991.

At sedimentary sites, sediment samples were collected for hydrocarbon analysis, sediment toxicology, and biological (infaunal) analysis. At bedrock/rubble sites, filter wipes and surface scrape samples were gathered to assess chemistry and epibiota. Samples of mussels were taken, when present, to determine the bioavailability of any petroleum residues.

Spill-affected shorelines are judged to have recovered when the biological communities are statistically indistinguishable from those at unoiled reference sites. Given the large natural variability observed among sites and over time, this study provides a more accurate and comprehensive picture of shoreline recovery than more traditional approaches that focus on only a few species at a number of subjectively chosen locations.

Pearson, W.H., D.L. Woodruff, P.C. Sugarman, and B.L. Olla (1981)
Effects of oiled sediment on predation on the littleneck clam, *Protothaca staminea*, by the Dungeness crab, *Cancer magister*

Est., Coast., and Shelf Sci. 13: 445-454.

ABSTRACT
Field and laboratory experiments examined how oiled sediment influenced predation on littleneck clams, *Protothaca staminea*, by Dungeness crabs, *Cancer magister*. In two field enclosure experiments lasting 13 and 29 days, crabs consumed more clams from oiled than clean sand. Clams were shallower in oiled than clean sand. To test whether the observed increase in predation rate on clams from oiled sand was due to shallow burial, a 19-day laboratory experiment examined predation rates on clams buried in different depths of sand. The high consumption rate of clams from shallow-clean sand indicated that shallow burial could have accounted for most but not all the higher consumption of clams in oiled sand. In a second laboratory experiment without crabs, clams were again shallower in oiled than clean sand. Clams did not actively emerge from oiled sand but did burrow slower into oiled sand. Shallow burial and slow reburrowing in oiled sand led to increased predation of littleneck clams through increasing the accessibility of clams to Dungeness crabs.

Peckol, P., S.C. Levings, and S.D. Garrity (1990)
Kelp response following the *World Prodigy* oil spill

Mar. Poll. Bull. 21:473-476

ABSTRACT
The June 1989 grounding of the tanker *World Prodigy* on Brenton Reef, Rhode Island, released approximately 922 tons of No. 2 fuel oil into surrounding coastal waters. The authors investigated effects of oiling on the subtidal kelps, *Laminaria saccharina* and *L. digitata*. Kelp condition, growth rates with depth, and pigment acclimation were compared with prespill measurements of kelp performance at the same site from 1984 to 1987. There was no evidence that kelps were detrimentally affected by oiling; we observed no necrotic or bleached tissue on any kelps in an oiled cove. Growth rates of both species were within the range of our previous years' data and pigment acclimation was similar for all years. Lowest growth rates occurred in 1985 during a severe brown tide. This study and other data suggest that Narragansett Bay was spared potential disaster because little fuel oil mixed into the water column and contacted subtidal organisms.

Pople, A., R.D. Simpson, and S.C. Cairns (1990)
An incident of Southern ocean oil pollution: effects of a spillage of diesel fuel on the rocky shore of Maquarie Island (sub-Antarctic)

Aust. J. Mar. Freshwater Res. 41:603-620.

ABSTRACT
On December 3, 1987, the Australian resupply ship *Nella Dan* ran aground at Macquarie Island, releasing approximately 270,000 liters of oil, mostly light marine diesel, into the sea. This represented one of the few spills to have occurred in southern hemisphere cold waters. Following the spill, thousands of marine invertebrates were washed up dead on beaches along 2 km of the shore. Twelve months after the spill, a study was conducted to examine the shore community in five zones at two oil-affected and two control locations; three sites were examined within each of these locations. Densities of marine invertebrates appeared to have been markedly reduced in the lower littoral and sublittoral zones in the vicinity of the wreck. In the upper littoral zones, algal cover and invertebrate abundance were similar at oil-affected and control locations. The significance of the oil spill and its long-term effects are discussed.

Pratt, S.D. (1978)
Interactions between petroleum and benthic fauna at the *Argo Merchant* spill site

In the Wake of the Argo Merchant, Proceedings of a Symposium, University of Rhode Island, Kingston, pp. 131-136.

ABSTRACT
Funding was provided for collection and archiving of quantitative benthic grab samples from the *Argo Merchant* spill site. Oil was found in sediments within three to four km of the wreck in February and July 1977. The basis for the conclusions of this report are visual inspection of samples during collection and partial identification of benthos in 14 samples. The spill occurred on a sand ridge bordered by gravel-bottomed channels. Both sand and gravel environments were exposed to oil. On the ridge continuous movement of sand waves may bury oil, break it into smaller particles, or release it into the water. Sand collected at the bow of the wreck contained 2 to 0.03-mm diameter oil particles which only weakly adhered to sand grains. Few aggregated or coated grains were seen. The channel-bottom fauna had a high standing crop of both sessile and motile species in all samples obtained, but could not be described quantitatively. The ridge sand supported few macrobenthos and a relatively homogeneous interstitial community. At the bow of the wreck 4 to 122 ppm of oil was found in February and 0.2 to 0.6 ppm in July. There was a slight increase in density and diversity of interstitial benthos at the later date. In the February samples oil was observed in the guts of interstitial harpacticoids and a polychaete (*Ophyrotrocha* sp.) and adhering to the appendages of a burrowing amphipod.

Pruell, R.J., J.L. Lake, W.R. Davis, and J.G. Quinn (1986)
Uptake and depuration of organic contaminants by blue mussels (*Mytilus edulis*) exposed to environmentally contaminated sediment

Mar. Biol. 91:497-507.

ABSTRACT
Experiments were designed to expose blue mussels (*Mytilus edulis*) to contaminated sediment collected from Narragansett Bay, Rhode Island in 1982. Measurements were taken to allow comparisons of the uptake and depuration of PAHs and polychlorinated biphenyls (PCBs). In addition, concentration factors in the mussels were calculated separately against the dissolved and particulate phase concentrations and the results from the exposure and control systems were compared. Both PAHs and PCBs were rapidly accumulated by the mussels exposed to the contaminated sediment. After the mussels were transferred to control seawater, individual PAHs were depurated with half-lives ranging from 12 to 30 days. Individual PCBs showed depuration half-lives which ranged from 16 to 46 days. Concentration factors in the mussels calculated against the particulate phase concentrations were very different in the exposure and control systems. Concentration factors calculated using only the dissolved phase concentrations (bioconcentration factors) showed excellent agreement in the two systems, possibly an indication that the dissolved phase was the direct source of the contaminants accumulated by the mussels. The bioconcentration factors for PCBs were higher than those of PAHs when compounds with similar n-octanol/water partition coefficients were compared.

Renaud-Mornant, J. and N. Gourbault (1980)
Survival of meiofauna after the *Amoco Cadiz* oil spill (Morlaix Channel and Roscoff Beach, Brittany, France) (in French). Original Title: (Survire de la Meiofaune Apres l'Echonement del *Amoco Cadiz* (Chenal de Morlaix, Greve de Roscoff)

Bull. Mus. Natl. Hist. Nat. (France)(4e Ser., Zool. Biol. Ecol. Anim.) 2:759-772

ABSTRACT
The effects of hydrocarbon contamination on subtidal and intertidal meiofauna were studied a few days after the *Amoco Cadiz* spill (March 1978) and surveyed one month and seven months later. Apparently no drastic reduction in species had occurred, but reduced densities were observed after one month. Turbellaria and particularly Harpacticoidea seemed to have been more affected than other taxonomical groups. Recovery within seven months seemed related to both hydrodynamism and sediment porosity allowing a proper restoration of living conditions. Resistance to hydrocarbon toxicity may be due to the ability of faunal taxa to withstand large trophic temporary fluctuations. High reproduction rates, protection of brood and adaptability to unstable habitats, might have been important recovery factors.

Riaux-Gobin, C. (1985)
Amoco Cadiz oil spill

Mar. Ecol. Prog. Ser. 24:51-56

ABSTRACT
After the *Amoco Cadiz* oil spill (Mar. 1978), a four-year survey of the microphytobenthos (cell numbers and chlorophyll a content) was carried out on a mudflat polluted by petroleum

hydrocarbons. There was an obvious peak of microphytic biomass seven months after the spill, a decrease during 1979-1980, and a slow increase again in 1981. Moreover an annual pattern in biomass variations, involving early spring and autumn maxima, was noticed for 1979-80-81, whereas this seasonal cycle did not appear in 1978. During the unexpected increase in chlorophyll a content in Autumn and Winter 1978, a bloom of Euglenophyta and small epipelic diatoms was observed. Results suggest that the hydrocarbons affected the long-term trend of the biocenosis.

Rice, S.D., A. Moles, T.L. Taylor, and J.F. Karinen (1979)
Sensitivity of 39 Alaskan marine species to Cook Inlet crude oil and No. 2 fuel oil.

Proceedings of the 1979 Oil Spill Conference, pp. 549-554.

ABSTRACT
The sensitivities of 39 Subarctic Alaskan species of marine fish and invertebrates to water-soluble fractions of Cook Inlet crude oil and No. 2 fuel oil were determined. This is the largest group of animals ever tested under similar test conditions with the same petroleum oils and analytical methods. Organisms bioassayed represent several habitats, six phyla, and 39 species, including fish (9), arthropods (9), molluscs (13), echinoderms (4), annelids (2), and nemerteans (2). Sensitivities were determined by 96-hour static bioassays. Concentrations of selected aromatic hydrocarbons were determined by gas chromatography; concentrations of paraffins were determined by infrared spectrophotometry. Although sensitivity generally increased from lower invertebrates to higher invertebrates, and from higher invertebrates to fish, sensitivity was better correlated to habitat. Pelagic fish and shrimp were the most sensitive animals to Cook Inlet crude oil with 96-hour median tolerance limits (TLms) from 1-3 mg/l total aromatic hydrocarbons. Benthic animals, including fish, crabs, and scallops were moderately tolerant (TLms to Cook Inlet crude oil of 3 to 8 mg/l total aromatic hydrocarbons). Intertidal animals, including fish, crabs, and starfish, and many molluscs, were the most tolerant forms to water-soluble fraction of petroleum (TLms greater than 8 to 12 mg/l of total aromatic hydrocarbons). Most of the intertidal animals were not killed by static oil exposures. No. 2 fuel oil was more toxic to most species than Cook Inlet crude oil. Sensitive pelagic animals are not necessarily more vulnerable to oil spills than tolerant intertidal forms—oil may damage intertidal environments more easily and adverse effects may persist longer than in damaged pelagic environments.

Riebel, P.N., and J.A. Percy (1990)
Acute toxicity of petroleum hydrocarbons to the Arctic shallow-water mysid, *Mysis oculata* (Fabricius)

Sarsia 75:223-232.

ABSTRACT
Acute lethal toxicity tests were conducted with young-of-the-year *Mysis oculata* exposed to oil-in-water dispersions (OWDs) and water-soluble (WSFs) of Norman Wells crude oil. Median lethal concentrations (96-hour LC50s) are among the lowest reported for Arctic marine crustaceans, ranging from 0.49-0.62 mg/l for WSFs and 4.51-7.57 mg/l for OWDs. Sublethal behavioral effects occurred at concentrations as low as 0.3 mg/l for WSFs and 1.5 mg/l for OWDs. Adverse effects were caused primarily by the chemical toxicity of water-soluble hydrocarbons since there were no apparent physical effects due to dispersed oil droplets. OWDs were more toxic to mysids in sealed containers than in open ones. Median effective concentrations (96-hour EC50s) causing gross behavioral disturbances, morbidity and 'ecological death' suggest that high molecular weight volatile

hydrocarbons found in OWDs are more toxic to mysids than low molecular weight volatiles present in WSFs. Due to its sensitivity, vulnerability, availability in nearshore waters, and ease of maintenance under laboratory conditions, *M. oculata* is recommended as a test organism for Arctic marine toxicity testing and environmental monitoring.

Roesijadi, G., J.W. Anderson, and J.W. Blaylock (1978)
Uptake of hydrocarbons from marine sediments contaminated with Prudhoe Bay crude oil: influence of feeding type of test species and availability of polycyclic aromatic hydrocarbons

J. Fish. Res. Bd. Can. 35:608-614

ABSTRACT
Selected benthic animals were exposed to marine sediments contaminated with Prudhoe Bay crude oil, and uptake of hydrocarbons was monitored under various experimental schemes. When uptake of aliphatic and diaromatic hydrocarbons by two deposit feeders, *Macoma inquinata* and *Phascolosoma agassizii*, was compared with that of a suspension feeder, *Protothaca staminea*, it was found that the deposit feeders generally accumulated hydrocarbons to a greater extent than the suspension feeder. However, other factors, such as the intrinsic capabilities of species to accumulate hydrocarbons, also played an important role in the extent of contamination. Hydrocarbon concentrations in the bivalve species (*M. inquinata* and *P. staminea*) increased during the 60-day exposure period; whereas concentrations in the sipunculid *Phascolosoma agassizii* appeared to have reached an equilibrium relatively early in the exposure. Experiments on uptake of ^{14}C-phenanthrene, -chrysene, -dimethylbenz(a)anthracene, and -benzo(a)pyrene by *M. inquinata* indicated that compounds directly associated with sediment were less available for uptake than those released from sediment to surrounding seawater. Concentration factors for uptake from sediment were ≤ 0.2, while those for uptake from seawater were 10 to 1,349. Additionally, the heavier molecular weight aromatic compounds tended to be more concentrated in tissue and retained for longer periods of time than the lighter compounds.

Rolan, R.G. and R. Gallagher. (1991)
Recovery of intertidal biotic communities at Sullom Voe following the *Esso Bernicia* oil spill of 1978

Proceedings of the 1991 International Oil Spill Conference, pp. 461-465

ABSTRACT
In December 1978, the *Esso Bernicia* spilled 8,000 barrels of Bunker C oil during a berthing accident near Sullom Voe oil Terminal. About 100 miles of shoreline were oiled, much of that span heavily. Sullom Voe is a bay of the Shetland Islands, north of Scotland, an area environmentally similar to Prince William Sound. The highly indented, rocky shoreline is inhabited by typical intertidal communities characterized by fucoid algae (rockweed), barnacles, and snails. Biological survey data for the intertidal communities had been collected for three years prior to the spill. During the cleanup, most of the shores that were accessible to heavy equipment were stripped of oily rock, cobble, and gravel. Other fairly accessible areas were hand-cleaned. Dispersants were tried on a few shores, but were ineffective. Many of the less accessible locations were not cleaned at all. The oiled shorelines were resurveyed every year from 1979 through 1987, except 1982 and 1983. Except for the mechanically cleaned areas, the biological communities in the rocky intertidal zone returned to very near normal within the first year, and have remained so in spite of the presence of traces of weathered oil. Normal populations of snails and small crustaceans have thrived in intimate contact with asphaltic residues that still remain in some locations. In contrast, the biological communities

at the sites that were cleaned mechanically were obliterated, and still had not fully recovered after almost nine years.

Rounds, P., S. Rice, M.M. Babcock, and C.C. Brodersen (1993)
Variability of *Exxon Valdez* hydrocarbon concentrations in mussel bed sediments

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska, pp. 182-183.

ABSTRACT
Concern for mussel beds contaminated by the *Exxon Valdez* oil spill increased rapidly in 1991 when poor recovery in several predator species was thought to be linked to oiled mussels. A pilot survey confirmed the persistence of *Exxon Valdez* oil at relatively high concentrations in mussels and underlying sediments in several beds (Babcock et al. 1993). The uneven distribution of oil within beds observed during the survey prompted us to sample several beds intensively in 1992 to determine the within-bed variation in sediment hydrocarbon concentrations. In this paper we document concentrations and distribution of hydrocarbons within one bed and examine the effects of several variables. The study site, on the northern tip of Chenega Island, is fairly typical of highly oiled beds. It is small (approximately 50 m^2) and on a low angle beach (4.4 percent slope) protected from intense wave action by bedrock headlands. Tidal range occupied by the bed is approximately 1.43 m to 1.77 m above mean lower low water. Mussel densities average 1,900 animals per m^2 on sediments ranging from small pea gravel to fine silt. At each of the fifteen subsites within this bed, mussel density was determined and sediments entrained in the mussel byssal mat (threadlike mass holding mussels together), and sediments under this mat to a depth of 2 cm were sampled for hydrocarbons. All sediment samples were extracted and analyzed by ultraviolet spectrophotometry at the Auke Bay Laboratory. This method, adapted from Krahn (1991), approximates total oil concentrations based on the concentrations of two and three ring aromatic compounds that fluoresce at the phenanthrene wave-lengths (260/380 nanometers). Although analytical results are not strictly quantitative and can not be compared with results produced by gas chromatograph-mass spectrometer analysis, they are extremely useful in comparing large numbers of samples.

Ruhnhold, W.W. (1978)
Impact of the *Argo Merchant* oil spill on macrobenthic and pelagic organisms

Proceedings of Conference on Assessment of Ecological Impacts of Oil Spills, American Institute of Biological Sciences, pp. 153-179.

ABSTRACT
Abundance studies in benthic and pelagic communities including commercial fish species were done but did not suggest a major adverse impact. Zooplankton was, at some stations, fouled with oil. At some stations within the slick area and close to the margin lower densities of ichthyoplankton were found; pelagic fish eggs of the only two species present were contaminated and found moribund to a high degree. Laboratory experiments with cod eggs and young larvae were conducted with a No. 6 fuel oil to determine toxic levels of dissolved hydrocarbon concentrations. Very few of the fish examined, showed traces of *Argo Merchant* oil in stomach contents or muscle tissue. Prey-predator relationship seemed to have remained normal. Shortcomings in sampling methodology and evaluations are discussed.

Sanders, H.L. (1978)
Florida oil spill impact on the Buzzards Bay Benthic fauna: West Falmouth

J. Fish. Res. Bd. Can. 35:717-730

ABSTRACT
No matter what criterion is used to measure the effects of the *Florida* oil spill, the densities and species composition and the array of statistical methods demonstrate that the same hierarchical pattern emerges. Densities and species composition remain stable over time at the minimally oiled and unoiled stations, but display considerable fluctuations and marked changes at the more heavily oiled stations. With simple presence or absence data, highest fidelity is present at the marginally oiled stations, lower fidelity at the intermediately oiled stations, and lowest fidelity at the severely oiled stations. The discrepancy index measures mean yearly differences in fauna composition at each of the stations. Very large and large differences are documented for the severely and intermediately oiled stations but only small differences are found for the marginally oiled stations. The coefficient of variation is a measure of faunal variability throughout the entire sampling period for each of the stations. Faunal variation remains very high at the severely and intermediately oiled stations but low at the marginally oiled sites. Cluster analysis reveals profound temporal changes in the fauna from samples collected at the severely and intermediately oiled stations but demonstrates a much more homogeneous pattern with only small seasonal changes from samples obtained at the marginally oiled stations.

Sanders, H.L., J.F. Grassle, G.R. Hampson, L.S. Mose, S. Garner-Price, and C.C. Jones (1980)
Anatomy of an oil spill: long-term effects from the grounding of the barge *Florida* off West Falmouth, Massachusetts

J. Mar. Res. 38:265-380

ABSTRACT
To determine carefully the effects on the marine estuarine benthos of number 2 oil spilled by the barge *Florida* off West Falmouth, Massachusetts, the authors sampled along an onshore-offshore gradient of pollution. Analysis of hydrocarbons established that pollution was greater and more persistent in the intertidal and subtidal zones of Wild Harbor River, less severe in degree and duration at stations farthest from shore. Plant, crustaceans, fish and birds suffered both high mortality immediately after the spill, and physiological and behavioral abnormalities directly related to high concentrations of the fuel oil. Five years after the spill its effects on the biota were still detectable, and partly degraded no. 2 fuel oil was still present in the sediments in Wild Harbor River and estuary.

Sato, C., H. Kim, and J.T. Tanacredi (1992)
Characterization of polycyclic aromatic hydrocarbons (PAHs) by the kinetics of depuration in bivalve molluscs, *Mercenaria mercenaria*

Wat. Sci. Tech. 25:33-38.

ABSTRACT
The objectives of this study were to examine depuration aspects of PAHs in a hard-shell clam *Mercenaria mercenaria*, and to characterize PAHs by the depuration kinetics. In this investigation, clams were exposed to artificial sea water containing a mixture of eight PAHs (including naphthalene, fluorene, benz[a]anthracene, chrysene, benzo[a]pyrene) for 48 hours. The clams were

then transferred into clean (PAH-free) artificial seawater for release, and sampled at predetermined intervals. The target PAHs were extracted from the clam tissue and quantified by a gas chromatograph equipped with a capillary glass column and FID. The results revealed single- and multi-component release mechanisms which were described by single- and multi-stage first-order kinetics, respectively. Benz[a]anthracene and benzo[a]pyrene exhibited the single-stage depuration, while naphthalene, fluorene, phenanthrene, fluoranthene, pyrene, and chrysene showed the two-stage depuration.

Seneca, E.D. and S.W. Broome (1982)
Restoration of marsh vegetation impacted by the *Amoco Cadiz* oil spill and subsequent cleanup operations at Ile Grande, France

Ecological Study of the Amoco Cadiz Oil Spill: Report of the NOAA-CNEXO Joint Scientific Commission (E.R. Gundlach and M. Marchand, eds.) pp. 363-420

ABSTRACT
The authors developed a proposal for restoring marsh at the Ile Grande site adapting techniques and procedures developed for *Spartina alterniflora*, in North Carolina to restoration of a part of the Ile Grande marsh using vegetation indigenous to that region. Although there was considerable variation in response to fertilizer materials and rates, both nitrogen and phosphorus were required for good transplant growth on the disturbed sites tested. Slow-release fertilizer materials produced better growth than did the conventional, more soluble fertilizer materials. Higher survival and better growth were obtained with *Halimione portulacoides* and *Puccinellia maritima* transplants than with those of the other three species tested, *Juncus maritima*, *Spartina maritima*, and *Triglochin maritimus*. Above ground growth of the best experimental plantings of *Puccinellia* spread radially at the rate of about 10 cm annually. At this rate of spread, these experimental plantings would achieve complete substrate cover in about three years after planting.

Sergy, G.A. (1985)
The Baffin Island Oil Spill (BIOS) project - a summary

Proceedings of the 1985 Oil Spill Conference; pp. 571-575

ABSTRACT
After four years of multidisciplinary experimental investigations in the Canadian Arctic, the Baffin Island Oil Spill (BIOS) Project has successfully completed studies which address oil spill fate, effects, and countermeasures. In particular, the findings are relevant to decisions on the nearshore use of chemical dispersants and the cleanup of oiled shorelines. Much of the information gathered can be extrapolated to other geographic areas. Within the context of the project design, the experimental results offer no compelling ecological reasons to prohibit use of dispersants on oil slicks in the Arctic nearshore environment and they enable recognition of situations in which dispersant use would be advisable. The results also suggest that for much of the Arctic coastline the cleanup of stranded oil is not essential. Shoreline cleanup efforts should focus on low energy beaches with characteristics conducive to the long term retention of oil, but there will be many situations where cleanup will be severely limited and impractical.

Shaw, D.G., A.J. Paul, L.M. Cheek, and H.M. Feder (1976)
Macoma balthica: an indicator of oil pollution

Mar. Poll. Bull. 7(2):29-31.

ABSTRACT
The intertidal bivalve mollusc, *Macoma balthica* shows potential as an indicator of oil pollution. In experiments designed to simulate stranding of an oil slick on a mudflat, a significant increase in mortality of this species was found to accompany increasing concentration of petroleum in sediment and increasing duration of exposure.

Shaw, D.G., A.J. Paul, and E.R. Smith (1977)

Responses of the clam *Macoma balthica* to Prudhoe Bay crude oil

1977 Oil Spill Conference American Petroleum Institute Publ. 4284, pp. 493-494.

ABSTRACT
The responses of the bivalve mollusk to crude oil were studied under laboratory conditions designed to simulate the stranding of oil on intertidal sediments in which this animal resides. The relationship of dry tissue weight to shell length, an indirect indicator of general health and fitness, was not significantly altered by exposure to oil at a level which did result in significant mortalities. This suggests that death is caused by a metabolically specific mode of poisoning rather than by a general weakening of the animal. In a second experiment, animals were subjected to two temporarily separated oiling events. Neither in mortalities nor in gas chromatograph analysis of tissues for hydrocarbons were cumulative effects observed. A tendency to burrow to the sediment surface in the presence of oil increases with decreasing depth of available sediment. This behavior may be used as a convenient indicator of oil pollution.

Shaw, D.G., T.E. Hogan, and D.J. McIntosh (1986)
Hydrocarbons in bivalve mollusks of Port Valdez, Alaska: consequences of five years' permitted discharge

Est., Coast. and Shelf Sci. 23:863-872,

ABSTRACT
Petroleum hydrocarbons were investigated in *Mytilus edulis* and *Macoma balthica* at six intertidal sites in Port Valdez, Alaska after three to five years of oil terminal operation. Information about the concentrations of total hydrocarbons, unresolved complex mixture, normal alkanes, isoprenoids, olefins, hopanes and polycyclic aromatic hydrocarbons shows that petroleum accumulation in these bivalve mollusks is greatest at the Valdez municipal boat harbor and a crude oil terminal which has been permitted to discharge 170 kg oil day $^{-1}$. Accumulation two- to ten-fold less were observed at three km from the terminal and boat harbor. The temporal trends in petroleum hydrocarbon concentrations in *M. edulis* and *M. balthica* reflect the effects of selective retention and depuration of different hydrocarbon classes as well as variation in hydrocarbon sources. It is not clear whether the petroleum concentrations in Port Valdez bivalves had reached steady state by 1982, the final sampling time reported here.

Shaw, D.G., P.J.D. Lambshead, and H.M. Platt (1983)
Detection of pollution-induced disturbance in marine benthic assemblages with special reference to nematodes

Mar. Ecol. Progr. Ser. 11:195-202.

ABSTRACT
Benthic marine nematode assemblages were assessed for possible use in the detection of pollution-induced disturbance. Doubt is cast on a recently proposed method which claims to observe deviation from a log-normal distribution of species abundance. Little evidence is found to substantiate the belief that natural marine nematode assemblages in temperate waters are well described by the log-normal distribution. This conclusion may not be restricted to nematodes. Simple dominance is suggested as a potentially more practical method of assessing changes due to pollution.

Shigenaka, G. and C.B. Henry (1993)
Bioavailability of residual PAHs from the *Exxon Valdez* oil spill

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska; pp. 163-165.

ABSTRACT
Smith Island, 25 miles southwest of the Bligh Reef grounding site, had one of the more heavily impacted shorelines from the *Exxon Valdez* spill. The coast of Smith Island is exposed and rocky, with boulder/cobble pocket beaches. Many of these beaches overlie beds of sand and gravel and when oil came ashore it penetrated deeply into the substrate. Despite large-scale removal efforts through such means as high-pressure, hot-water washing, chemical agents, and excavation with heavy equipment, oil remains buried in portions of some beaches. At these locations, oil sheens have been observed to leach out from the substrate each year since the spill. The purpose of this study was to assess the extent to which residual PAHs were available for accumulation by intertidal organisms living at the site, and to evaluate the physical means by which organisms were exposed. Since 1990, National Oceanic and Atmospheric Administration staff have sponsored a monitoring effort in Prince William Sound to evaluate the effects of both oiling and treatment at selected sites. An integral part of the program has been chemical hydrocarbon analysis of both sediments and tissues of intertidal invertebrates found at the sites. In 1990, mussels collected at the Smith Island site contained the highest concentration of PAHs of the 23 sites sampled for the National Oceanic and Atmospheric Administration Prince William Sound monitoring study, 84 ppm (dry weight). Mussel tissue samples from nearly all other sites contained less than ten parts per million. The comparatively high value encountered for Smith Island mussels was not reflected in results of hydrocarbon analyses of surface sediment samples from the site, although very high concentrations of both total petroleum hydrocarbons and PAHs have been consistently found in subsurface sediments over the period from 1989 to 1992.

Short, J.W. and P. Rounds (1993)
Determination of petroleum-derived hydrocarbons in seawater following the *Exxon Valdez* oil spill II: analysis of caged mussels

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska, pp. 186-187.

ABSTRACT
We deployed bay mussels (*Mytilus trossulus*) that were initially free of hydrocarbons in nearshore waters along the path of oil spilled by the *T/V Exxon Valdez* to determine the persistence and the biological availability of petroleum-derived hydrocarbons to living marine resources. Mussels filter substantial volumes of seawater, and may therefore accumulate petroleum hydrocarbons integrated over the transplant period. Petroleum hydrocarbon-free mussels were collected from Admiralty Island in southeastern Alaska, and were transplanted to 12 locations inside Prince William Sound and to 18 locations outside the Sound for two to six weeks at depths of 1, 5, and 25 meters at each location. In Prince William Sound, four successive transplants were conducted in both 1989 following the spill and in 1990; two transplants were conducted during 1991. Three successive transplants to sites along the Kenai Peninsula, Alaska Peninsula, and Kodiak Island occurred in 1989 and 1990. Mussels were retrieved at the end of each transplant period and stored frozen at -20°C for petroleum hydrocarbon analysis. Transplanted and control mussels were analyzed using single ion mode gas chromatography-mass spectrometry for the most abundant two-to five-ring PAHs in the spilled oil, and using gas chromatography-flame ionization detection for alkane hydrocarbons including pristane, phytane, and the normal alkanes of 10 to 30 carbon atoms.

Singer, M.M., D.L. Smalheer, R.S. Tjeerdema, and M. Martin (1990)
Toxicity of an oil dispersant to the early life stages of four California marine species

Environ. Toxicol. and Chem. 9:1387-1395.

ABSTRACT
Continuous-flow toxicity tests using the oil dispersant Corexit 9527 were performed on the early life stages of four California marine species. Newly released zoospores of the giant kelp, *Macrocystis pyrifera*, embryos of the red abalone, *Haliotis rufescens*, four-day old juveniles of the mysid, *Holmesimysis costata* and ten-day old larvae of the topsmelt, *Atherinops affinis*, were all used in triplicate 48- and 96-hour tests. Quantitative verification of dispersant concentrations using UV spectrophotometry was performed twice daily during testing. Results indicated growth of kelp gametophytes was significantly reduced at <2.4 ppm after a 48-hour exposure. Of the three animals tested, developing red abalone were the most sensitive (NOEC = 0.63 to 1.50 ppm; LC50 = 1.60 to 2.20 ppm). Mysid juveniles were intermediate in sensitivity (NOEC = 1.66 to 4.20 ppm; LC50 = 4.26 to 7.26 ppm), whereas topsmelt larvae were the least sensitive (NOEC = 12.27 to 14.18 ppm; LC50 = 25.51 to 40.63 ppm). Reproducibility of test data was very high (coefficient of variation = 15.7 to 27.1 percent).

Southward, A.J., and E.C. Southward. (1978)
Recolonization of rocky shores in Cornwall after use of toxic dispersants to clean up the *Torrey Canyon* spill

J. Fish Res. Bd. Can. 35:682-706.

ABSTRACT
Fourteen thousand tons of Kuwait crude oil, reduced from 18,000 tons by weathering at sea, was stranded along 150 km of the coast of West Cornwall, England, in March 1967. The oil was treated with 10,000 tons of toxic dispersants during cleaning operations. By itself the oil was not very toxic, although it killed some limpets and barnacles, and most of the mortalities that followed clearing were due to the dispersants. There was a graded effect. Most animals and some algae were killed on the shores treated heavily with dispersants, while a few animals and most algae survived in places less heavily treated. However, long stretches of coast were contaminated to some extent by drifting of patches of oil and dispersants along the shore and by indiscriminate dispersant use in remote coves. The general sequence of recolonization was similar to that which has been found after small-scale experiments, where the rocks were scraped clean, or where limpets were removed, but took longer to complete. There was first a rapid "greening" by the alga *Enteromorpha*; then a heavy settlement and growth of perennial brown algae (*Fucus* species), leading to loss of surviving barnacles. A settlement of limpets and other grazing animals followed, with eventual removal or loss of the brown algae. The final phases were a reduction in the limpet population and a resettlement of barnacles. Lightly oiled, wave-beaten rocks that received light dispersant treatment showed the most complete return to normal, taking about five to eight years; heavily oiled places that received repeated application of dispersants have taken nine to ten years and may not be completely normal yet. Most common species returned within ten years, but one rare hermit crab is still missing from places directly treated with dispersants. The early recolonization by algae resulted in a raising of the upper limit of *Laminaria digitata* and *Himanthalia elongata* by as much as 2 m in wave-beaten places, demonstrating that grazing pressure by limpets must be one of the factors controlling the zonation of these plants. Later, other species of plants and animals were found higher up the shore than usual, under the shade and shelter provided by the dense canopy of *Fucus*. Fluctuations in the populations of algae and herbivorous animals during the course of the recolonization illustrate the importance of biological interactions in controlling the structure of intertidal communities. Pollution disturbance affects the herbivores more than plants, hence the point of stability of the community is shifted towards the sheltered shore condition of low species richness and greater biomass.

Stainken, D.M. (1978)
Effects of uptake and discharge of petroleum hydrocarbons on the respiration of the soft-shell clam, *Mya arenaria*

J. Fish. Res. Bd. Can. 35:637-642.

ABSTRACT
A winter (4°C) spill condition was simulated in which young soft-shell clams, *Mya arenaria*, were exposed to subacute concentrations of No. 2 fuel oil-in-water emulsions for 28 days. Clams were exposed at the beginning of the experiment to single dose concentrations of 10, 50, and 100 ppm. Hydrocarbons were rapidly accumulated by clams within 1 wk after exposure. The accumulated hydrocarbons then decreased each week as the hydrocarbon content of the water decreased. Methyl substituted naphthalene isomers were the principal compounds accumulated and retained by the clams after three weeks of oil exposure. A dose-response relationship was observed in the respiratory rates as measured by oxygen consumption (QO_2). Significant differences ($p=0.05$) in

respiratory rates were found in clams exposed to low concentrations of oil. The lowest concentrations of oil caused a doubling of the respiratory rates and greater oil concentrations caused a depression in rate. The respiratory rates of the clams exposed to low oil concentrations decreased as the hydrocarbon content of the water and clam tissues decreased, but remained significantly altered from the controls. Clams were transferred to an uncontaminated system for fourteen days after the 28-day oil exposure to determine effects of depuration on the respiratory rate. During the depuration period, many of the hydrocarbons present in clam tissue were again found to be methyl substituted naphthalene isomers. During this period, the respiratory rates of the clams initially exposed to 10 ppm fuel oil emulsion remained significantly altered above the controls. The respiratory rates of all groups of oil-exposed clams remained altered from the controls, but the magnitude of difference tended to decline toward the controls. A dose-response narcosis may have been evident during this period.

Stekoll, M.S., L. Deysher, and T.A. Dean (1993a)
Seaweeds and the *Exxon Valdez* oil spill

Proceedings of the 1993 Oil Spill Conference, pp. 135-140.

ABSTRACT
A three-year study, initiated in 1989, has evaluated the response of subtidal and intertidal seaweed communities to the *Exxon Valdez* oil spill and subsequent cleanup activities. The project was part of the coastal habitat injury assessment research sanctioned under the natural resource damage assessment program. A stratified random design was used to select oiled sites for the study. Paired control (unoiled) sites were then matched to the oiled sites. The most consistent effect found in subtidal populations in Prince William Sound was the higher relative abundance of small-size classes of kelps at the oiled sites, indicating the prior disappearance of larger plants. This disappearance was possibly caused by activities associated with the cleanup operations. Intertidal populations of algae were affected by the spill and cleanup in all three major areas studied: Prince William Sound, Cook Inlet-Kenai, and Kodiak-Alaskan Peninsula. The most obvious effect was a significant removal of the dominant intertidal plant *Fucus gardneri* from the mid and upper intertidal zones. The limited dispersal of this plant combined with the relatively harsh conditions of the upper intertidal will cause a slow recovery of the upper intertidal zone in the affected areas. Effects of the spill extended to other algal species. Species such as *Cladophora, Myelophycus, Odonthalia, Palmaria,* and *Polysiphonia* showed decreases in their percent cover at oiled sites. Only *Gloiopeltis* populations appeared to increase in percent cover in oiled areas. In 1991, both the Cook Inlet-Kenai and the Kodiak-Alaskan Peninsula areas *Fucus* populations appeared to be enhanced in the lower intertidal zone - between two and three meters below the high-tide mark.

Stekoll, M.S., L. Deysher, and Z. Guo (1993b)
Coastal habitat injury assessment: intertidal algal communities

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska; pp. 169-172.

ABSTRACT
The Coastal Habitat Injury Assessment program, part of the Natural Resource Damage Assessment plan, investigated the effects of the *Exxon Valdez* oil spill on the biota of the subtidal, intertidal, and supratidal habitats from Prince William Sound to the Alaskan Peninsula. Here we report the results of a study on the effects of the *Exxon Valdez* oil spill on the intertidal algal communities. A random stratified experimental design was used to compare data from matched

pairs of oiled and control sites in several different habitats in the three main areas of the spill: Prince William Sound, the Cook Inlet and Kenai Peninsula area, and the area including Kodiak Island and the Alaskan Peninsula. Each area was stratified by beach type: sheltered rocky, coarse textured, exposed rocky, and estuarine. Oiled sites were selected randomly from information made available from other agencies (Sundberg et al. 1993). Control sites were selected to match each oiled site using physical criteria such as slope, aspect, beach texture, and wave exposure. The overall statistical design was to compare data sets within site pairs and then to compare across all sites of one habitat from an area.

Stoker, S.W., J.M. Neff, T.R. Schroeder, and D.M. McCormick (1993)
Biological conditions of shorelines following the *Exxon Valdez* spill

Proceedings of the 1993 Oil Spill Conference, pp. 287-292.

ABSTRACT
Following the *Exxon Valdez* oil spill of March 24, 1989, in Prince William Sound, Alaska, Exxon conducted a comprehensive shoreline survey program in cooperation with federal and state authorities. Objectives of surveys during the spring and summer of 1989 were to assess the distribution and magnitude of oiling, to evaluate impacts of the oil on key shoreline biological communities, and to identify ecological and archaeological resources requiring special care during the massive cleanup effort that followed. Similar shoreline surveys were performed during the springs of 1990, 1991, and 1992 on all shorelines in Prince William Sound and the Gulf of Alaska suspected of having residual oil. These subsequent surveys were conducted to provide information on the distribution and amounts of residual shoreline oil and to assess the condition of intertidal biological communities in order to make environmental sound decisions regarding the need for additional cleanup. The following report is based primarily on survey results from Prince William Sound, where most of the heavy shoreline oiling occurred. Although not strictly quantitative, the shoreline surveys provide an unprecedented, broad base of professional observations covering the entire spill-affected area from 1989 through 1992 by which to evaluate spill impacts and recovery. Shoreline surveys documented the extent of shoreline oiling declined substantially from 1989 to 1992. In 1989, oil was found on about 16 percent of the 3,000 miles of shoreline in Prince William Sound; by the spring of 1991, oil was found on only about 0.2 percent. In all years, most of this oil was located in the biologically least productive upper intertidal and supratidal zones. In both 1991 and 1992, small, isolated pockets of subsurface oil were found on some boulder/cobble beaches. Most of these deposits were also located in the upper intertidal and were usually buried beneath clean sediments. In almost all cases, the condition of intertidal biological communities improved correspondingly from 1989 to 1992. By the spring of 1991, recovery appeared to be well under way on virtually all previously oiled shores, with species composition, abundance, and diversity levels usually comparable to those of nearby shores that were not oiled in 1989. Recruitment of intertidal plants and animals was observed as early as the summer of 1989, and increasingly through 1991 and 1992. Recruitment was evident even in areas with remnant deposits of surface and subsurface oil, indicating that toxicity levels of the oil had declined substantially and that, in most cases, the residual oil no longer interfered with biological recovery. Observations of birds and marine mammals on or near shorelines surveyed during 1991 and 1992 confirmed that species present before the spill were still present and were feeding and reproducing in areas affected by oil in 1989. In most cases, observed densities were comparable to those recorded prior to the spill, and to those found in similar but unaffected areas.

Strand, J.A., V.I. Cullinan, E.A. Crecelius, T.J. Fortman, R.J. Citterman, and M.L. Fleischmann (1992)
Fate of Bunker C fuel oil in Washington coastal habitats following the December 1988 *Nestucca* oil spill

Northwest Sci. 66(1):1-14.

ABSTRACT
Following the December 1988-spill of 230,000 gallons of Bunker C fuel oil from the barge *Nestucca*, a year-long monitoring program was conducted to follow the fate of spilled oil in selected intertidal and shallow subtidal habitats of the Washington coast, including a 40-mile-long strip of Olympic National Park (ONP). Following clean-up, beach surveys were conducted in July and September 1989 and February 1990 at eight coastal sites inside ONP: four oiled areas, four unoiled areas; and at four oiled sites (coastal and estuarine) outside ONP. The finding of only trace levels (63-250 μg/g dry weight by infrared spectrometry) of oil in surface (0-15 cm in depth) sediments associated with coastal sites 13 months after oiling suggested that depuration had occurred rapidly and that little oil residual remained. The essentially background levels (mostly <45 ng/g dry weight by gas chromatographic mass spectrometry) of aromatic hydrocarbons found in invertebrates associated with oiled sediments also suggested that most oil had been rapidly metabolized and depurated or was no longer biologically available. Factors contributing to these findings likely included: 1) the time of year when the spill occurred, 2) the type of beach or coastline affected, and 3) the timely and efficient clean-up. Most spilled oil congealed before stranding due to cold air and water temperatures. The area of the coast most affected consisted of unprotected, high-energy, sand beaches and rocky headlands, which self-cleanse rapidly. Finally, clean-up was immediate and congealed oil was easily removed from affected beaches.

Straughan, D. (1971)
Oil pollution and wildlife and fisheries in the Santa Barbara Channel

Transactions of the 36th North American Wildlife and Natural Resources Conference, pp. 219-229

ABSTRACT
The known biological effects of the Santa Barbara, California oil spill of January 28, 1969 are reviewed. Areas of ignorance are noted, and difficulties obtaining reliable baseline data commented upon. The total loss of birds attributed to the spill was 3,686 by May 31, 1969. Loons and grebes were the most abundant dead birds, while cormorants and pelicans were the second most abundant populations of marine mammals were apparently not seriously affected. Similarly, no significant effect on fish was observed. Although a decrease in commercial landings was caused by a decrease in local fishing effort during and immediately after the spill. No flavor taint was found in fish or invertebrates.

Straughan, D. (1983)
Sandy beach communities exposed to natural oil seepage

Proceedings of the 1983 Oil Spill Conference, pp. 485-489.

ABSTRACT
Studies of the intertidal sandy beach community in the region of natural oil seepage at Coal Oil Point commenced in 1969. This research continued as part of a long term study of natural variation in

sandy beach communities as well as an investigation of the impacts on the biota of intermittent exposure to natural oil seepage. Community data were related to both localized and widespread environmental changes. Changes in the overall macrofaunal community correlate with localized sand movement in the intertidal area. Changes in species composition were related to the widespread oceanographic changes (e.g., water temperature) that occurred in the Southern California Bight during the past decade. A positive correlation between number of specimens and weight of tar on the beach is attributed to seasonal recruitment patterns rather than the presence of petroleum. Therefore the periodic stranding of petroleum is not the dominant abiotic factor influencing this community as a whole.

Suchanek, T.H. (1993)
Oil impacts on marine invertebrate populations and communities

Am. Zool. 33:510-523.

ABSTRACT
It is likely that roughly one billion gallons of oil enters our oceans each year as a result of man's activities. Only 8 percent of this input is believed to derive from natural sources. At least 22 percent is intentionally released as a function of normal tanker "operational discharges," 12 percent enters from accidental tanker spills and another 36 percent from runoff and municipal and industrial wastes. Invertebrate populations and communities form the foundation for marine ecosystems and are continually subjected to stresses from both chronic and acute oil toxicity. The diversity of invertebrate taxa represented in the marine environment exhibit a wide range of responses to oil. Mortality is an obvious impact resulting from catastrophic spills or even chronic toxicity. Sublethal impacts on individuals are manifested by physiological, carcinogenic and cytogenetic effects. Impacts typically felt at the population level involve changes in abundance, age structure, population genetic structure, reproduction and reduced recruitment potential. Community level impacts are typified by modified interactions between competitors, predator/prey and symbionts. Most importantly, changes in community structure represented by altered trophic interactions tend to produce the most dramatic alterations to natural invertebrate assemblages. Invertebrate communities respond to severe chronic oil pollution and/or acute catastrophic oil pollution in much the same way. Initial massive mortality and lowered community diversity is followed by extreme fluctuations in populations of opportunistic mobile and sessile fauna (and flora). Oscillations in population numbers slowly dampen over time and diversity slowly dampen over time and diversity slowly increases to original levels. The time over which these events occur depends on the type of oil, the extent of the initial contamination, habitat type, weather conditions, latitude, the species assemblages represented and a myriad of other complex factors.

Teal, A.R. (1991)
Shoreline cleanup - reconnaissance, evaluation, and planning following the *Exxon Valdez* oil spill

Proceedings of the 1991 Oil Spill Conference, pp. 149-152.

ABSTRACT
The shoreline cleanup following the *Exxon Valdez* oil spill was a mammoth task complicated by geographical and ecological factors. Shoreline assessment was a prerequisite to the cleanup program in both 1989 and 1990, and provided the cornerstone for the development and monitoring of the cleanup program. Information provided by the assessment teams included geomorphological, biological, archaeological, and oiling information that led to site specific treatment plans. These

plans were submitted for interagency review prior to approval by the federal on-scene coordinator. This process was instrumental in developing an environmentally sensitive approach to the cleanup of over 1,000 miles of remote shoreline in 1989.

Teal, J.M. and R.W. Howarth (1984)
Oil spill studies: a review of ecological effects

Environmental Management 8:27-44

ABSTRACT
We reviewed seven particularly well known and/or studied oil spills that have occurred since the National Academy of Science's 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 held 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.

Teal, J.M., J.W. Farrington, K.A. Burns, J.J. Stegeman, B.W. Tripp, B. Woodin, and C. Phinney (1992)
The West Falmouth oil spill after 20 years: fate of fuel oil compounds and effects on animals

Mar. Poll. Bull. 24(12):607-614.

ABSTRACT
The barge *Florida* spilled No. 2 fuel oil into Buzzards Bay, Massachusetts on September 29, 1969. Sediments from five of the original stations were sampled in August 1989 and analyzed for fuel oil hydrocarbons. Two subtidal and one intertidal marsh station showed no evidence of fuel oil. One subtidal mud core had traces of biodegraded fuel oil at 10 to 15 cm. One marsh core contained 10^6 g per g^{-1} dry wt of weathered and biodegraded fuel oil aromatic hydrocarbons and cycloalkanes at 5 to 10 cm with lesser concentrations at 0 to 5 and 10 to 15 cm. Although present in trace concentrations, these hydrocarbons appear to be slightly inducing cytochrome P4501A in marsh fish (*Fundulus heteroclitus*).

Thom, R., L.D. Antrim, W.W. Gardiner, V.L. Cullinan, D.K. Shreffler, and R.W. Bienert (1993)
Effects of petroleum products on bull kelp (Nereocystis luetkeana P. & R.)

Washington Department of Natural Resources, Olympia, 31 pp.

ABSTRACT
This study tested whether petroleum products, like those spilled in coastal waters of Washington State from the fishing vessel *Tenyo Maru*, could result in the loss of coloration and death of bull kelp (*Nereocystis luetkeana*) as was observed in the field. In total, the study investigated the effects of three petroleum products: intermediate fuel oil (IFO), diesel fuel, and Prudhoe Bay crude oil. Each product was tested unweathered and weathered. Whole bull kelp plants were exposed to the various petroleum products for time periods of four hours and 24 hours to simulate exposure during one slack tide and a full lunar tidal cycle, respectively. Following exposure, the plants were attached by their holdfasts at about 1-m intervals to a line suspended at a fixed depth of -1.5 m at the mouth of Sequim Bay, near the Battelle/Marine Sciences Laboratory (MSL). Observations on the condition of the plants were made daily for seven days. In addition, controlled bioassays were performed to measure the effects of petroleum exposure on net photosynthetic rate (NP) and respiration rate (R), using light and dark bottle techniques. Finally, samples of weathered and unweathered diesel, IFO, and crude oil were analyzed to characterize their chemical composition. The experiments verified the susceptibility of *N. luetkeana* tissue to the damaging effects of direct exposure to several oil types. The four-hour exposures to weathered diesel and unweathered IFO, and 24-hour exposures to weathered and unweathered diesel and IFO resulted in moderate to severe damage (i.e., a clearly delineated bleached line accompanied by decay of the tissue) to the stipe, bulb, and blade tissue. The 24-hour exposure showed an increased frequency of severely damaged plant parts relative to the 4-h exposure. All treatments, including the controls, resulted in mottling (patchy color loss) of either the stipe, bulb, or blade tissue. Mottling is commonly found under normal conditions in the field, which suggests that mottling may or may not be caused only by petroleum treatments. Petroleum type significantly affected blade and stipe NP, respiration, and NP:R ratios. Diesel treatments had a greater negative effect on NP than did the IFO treatments. Based on the photosynthetic rate studies, whole-plant experiments, and blade growth-rate measurements, the relative ranking of petroleum-treatment effects to kelp are weathered diesel> unweathered IFO> unweathered diesel> weathered IFO> unweathered crude> weathered crude. Although research has been conducted on the effects of oil on the giant kelp *Macrocystis pyrifera*, no similar studies have been completed on *N. luetkeana*, the dominant kelp in Washington, British Columbia, and Alaska. The present study provides the first evidence that can help in assessing the damage of oil spills on kelp forest habitat, and should stimulate further research on this topic. Further studies should include controlled experiments on mucus production, tissue uptake of hydrocarbons, pigment degradation, cellular damage, reproductive cycle disruption, and modeling of the total effect of an oil spill on populations in the region of a spill.

Thomas, M.L.H. (1973)
Effects of Bunker C oil on intertidal and lagoonal biota in Chedabucto Bay, Nova Scotia

J. Fish. Res. Bd. Can. 30:83-90

ABSTRACT
In February 1970, a large spill of Bunker C oil occurred in Chedabucto Bay, Nova Scotia. The *Arrow* incident was of particular interest since large spills of this type of oil had not previously been studied. Further interest was added by the unusually cold temperatures and by the nonuse of detergents in cleanup. The effects of the oil on intertidal and lagoonal biota have been followed since

the accident. Many rocky shores and lagoons were heavily oiled. on exposed shores, oil has decreased steadily since oil stopped coming ashore in mid-1970 and by August 1971 only small amounts remained. In sheltered areas, particularly lagoons, heavy oil contamination remains. The summer demobilization and subsequent redeposition of oil added a chronic aspect to the pollution. Initial effects of oil involved minor smothering of fauna and tearing loose of algae. Longer term effects involved extensive mortalities of *Fucus spiralis* on rocky shores and *Mya arenaria* and *Spartina alterniflora* in lagoons. Other biota were not visually affected. In all three affected species, mortalities took place either continuously or only in the second year of pollution. Causes of death are unknown. It is recommended that in all intertidal areas very heavy oil deposits should be mechanically removed and the remainder of the oil left to natural degradation.

Thomas, M.L.H. (1977)
Long term biological effects of Bunker C oil in the intertidal zone

Proceedings of the Seattle Symposium, 238-246.

ABSTRACT
In February 1970 a large spill of Bunker C oil occurred in Chedabucto Bay, Nova Scotia, Canada when the tanker *Arrow* grounded. Oil from the tanker has persisted for over six years on rocks and in intertidal sediments on the shores of the bay. During this period mortalities of common species in all major communities on both exposed and sheltered shores have occurred on rocky shores, the dominant fucoid algae suffered heavy initial mortalities which were more severe at high tidal levels. Recolonization has proceeded from lower to higher levels but has not yet occurred in the high tide zone. Delayed recolonization appears to be related to long term toxicity. In salt-marsh and sheltered lagoonal communities, the dominant grass, salt marsh cordgrass, suffered heavy mortality delayed one year from the initial spill, recovery commenced two years later and is proceeding steadily. Soft-shell clams in lagoonal sediments have shown persistent mortalities proportional to oil content of sediments. This pattern appears to be a result of direct toxicity, environmental change caused by oil and sub-lethal metabolic effects.

Thomas, M.L.H. (1978)
Comparison of oiled and unoiled intertidal communities in Chedabucto Bay, Nova Scotia

J. Fish. Res. Bd. Can. 35:707-716.

ABSTRACT
During 1976, detailed surveys of four oiled and four unoiled control stations. each subdivided into seven standardized intertidal levels, were carried out in Chedabucto Bay. Seventy-one species were found, 14 unique to control and nine to oiled locations. Species diversity was uniformly higher at control than oiled stations. No differences in horizontal zonation of major species were apparent. Analysis of abundance and biomass data for the eight stations and seven tidal levels showed a significant overall difference between oiled and control situations. However, no particular station or tidal level was significantly different from any other. Ten species accounted for most of the variance between oiled and control stations. Six of these were more important at controls and four more important at oiled stations. The flora were particularly affected at oiled stations and species dominant on both sedimentary and rocky shores at all but the lowest tidal levels have been reduced. Length and weight data for the clam, *Mya arenaria* showed significantly lower values at oiled stations, but that for the periwinkle *Littorina littorea* showed the opposite. The length-weight relationship for both of these species showed a significantly lower increase in weight per unit of

length at oiled than at control stations. oiled stations showed significantly greater concentrations of oil in biota and sediments than unoiled, where concentrations were essentially at background levels.

Thomas. M.L.H. (1982)
Communities and Ecosystems

Oil and Dispersants in Canadian Seas: Research Appraisal and Recommendations, EPS 3-EC-82-27 Environmental Protection Service, Ottawa, pp 125-134.

ABSTRACT
Research involving the effects of oil on marine communities and ecosystem is fairly recent. The magnitude and persistence of ecological effects on shoreline ecosystems depends on the amount of oil retained in the habitat. Disappearance rates vary with type of oil, climate, and weather conditions. Planktonic ecosystems vary in their response to oil depending on the species present and the type and concentration of the oil. Circumstantial evidence suggests that fish species composition and diversity of the stock may change in an oil spill area. Benthic communities show increases in opportunistic species in oiled sites and take several years to return to normal. Shoreline ecosystems are often devastated by oiling. In general, shore algae are quite resistant to oil pollution, while severe oil pollution causes either extensive mortality or narcosis to shore animals. Disappearance of grasses in salt marshes may cause accelerated erosion and habitat degradation. The use of dispersants for cleanup of oil on shorelines or in very sheltered or shallow bodies of water generally results in more extensive ecological disturbance than the oil alone.

Thurberg, F.P., E. Gould, and M.A. Dawson (1978)
Some physiological effects of the *Argo Merchant* oil spill on several marine teleosts and bivalve molluscs

In the Wake of the Argo Merchant, Proceedings of a Symposium, University of Rhode Island, Kingston, pp. 103-108.

ABSTRACT
Subsequent to the oil spill from the tanker *Argo Merchant*, two cruises provided animals for physiological and biochemical testing. Blood samples were taken from a variety of teleost species, and although the sample number for most species was too small for valid statistical analysis, there did appear to be a disruption of serum ions in winter flounder, *Pseudopleuronectes americanus*, yellowtail flounder, *Limanda ferruginea*, and haddock, *Melanogrammus aeglefinus*. Serum osmaolality, sodium, and potassium values were variously depressed in fish collected from oil-impacted areas, as compared to fish from clean or unimpacted areas. Ocean scallops, *Placopecten magellanicus*, and horse mussels, *Modiolus modiolus*, collected during the first cruise from oil-impacted areas had depressed gill-tissue oxygen consumption, but normal values were recorded from scallops collected during a second cruise six weeks later. Serum sodium and calcium levels of scallops collected from oil-impacted areas during the second cruise were elevated, as compared to scallops collected from clean areas. Malic dehydrogenase activity of scallop muscle was significantly decreased in scallops from oil-impacted areas. Lactate oxidation was also significantly lower in these animals, although pyruvate reduction, catalyzed by the same enzyme, remained the same. Both observations suggest a possible weakening of the ability to shift to anaerobiosis.

Underwood, A.J. and Peterson, C.H. (1988)
Towards an ecological framework for investigating pollution

Mar. Ecol. Progr. Ser. 46:227-234.

ABSTRACT
Three aspects of the study of effects of pollution in marine systems are discussed. First is the evaluation of relative sensitivities and reliabilities of different methods of detecting pollution, including a brief contrast of processes operating in mesocosms and in the field. Second is the problem of interpretation of pollution, i.e. determining the importance of the observed effects of pollution to the biological system. Species selected for detecting pollution may not provide useful information about the economic effects on exploited parts of natural systems, nor about trophic structure of a community, nor about future sizes of populations of important species. The choice of appropriate species as indicators or detectors of pollution also requires determination of how representative they are of other species likely to be affected by pollution. Finally, there is the problem of prediction of future consequences of pollution. Some methods used to detect pollutants might be useful as early warnings of future deleterious effects, although the usefulness of these measures may be lessened by the decoupling of reproductive rates of many marine invertebrates from the eventual recruitment to adult populations. Other measures such as patterns in whole assemblages of species can usually only detect pollutants after sufficient time has elapsed for populations to have changed. Nevertheless, these offer more direct measurements of the importance of pollution to the continued functional well-being of the system. A mixture of different types of measures allows the best synthesis of predictive power while providing the most useful information for interpretation of the consequences of pollution to a marine system.

University of Alaska, Fairbanks; School of Fisheries and Ocean Sciences (1993)
Comprehensive Assessment of Coastal Habitat Final Status Report; Volume I; Coastal Habitat Study No. 1A, 488 pp.

ABSTRACT
The Coastal Habitat Injury Assessment Study (CHIA) was initiated to document and quantify injury to biological resources in shallow subtidal, intertidal and supratidal habitats impacted by the *Exxon Valdez* Oil Spill (EVOS). The CHIA study encompassed three major geographic areas: Prince William Sound (PWS), Cook Inlet-Kenai Peninsula (CIK) and Kodiak-Alaska-Peninsula (KAP). Oiled sites were selected randomly and matched with unoiled, control sites. All sites were classified into the following habitats: sheltered rocky, exposed rocky, coarse textured and estuary. Most sampling was done by use of randomly placed quadrats in the upper three meters of the intertidal. This report documents the impacts of the EVOS on the intertidal community through studies on algae, invertebrates and fish.

Results of intensive sampling during three summers (1989-1991) and limited sampling during the summers of 1992 and 1993 indicate that the EVOS had serious and long lasting effects on the intertidal algae. Analyses of algal percent cover and biomass data from the three areas studied: Prince William Sound (PWS), Cook Inlet-Kenai (CIK), and Kodiak-Alaska Peninsula (KAP), showed that generally there were lower abundances of marine algae, especially the perennial *Fucus* on oiled sites compared to unoiled, control sites. However, each tidal elevation zone (as defined by meter of vertical drop, MVD), each habitat, and each area had different patterns.

Data on *Fucus* reproduction showed that *Fucus* plants in oiled sites were not as reproductive as those in control sites and suffered from a higher level of epiphyte infestation. In the upper intertidal

in oiled sites the *Fucus* plants had fewer receptacles, fewer receptacles per mature plant, and a lower reproductive index. *Fucus* from oiled areas had more adult plants with attached epiphytes and these plants had a greater percentage of their surface covered with epiphytes.

Recovery of the intertidal communities proceeded at varying rates depending on the intertidal zone and habitat. Our intensive collection of biomass data that ended during the summer of 1991 showed that most habitats were recovering, but had not yet fully recovered. The percent cover data collected during 1992 and 1993 showed that many habitats appeared to meet our criteria of recovery by the summer of 1992. A few regions, however such as the upper meter of the intertidal zone in protected rocky habitats and MVD 3 of coarse textured sites in PWS had not completely recovered by the summer of 1993.

An examination of trends for invertebrate species diversity, richness and dominance indicates that sheltered rocky and exposed rocky habitats were in a state of recovery at last observation (1991). For most cases in which significant differences were observed (>75%), diversity and/or richness were higher on the oiled sites. Results for coarse textured and estuarine habitats were the reverse-lower diversity and richness and higher dominance on oiled sites for cases in which significant differences between site pairs were observed (7 of 8 site-pair comparisons). Apparently, coarse textured and estuarine habitats had not begun to recover or were in a state of delayed recovery as of the last observation in 1991. Abundance-biomass comparison (ABC or k-dominance) curves representing communities for several oiled sites were non-standard (indicative of disturbance) and in many cases were the same oiled sites for which significantly different (in comparison with control sites) diversity indices were identified. Of the 16 instances in which ABC curves were non-standard, 14 represented oiled sites.

A few select organisms were primarily responsible for the changes in community composition reflected in species diversity data and ABC curve comparisons. Many organisms responded negatively to the oiling/clean-up either due to sensitivity to the disturbance or through loss of protective cover or food source. Others responded positively due to superior colonizing abilities or sudden increases in food source availability.

Analyses of intertidal invertebrate abundance and biomass revealed differences between oiled and control sites for several major taxa. These were the limpet *Tectura persona*, the barnacle *Chthamalus dalli*, the mussel *Mytilus edulis*, two species of littorines, *Littorina sitkana* and *L. scutulata*, and oligochaetes. Differences varied between regions and habitat types. In addition, the degree of oiling, duration of exposure and cleaning methods used may have affected the extent of impacts at a site.

Recovery of sheltered and exposed rocky invertebrate communities was detected in some areas based on comparisons of significant differences in oiled and control sites. Coarse textured and estuarine invertebrate communities had not fully recovered as of last observation in 1991 and most likely will require several years to return to pre-spill conditions.

Although intertidal communities showed widespread impact from oiling/clean-up for algal, invertebrate and fish components, all three studies observed recovery to some degree. Without baseline data, it is difficult to assess biological impact and to determine the level to which a community must return in order to have "recovered". Full recovery of the intertidal is anticipated, especially since the impacted environment (boreo-Arctic) is one in which the life-history strategy of a number of opportunistic organisms is r-selected. Larger, less abundant K-strategists will require more time for recovery, but have recently reappeared on damaged sheltered rocky shorelines in PWS

(personal observation 1993). A fully accurate documentation of the recovery process in the intertidal would require continual annual monitoring of successional patterns.

Vanderhorst, J.R., J.W. Blaylock, P. Wilkinson, M. Wilkinson and G. Fellingham (1980)
Recovery of Strait of Juan de Fuca Intertidal Habitat Following Experimental Contamination with Oil

Office of Environmental Engineering and Technology, Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C. 20460

ABSTRACT
This is a second-year interim report on the effects of experimental oiling with Prudhoe Bay crude oil on recovery of intertidal infauna and epi-fauna of the Strait of Juan de Fuca, Washington. It describes completed studies of the recovery of infauna as recovery rate relates to the experimental oiling, the site of study, tidal height, season of study, and duration of recovery. The report also describes the methods and initial results of studies of the effects from experimental oiling on epifauna colonization of hard substrates. Full recovery is defined within the experimental framework for infauna as that composition and density of species which had colonized trays of untreated coarse substrate within the 15-month study period. The relevance of this definition is supported by presentation of data on composition and density of infauna at adjacent baseline stations as measured by other investigators. In terms of species composition, nearly full recovery of oiled substrates occurred in 15 months. For individual species densities, as well as overall abundance, however, oiled substrates had recovered only about one-half in 15 months. Total hydrocarbons in treated substrates were reduced from initial concentration by 85 and 97 percent for fine and coarse sediments, respectively, in 15 months. Based on rate of loss between three and 15 months, it is speculated that total hydrocarbons would have reached background levels in 18.5 months. Analyzed saturate compounds appeared to be lost from treated sediments at a rate similar to total oil. Analyzed aromatic compounds exhibited a much more rapid reduction in concentration than did saturate compounds or total oil. As analyzed experimental variables, the site of study, tidal height, and sediment type, produced significant effects on the density of primary biological species. overall, there were much higher densities at two feet below Mean Lower Low Water (MLLW) than at MLLW. overall abundance appeared about equal between sediment types. Although not analyzed statistically, there appeared to be an order of magnitude higher density in the summer-fall experimental period than in the spring-summer experimental period. The most severe effects from oiling on infauna density, as an expression of recovery, were seen for detritivorous and herbivorous species. The species for which significant effects on recovery were demonstrated were among those identified as having major trophic importance for a variety of bottom feeding fishes by other Strait of Juan de Fuca investigators. The experimental oil treatment, while perhaps a "worst" case in the sense that the oil was mixed in sediment, was well within the concentration measured in sediments following some actual oil spills.

Vandermeulen, J. H. (1977)
The Chedabucto Bay Spill - *Arrow*, 1970: The self-cleaning processes and the biological recovery

Oceanus 20(4):31-39

ABSTRACT
A study was made of the biological damage and recovery of Chedabucto Bay following the wreck of the *Florida*. The Bunker C petroleum hydrocarbons still resident on or in the shoreline sediments are measured. Also measured are the rates of hydrocarbon movement between water column and

sediment, the degradation rates and the tissue oil load and physiological responses of oiled organisms.

Vandermeulen, J. H. (1982)
Some conclusions regarding long-term biological effects of some major oil spills

Phil. Trans. R. Soc. Lond. B 297:335-351.

ABSTRACT
Many of the world's major spills exhibit long-term consequences, associated mainly with lagoons, estuaries and marshes. This is due to the persistence of oil or petroleum fractions in these low-energy environments. The bioavailability of residual oil to infauna is influenced by several factors, such as solubility in water, feeding habit, weathering rate and sediment grain size. The time-courses for these long-term effects vary, but may run into decades for some community perturbations. The effects are at all levels of organization, including cellular, organismic and the community. Although the number of documented long-term effects is small, they involve a wide range of biological processes: development, genetic, growth, feeding and assimilation, photosynthesis, recruitment and fecundity, and community stability. It is important to note that the known effects are probably only representative of a much wider range of possible disorders that have occurred, but which have not been detected. This is due mainly to the selective nature of spill follow-up studies. Long-term spill consequences are generally local phenomena and so far no single spill has, to our limited knowledge, significantly altered entire ecosystems or materially affected fisheries. The combination of several spills can, however, place considerable stress on an environment. Also, so far there is no indication of an increasing mutagenic or carcinogenic load in the marine environment due to biologically active petroleum fractions or to carcinogenic or mutagenic metabolites. There is, however, the possibility of local build-up of these compounds, as in "hydrocarbon sink" areas, where such a burden may become a local problem.

van Tamelen, P.G. and M.S. Stekoll (1993)
Damage and recovery rates of *Fucus* in Herring Bay, Knight Island

Exxon Valdez Oil Spill Symposium Abstracts, February 2-5, 1993, Anchorage, Alaska, pp. 173-175

ABSTRACT
The brown alga *Fucus gardneri* is the most abundant intertidal seaweed in Herring Bay, Knight Island, Prince William Sound, comprising up to 90 percent of the total algal biomass. The abundance of this plant and its simple and observable life cycle allowed detailed observations and experiments to be carried out regarding the consequences of the *Exxon Valdez* oil spill. Much of Herring Bay was heavily oiled, and a variety of clean-up technologies were performed throughout the bay. However, the southeast arm of the bay received little or no oil, allowing comparisons of oiled and unoiled areas within the same bay. Over three field seasons, 1990-92, we quantified the damage done by the oil spill and associated clean-up to *Fucus* populations in Herring Bay. Using a variety of experimental techniques we also determined some of the factors influencing recovery of *Fucus* populations. Five pairs of oiled and control sites were monitored, but for brevity and clarity we will report only the results from one representative pair of sites. The pair we will consider are two sheltered rocky sites. The oiled site was heavily oiled and probably received high pressure-hot water clean-up treatment. To assess damage to *Fucus* populations and assess recovery rates, we monitored eighteen permanent plots (20 by 50 cm) at each oiled and control site. There were six randomly located plots in each of three tidal levels. Sampling consisted of estimating per cent cover

of all sessile organisms using a systematic point contact method. All *Fucus* plants were then measured, and, if they were reproductive, the number of receptacles and stage of development were recorded.

Varanasi, U., W.L. Reichert, J.E. Stein, D.W. Brown, and H.R. Sanborn (1985)
Bioavailability and biotransformation of aromatic hydrocarbons in benthic organisms exposed to sediment from an urban estuary

Environ. Sci. Technol. 19:836-841

ABSTRACT
Phylogenetically diverse benthic organisms [amphipods (*Rhepoxynius abronius* and *Eohaustorius washingtonianus*); clams (*Macoma nasuta*); shrimp (*Pandalus platyceros*); fish (*Parophyrs vetulus*)] were exposed to an urban estuarine sediment [16 ppm of two to six benzenoid ring aromatic hydrocarbons] to which trace amounts of [^{3}H]benzo(a)pyrene (BaP) were added. The techniques used to assess uptake and metabolism of aromatic hydrocarbons were gas chromatography/mass spectrometry for aromatic hydrocarbons, high-pressure liquid chromatography/fluorescence spectrometry for aromatic hydrocarbon metabolites in fish bile, and radiometric analyses for biotransformation of [^{3}H]BaP. Generally, the extent of metabolism of [^{3}H]BaP (*M. nasuta* < *E. washingtonianus* < *R. abronius* <= *P. platyceros* < *P. vetulus*) was negatively correlated to tissue concentrations of aromatic hydrocarbons (three to six ring), except that amphipod species accumulated higher concentrations of aromatic hydrocarbons than did clams, indicating that other factors (e.g., feeding strategy and rate of excretion) also influenced accumulation of aromatic hydrocarbons. Radiometric and gas chromatograph analyses for BaP in both sediment and tissues suggested that not all of the BaP (and presumably other aromatic hydrocarbons) extracted chemically from sediment was bioavailable.

Weston, D.P. (1990)
Hydrocarbon bioaccumulation from contaminated sediment by the deposit-feeding polychaete *Abarenicola pacifica*

Mar. Biol. 107:159-169.

ABSTRACT
This study examines the role of the organic carbon content of sediment in aromatic hydrocarbon bioaccumulation and assesses the importance of two routes of hydrocarbon uptake: (1) the uptake of the particulate contaminant fraction from ingested sediment; (2) the uptake of the dissolved contaminant fraction from interstitial or overlying water. The lugworm *Abarenicola pacifica* was collected from San Juan Island, Washington in January 1989 and exposed to three sediments contaminated with [^{3}H]benzo(a)pyrene (BaP). By manipulating the organic content of these sediments, it was possible to establish three treatments with similar BaP concentrations in the interstitial water, but differing in the amount of BaP in the bulk sediment. BaP bioaccumulation over the first few days of exposure was correlated with feeding rate, suggesting that ingested sediments were a source of BaP. The greatest body burden, however, was attained in those individuals held in sediments with the lowest organic carbon content and the lowest BaP concentration. Body burden at steady state was not correlated with either BaP concentrations in bulk sediment (dry weight or organic carbon-normalized bases) or the interstitial water. Increased organic matter decreased BaP bioavailability in a non-linear fashion. Bioaccumulation factors relative to water and organic content were relatively constant between one and two percent organic

carbon in the sediment, but these same accumulation factors substantially underestimated body burden if applied to sandy sediments with little (0.3 percent) organic carbon.

Williams, U.P., J.W. Kiceniuk, J.E. Ryder, and J.R. Botta (1988)
Effects of an oil spill on American lobster (*Homarus americanus*) from Placentia Bay, Newfoundland

Can. Tech. Rep. Fish. Aquat. Sci. 1650:13 pp.

ABSTRACT
In March 1988 an accidental spill of crude oil occurred at the wharf of the Come by Chance oil refinery, Placentia Bay, Newfoundland. Studies of selected parameters were undertaken to determine the possible short and long term effects on the local lobster fishery. Elevated levels of PAH were not detected in any of the sediments from the Bay. The results indicate that lobster were not contaminated as a result of the oil spill. Based on the results of analyses of sediments for PAHs, future contamination, as a result of the spill at the oil refinery wharf, is not anticipated.

Winfrey, M.R. and D.M. Ward (1981)
Effect of the *Amoco Cadiz* oil spill on predominant anaerobic microbial processes in intertidal sediments

Amoco Cadiz: Fates and Effects of the Oil Spill. Proceedings of the International Symposium, pp. 257-267

ABSTRACT
Sediment porewater chemistry, sulfate reduction and methane production were examined in intertidal beach, marsh and estuary sediments along the Brittany coast in order to assess the impact of oiling from the *Amoco Cadiz* oil spill. Sediment cores (20-25 cm) were collected from a heavily oiled site and an unoiled site from each sediment type. Results and the comparison of electron flow through sulfate reduction and methane production demonstrate the dominance of sulfate reduction as a terminal process. Variations in methanogenesis and sulfate reduction between oiled and control sites were minimal. However, at the oiled site at Ile Grande, conversion of $2^{14}C$ acetate to $^{14}CH_4$, increased conversion of $^{14}CO_2$ to $^{14}CH_4$ during early incubations, and lower rates of sulfate reduction suggest the possible alteration of normal anaerobic processes.

Winfrey, M.R., E. Beck, P. Boehm, and D.M. Ward (1982)
Impact of crude oil on sulphate reduction and methane production in sediments impacted by the *Amoco Cadiz* oil spill

Mar. Environ. Res. 7:175-194

ABSTRACT
The activities of methane-producing and sulfate-reducing bacteria in intertidal sediments along the Breton coast of France were examined in order to determine the effect of the *Amoco Cadiz* oil spill on sediment microbial processes. Porewater chemistry, methane production, sulphate rate and 2^{-14} C-acetate metabolism did not vary significantly between beach, estuary, and marsh sites, oiled or unoiled, after the *Amoco Cadiz* spill. The oxidation of 2^{14} C acetate to $^{14}CO_2$ was significantly decreased when mousse, crude oil, benzene or toluene was added to sediments from the unoiled site. Inhibition seemed to be proportional to the extent of weathering.

Wolfe, D.A., R.C. Clark, Jr., C.A. Foster, J.W. Hawkes, and W.D. Macleod, Jr. (1981)
Hydrocarbon accumulation and histopathology in bivalve molluscs transplanted to the Baie de Morlaix and the Rade de Brest

Amoco Cadiz: Fates and Effects of the Oil Spill. Proceedings of the International Symposium, pp. 599-616

ABSTRACT
Experimental populations of cockles (*Cerastoderma edule*) and mussels (*Mytilus edulis*), obtained from Presqu'ile Quiberon, were held in cages at a depth of one meter in the Baie de Morlaix, a site known to have been heavily oiled by the *Amoco Cadiz*, and the Rade de Brest, a site known to be minimally exposed, from April 27 to May 22, 1978. Organisms were sampled three or four times over a 25-day period for histological examination and analysis of hydrocarbons. Subsurface seawater samples were taken and analyzed for hydrocarbons by ultraviolet/gas chromatograph. Body burdens of hydrocarbons increased in both molluscan species at both sites, up to fivefold increases within five days after transplantation, and these concentrations were maintained throughout the sampling period. There were clear histological and chemical differences detected between mussels held in Baie de Morlaix and the Rade de Brest, associated with the occurrence of dibenzothiophene and polynuclear aromatic hydrocarbons in the tissues.

Wolfe, D.A., M.J. Hameedi, J.A. Galt, G. Watabayashi, J. Short, C. O'Clair, S. Rice, J. Michel, J.R. Payne, J. Braddock, S. Hanna, and D. Sale (1994)
The fate of the oil spilled from the *Exxon Valdez*

Environ. Sci. Technol. 28(13): 561-568.

ABSTRACT
The energetic environmental conditions in Prince William Sound and the extensive cleanup activities led to wide dispersion of the *Exxon Valdez* oil, which simultaneously underwent biodegradation and photooxidation. Although some more refractory residuals of the petroleum (*e.g.*, high molecular weight PAH, resins, and asphaltenes) persist, many of these constituents are not readily distinguishable from other petroleum sources and naturally occurring hydrocarbon residues (*e.g.*, seeps, combustion products, and biogenic organic materials). We estimate that about 20 percent of the spilled oil evaporated and underwent photolysis in the atmosphere; about 50 percent biodegraded either in situ on beaches or in the water column; about 14 percent was recovered or disposed; less than one percent remained in the water column (except as biodegradation products); about two percent remained on intertidal shorelines (with a very large proportion of this as highly weathered, biologically inert residuals); and about 13 percent remained in subtidal sediments, mostly in the Gulf of Alaska and again mostly as highly weathered residuals. Although many of the processes identified here could not be quantified directly under the conditions applicable to the spill, their occurrence was well documented, and we believe that our estimates provide a reasonable approximation of the overall fate of the oil spilled from the *Exxon Valdez*.

Zieman, J.C., R. Orth, R.C. Phillips, G. Thayer, and A. Thorhaug (1984)
Effects of Oil on Seagrass Ecosystems

In: *Restoration of Habitats Impacted by Oil Spills* (J.R. Cairns, Jr. and A.L. Buikema, Jr., eds.) Butterworth, Boston pp. 37-64.

ABSTRACT
A review of seagrass ecology is given to facilitate a discussion of the effects of oil spills on one of the most productive ecosystems known. Physically, seagrasses prevent erosion and stabilize the effects of tidal actions and provide habitat for numerous epiphytic organisms. Biologically, seagrasses perform an essential cycling of nutrients by absorbing P through the roots and leaves and returning both N and P to water column from sediments via the plant. Seagrass ecosystems can be damaged by oil through direct suffocation or fouling of organisms or destruction of food market value of seagrass fisheries by tainting of flavor. Studies in the literature of major oil spills indicate that the greatest damage to aquatic organisms seems to be from aromatic hydrocarbon fractions of oil. The effects of oil dispersants on seagrass communities are not known. Inert absorbents present little hazard to seagrass systems if properly used. The normal recovery of seagrass systems from oiling depends on the extent of damage to sediments. Efforts of restoring oil-damaged seagrass systems by transplanting plugs or shoots have met with variable success. It is suggested that research be carried out on the toxicity levels of the major hydrocarbon substances on the major seagrass species in laboratory and field tests.