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REVIEW PAPER

Long-term Environmental Impact of Oil Spills

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Oil contamination may persist in the marine environment for many years after an oil spill and, in exceptional cases such as salt marshes and mangrove swamps, the effects may be measurable for decades after the event. However, in most cases, environmental recovery is relatively swift and is complete within 2–10 years. Where oil has been eliminated from the scene, the long-term environmental impacts are generally confined to community structure anomalies that persist because of the longevity of the component species. © 2002 Elsevier Science Ltd. All rights reserved.

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Introduction: Origin and Nature of Oil

Oil is a naturally occurring substance. It is believed to have formed from decaying plant and animal material that has become incorporated in the sediments of shallow seas and later overlaid by a succession of strata. Over time these organic residues are converted by heat and pressure into petroleum, migrating upwards, sometimes over extensive areas, either to reach the surface or be occasionally trapped in what are to become oil reservoirs. The important point here is that only a small proportion of the oil produced in the rocks is trapped; most of it has found its way to the surface. Oil has been part of the natural environment for millions of years.

Some Definitions

Before considering the long-term effects of oil spills, it is important to define what is meant by "clean" and "recovery" in the context of an oil spill.

What is meant by "clean"?

It is well known that biogenic and petrogenic hydrocarbons are ubiquitous in the marine environment (Myers and Gunnerson, 1976) and it would be unrealistic to define clean as a complete absence of hydrocarbons or a complete absence of petrogenic hydrocarbons. Baker *et al.* (1990) argues that in defining "clean" the size of the ecosystem is an important consideration. It should not be microscopic, but large enough to include the major plant and animal communities. Any definition should not necessarily require a return to some pre-existing background level, or the complete removal of hydrocarbons from the environment. Thus a working definition might be:

> *Clean, in the context of an oil spill, may be defined as the return to a level of petroleum hydrocarbons that has no detectable impact on the function of an ecosystem.*

What is meant by "recovery"?

Recovery processes may take many forms depending on the nature of the oil spill damage under

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consideration. Concern over damage to human resources such as fisheries or recreational amenities often takes precedence over damage to the ecosystem because of commercial interests. Human resources are usually quick to recover and, with the exception of some shellfisheries, human uses of a spill-impacted area generally resume as soon as the bulk oil is removed. In many cases, the availability of human services (e.g., amenity beaches) is not closely related to biological recovery and is usually more rapid than biological recovery.

Biological recovery of an ecosystem damaged by an oil spill begins as soon as the toxicity or other damaging properties of the oil have declined to a level that is tolerable to the most robust colonizing organisms (Baker *et al.*, 1990). However, the state to which an environment returns after damage is usually unpredictable. Recolonization will depend on the time of year, the availability of recolonizing forms, biological interactions, and climatic and other factors. Marine ecosystems are in a state of continual dynamic flux. Figure 1 shows an example of an offshore benthic community that has been monitored for many years, and has shown considerable annual fluctuation in numbers of individuals as well as long-term trends, none of which can be related to any known anthropogenic influences.

Recovery, thus must be judged in terms of the functioning of the ecosystem rather than simple head counts of individuals or their population structures. A possible definition of recovery might be:

> *Recovery of an ecosystem is characterized by the re-establishment of a biological community in which the plants and animals characteristic of that community are present and functioning normally.*

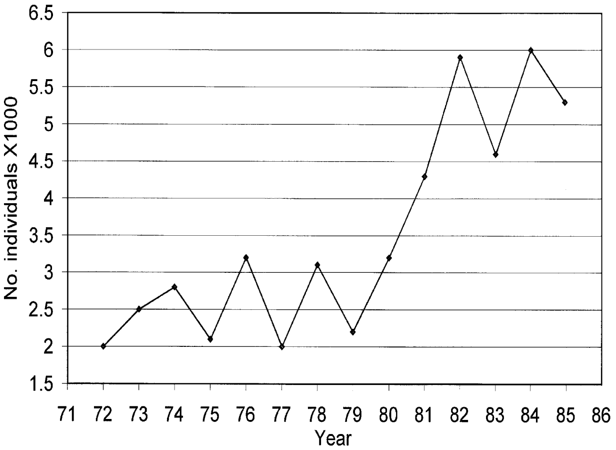

Fig. 1 Variation in the number of individuals of benthos off the Northumberland coast, UK 1972–1985 (after Buchanan *et al.*, 1978, and Buchanan & Moore, 1986).

It is impossible to say whether an ecosystem that has recovered from an oil spill is the same as, or is different from, that which would have persisted in the absence of the spill. The result of this is that there is often considerable controversy over the view taken of post-recovery changes.

Fate of Oil Spilled into the Sea

Oil spilled at sea initially spreads over the water surface as a slick a few millimeters thick (Fig. 2). The volatile components in crude oil rapidly evaporate after spillage. This includes most of the toxic components. For example, it is estimated that at least 30% of the oil spilled by the *Exxon Valdez* (35,000 tonnes) evaporated into the atmosphere. As much as 40% of the *Amoco Cadiz* oil (240,000 tonnes) disappeared in this way. The nature of the oil is an important factor in this respect. The lighter the oil the greater the power of evaporation to remove it from the sea surface. Over half the cargo of oil spilled by the *Jessica* in the Galapagos in 2001 was a light oil (diesel). Wind and current conspired to drive the oil slick away from the coast and the hot tropical sun caused almost all of the diesel to evaporate leaving just patches of the remaining cargo of fuel oil. It was partly for this reason that the spill was less of a disaster than originally feared.

UV radiation in sunlight will oxidize some of the components present in oil, a process known as photolysis. The oxidation products include acidic and phenolic compounds, some of which may be more toxic than the original hydrocarbons. Their concentrations, however, are so low as to be of insignificant ecological significance.

Some hydrocarbons dissolve into the seawater (dissolution), mostly low molecular weight compounds which are relatively toxic. This dissolution is small, less than 1% of spilled oil. This becomes quickly diluted and quickly degraded. Dispersion is probably responsible for the natural removal of most of the oil from the water surface. The oil is broken up by wave action into small droplets 0.01–1 mm in diameter and is retained in the water column until degraded by bacterial action. Typical concentrations under slicks are low, although they can reach concentrations of several parts per million under extenuating circumstances. For example, in the case of the *Braer*, the severe weather conditions resulted in almost all the oil released into the sea (85,000 tonnes) being dispersed with phenomenally high concentrations of oil in the water. However, the gross contamination was short-lived. Figure 3 shows the rapid fall in water hydrocarbon concentrations in the vicinity of the *Braer* wreck within a short period of time.

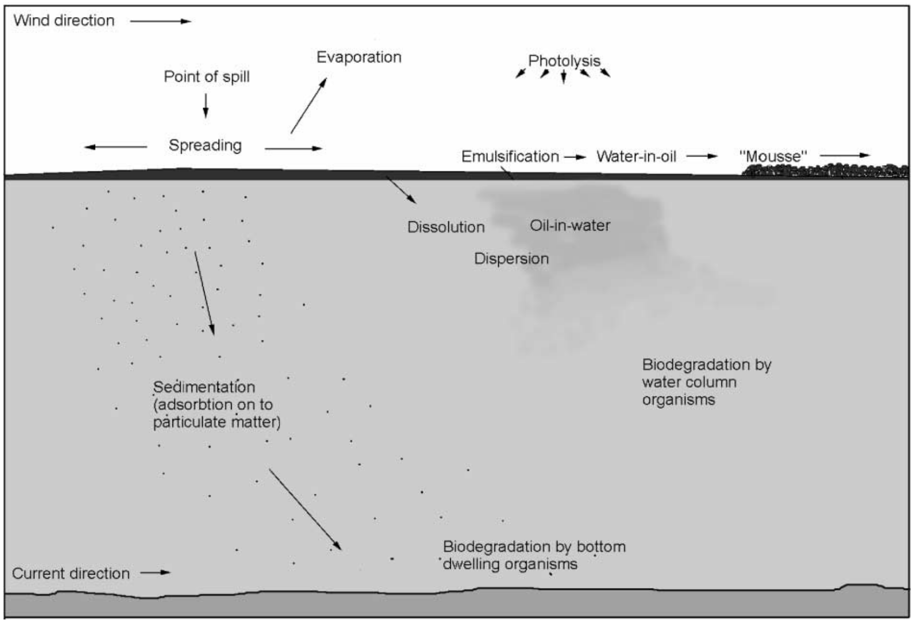

Fig. 2 Pathways by which spilled oil may enter the marine ecosystem.

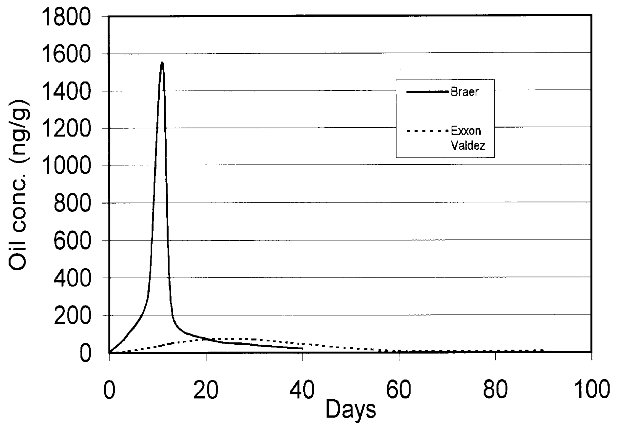

Fig. 3 Fall in water-borne hydrocarbons after the *Braer* oil spill with similar values for *Exxon Valdez* oil spill for comparison (Kingston, 1995).

Oil may be carried to the seabed in association with other substances in the water column, such as clay or sand (sinking). Accumulations of such materials can also cause tar balls to descend to the seabed. Usually, the quantities of oil involved are small and it is quickly biodegraded by benthic organisms. However, in exceptional circumstances such as in the case of the *Florida* that sank in Buzzards Bay, Massachusetts, spilling No. 2 fuel oil, substantial quantities of oil were carried to the seabed on sand that was dragged from the beaches by heavy wave action. After the *Braer* oil spill off Shetland, it was estimated that some 30,000 tonnes (35%) of oil ended up in subtidal sediments, having become adsorbed onto suspended particles and subsequently carried to the seabed (Davies *et al.*, 1997).

Under certain sea conditions a water-in-oil emulsion may be formed. This is a process in which droplets (less than 0.1 mm diameter) are incorporated into floating oil. These emulsions may contain 20–80% seawater forming a viscous substance called a mousse. Mousse formation and stability will depend on the type of oil. Rough sea conditions will accelerate the formation of a mousse leading to an increase in the quantity of material in a slick, its density, and its viscosity. Thus, mousse formation can increase the persistence of the slick.

Unless the oil spill occurs on the shore, there is usually some delay between the oil hitting the sea and it impacting the shore. During this time much of the oil evaporates or disperses and if the sea is turbulent a mousse may form. However, by this time, most of the toxic components of the oil should have disappeared leaving a viscous sticky fluid to foul the shore. It is during this initial stage of the spill that most of the damage to wild life occurs. Where the shores are completely inundated, the fauna and flora are killed outright. Light oiling, however, is usually survivable.

Long-term impacts on seabirds

Of all impacts on wildlife, seabird casualties probably attract the greatest public concern. Estimates of the number of seabird deaths from oil slicks are highly speculative. The only reliable figures are counts of the

Table 1 Comparison of the number of dead seabirds recovered following the *Exxon Valdez* and *Braer* oil spills

Species group	Alaskan spill	Shetland spill
Sea ducks (eiders, etc.)	1440	167
Mergansers	121	1
Loons	395	14
Grebes	462	0
Heron	1	3
Geese/swans	9	0
Gulls	696	74
Kittiwakes	1225	133
Cormorants/shags	836	864
Shearwaters	3399	0
Fulmars	870	31
Guillemots/murres	20 562	220
Other auks	2174	29
Bald eagles	125	n/a
Other birds	3152	0
Total	35 467	1536

number of carcasses washed up on the shore, but even these are subject to severe limitations depending on the intensity of the search, accessibility of the shoreline to recorders and the sea conditions at the time of the spill.

There is little relation between the size of an oil spill and the number of seabird casualties. For example, over 35,000 seabird carcasses were recovered after the *Exxon Valdez* spilled 35,000 tonnes of oil (Erikson, 1995). Only 1500 dead birds were counted after the *Braer* accident (Heubeck, 1997) even though the *Braer* spill (85,000 tonnes) was almost two and a half times as large that of the *Exxon Valdez* (Table 1).

An unknown number of oiled birds may die at sea and not reach the coast. Some estimates put the total number of casualties after the *Exxon Valdez* spill in the region of 250,000 birds mostly black guillemots (murres) (Piatt & Ford, 1996). Claims have been made that the murre population may not recover for between 20 and 70 years (Piatt *et al.*, 1990). However, post-spill studies of murre attendance at breeding sites in the spill path produced counts that were generally similar to historical estimates in the late 1970s (Wiens, 1995). By any standards, the *Exxon Valdez* seabird kill was very large. Murres have a low reproductive success rate. The closely related European guillemot has only a 20% chance of rearing a chick (Southern *et al.*, 1965) and does not begin to breed until it is 3–7 years old. The rapid recovery of the murre breeding colonies in Alaska suggests either that the number of dead birds might be lower than the estimates or breeding pairs are being replaced by younger birds that have come in from the open sea (Boersma *et al.*, 1995). Wiens (1995) argues that if this is so, then the impacts of the spill may have been diffused over a large area, permitting local recovery, and making it difficult to detect any changes in local abundance or habitat occupancy. Recently Lance *et al.* (2001) claim that after nine years the populations of most bird species affected by the *Exxon Valdez* spill have not recovered and others still show potential population effects. However, this is the only case where such long-term effects have been observed and the report is at variance with the findings of others (Wiens *et al.*, 1996; Day *et al.*, 1997).

Natural variation and the huge range of factors that influence bird population statistics makes it difficult to assess the impact and recovery of a single event such as an oil spill. However, there is little firm evidence that seabirds suffer long-term effects from individual oil spills.

Long-term impacts on benthic organisms

Biological recovery of the intertidal habitat is largely a function of the nature of the habitat and, in the case of intertidal impact, the degree to which the shore has been cleaned. After the *Braer* spill, in which the oil was dispersed into the sea and no slick was formed, the shores recovered remarkably quickly, the initial impact of the oil being narcotic rather than directly lethal (Kingston *et al.*, 1997). A rapid recovery was also reported for shores in Prince William Sound following the *Exxon Valdez* oil spill, most shores being restored in 1–3 years. For example, Figure 4 shows that long-term changes in percent cover of *Fucus* from oiled shores is indistinguishable from those from unoiled shores in Prince William Sound two years after the spill (Hoff & Shigenaka, 1999).

In general, exposed shores recover more quickly than sheltered shores. This is because strong wave action promotes the removal of contamination and the animals and plants of exposed shores tend to be more ephemeral and thus better able to recolonize an im-

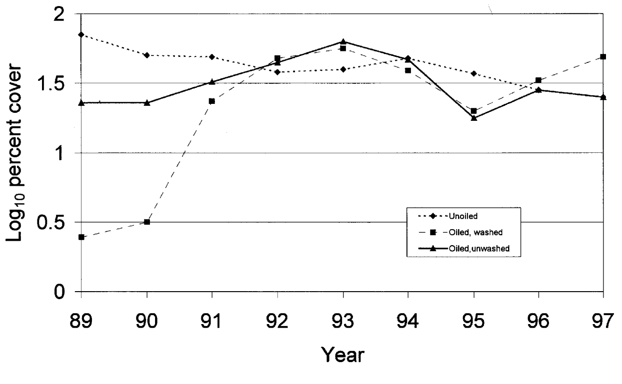

Fig. 4 Long-term changes in percent cover of *Fucus* from oiled and unoiled shores in Prince William Sound, Alaska, 1989–1997 following the *Exxon Valdez* oil spill in 1989 (after Hoff & Shigenaka, 1999).

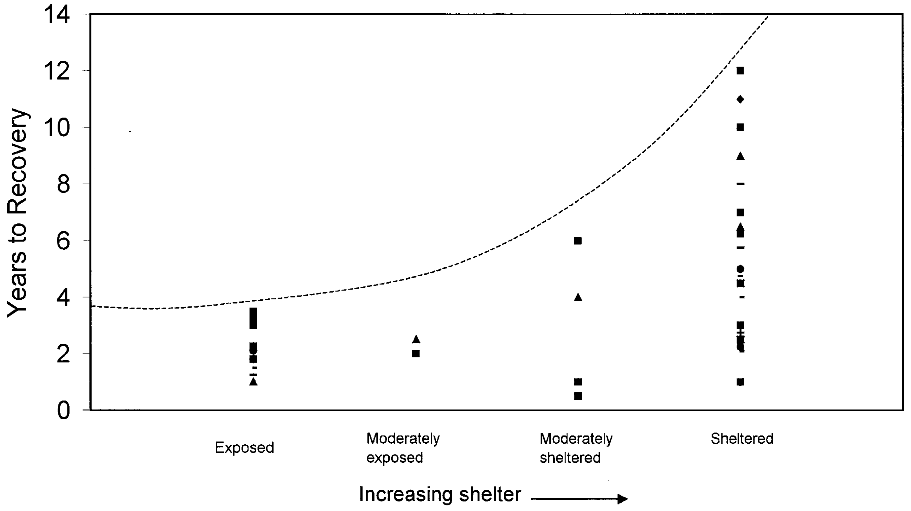

Fig. 5 General relationship between shore energy levels and biological recovery times following an oil spill (data derived from Baker, 1991 and Sell *et al.*, 1995).

pacted shore quickly. Sell *et al.* (1999) reviewed 27 oil spill case histories in which studies on the recovery rate of rocky shores had been made and found that in only four cases was recovery delayed beyond three years. Figure 5 indicates the influence of shore energy levels on biological recovery times. The figure is based on a wide range of reports that includes spills of various types of oil and various clean up scenarios (Baker, 1991; Sell *et al.*, 1999). Nevertheless a clear relationship emerges placing recovery times ranging from 3 to 4 years for an exposed rocky shore to over 12 for a sheltered shore such as a badly damaged salt marsh.

Recovery of subtidal communities impacted by oil spills usually takes a little longer since sublittoral habitats are generally contaminated by sedimentation of oiled particulate material for which there is no practical clean up. A fine sand community of the bivalve, *Abra alba* in the Bay of Morlaix, Brittany was severely affected by the *Amoco Cadiz* oil spill. The region was sampled immediately after the spill and has been continuously monitored ever since (Dauvin, 1998). Biomass values for the sand community fell immediately after the spill in 1978, but recovered to pre-spill levels within two years. Productivity also showed similar trends (Fig. 6).

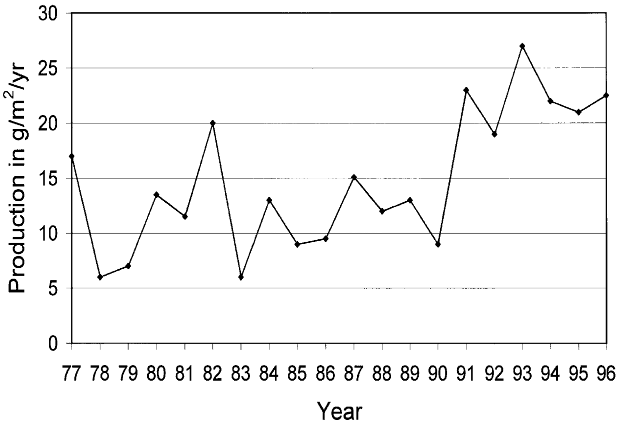

Fig. 6 Changes in annual production of benthos in the Bay of Morlaix 1977–1996 following the *Amoco Cadiz* oil spill in 1978 (data from Dauvin, 1998).

However, if individual populations are examined, for some species a picture of major impact and slow recovery emerges. For example, the initial impact of the spill was to kill off populations of the amphipod, *Ampelisca*, which dominated the community. This small sand hopper is particularly sensitive to oil pollution and is slow to re-populate for various demographic reasons. The result was that although the sediment was rapidly purged of the contaminating oil, it took 10 years before *Ampelisca* was back to its pre-spill population density (see Fig. 7). Standing crop biomass and productivity was restored much more rapidly as the place of the amphipods was taken by other opportunists that quickly filled the ecological niches vacated by the *Ampelisca* (see Fig. 8).

This brings us back to the point of how we define "recovery". One of the features of community response after the *Tsesis* oil spill in the Baltic in 1977 was the survival and recruitment of the clam *Macoma baltica*. This uncharacteristically became the dominant faunal species (Elmgren *et al.*, 1983), and would be likely to remain so over its life span of 5–10 years. Some would argue that this would maintain a 'disturbed community' signature well after overall community function had returned to pre-spill conditions

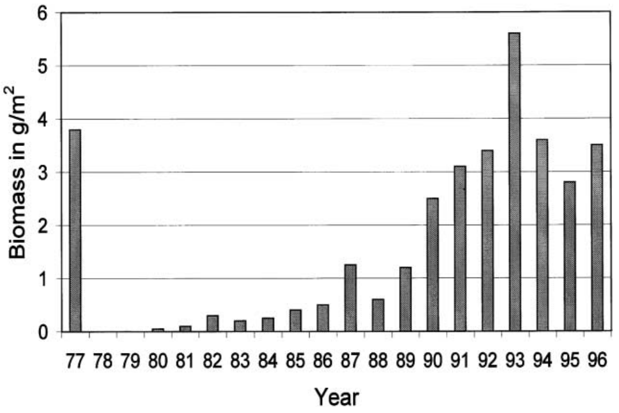

Fig. 7 Changes in the biomass of the sandhopper *Ampelisca* in the Bay of Morlaix 1977–1996 following the *Amoco Cadiz* oil spill in 1978 (data from Dauvin, 1998).

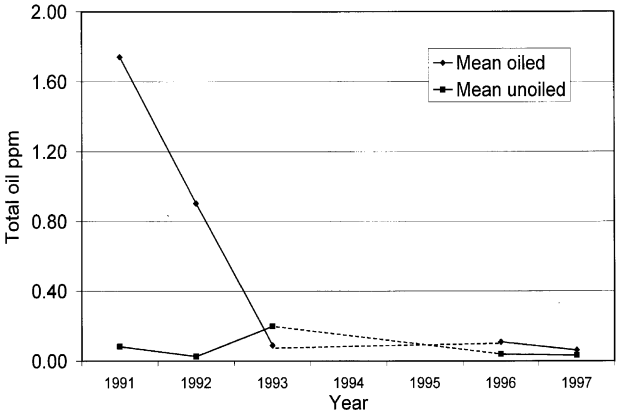

Fig. 9 Changes in the levels of hydrocarbon in the sediments from Prince William Sound, Alaska (after Hoff & Shigenaka, 1999).

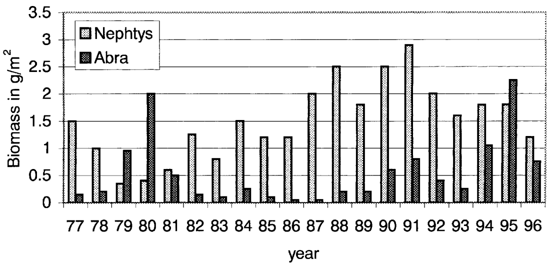

Fig. 8 Changes in the biomass of the bivalve *Abra* and the worm *Nephtys* in the Bay of Morlaix 1977–1996 following the *Amoco Cadiz* oil spill in 1978 (data from Dauvin, 1998).

and that full recovery could not be claimed until the *Macoma* had completed their life span.

How long does oil persist in the environment?

Oil is a naturally occurring substance and as such is readily degraded either by chemical oxidation or biodegradation. Over the millennia more oil has escaped into the environment than has ever become trapped in reservoirs under the ground. The rate at which these degradation processes take place is influenced by factors such as oil thickness, light intensity, aeration and availability of nutrients. Some approaches to oil spill clean up attempt to enhance natural degradation processes by tilling oiled shores to expose the oil to light and air and providing nutrients to encourage the activity of oil degrading micro-organisms. If bulk oil is removed from the shore after a spill, then oil degradation will normally proceed provided that the substratum is well aerated. For example eight years after the *Amoco Cadiz* oil spill, all but the most heavily oiled locations had reverted to conditions found at unoiled reference sites (Page *et al.*, 1989). Similarly after the *Exxon Valdez* oil spill (Fig. 9) levels at oiled sites began to approach those at unoiled sites after 3–4 years (Hoff & Shigenaka, 1999).

For most heavily oiled shores, failure to remove the bulk oil will result in it remaining for a considerable length of time. There are several instances where oil has persisted for 25 years or more. One such spill was that of the barge the *Arrow* that spilled heavy fuel oil into Chedabucto Bay, Nova Scotia in 1970. Asphalt "pavement" could still be found in nearby Black Duck Cove over 20 years later. Although the surface of the asphalt is quite hard, and may even support encrusting organisms, underneath fluid oil can be found that is little changed from the original spilled oil (Fig. 10). Another example is that of the *Metula* spill in Tierra del Fuego, Chile. Owing to the remoteness of the shores, no attempt was made at clean up. Asphalt pavements still persist on some of the less exposed shores, with unweathered oil underneath the protective crust (Owens *et al.*, 1999).

Bioaccumulation of petroleum hydrocarbons

There is a perception that petroleum hydrocarbons bioaccumulate in the tissues of marine organisms. It is true that animals such as mussels will concentrate contaminants above ambient levels through their filter feeding mechanisms, however, placed in hydrocarbon free conditions, the contaminants are quickly depurated. For example, mussels placed in water contaminated with dispersed crude oil will exhibit an initial rapidly accumulate the oil in its tissues bioconcentrating it to levels above ambient (see Fig. 11). However, when the animal is returned to clean water depuration is also rapid, tissue levels falling to less than 10% of the peak value in eight days, and almost back to background in 16 days (Ba-Akdah, 1996).

Other concerns center around the transfer of hydrocarbons up the food chain. Figure 12 shows the

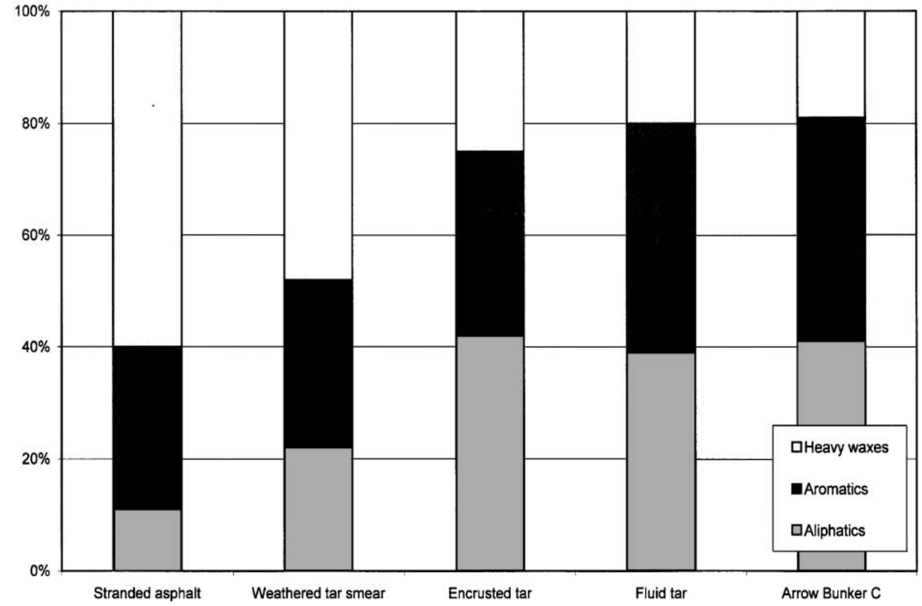

Fig. 10 Comparison of relative composition of tar residues from Chedabucto Bay in 1990 and original oil spilled by the *Arrow* in 1970 (adapted from Vandermeulan & Singh, 1994).

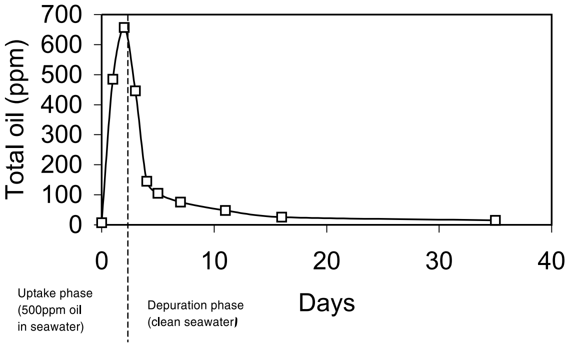

Fig. 11 Uptake and depuration of oil by the mussel (from Ba-Akdah, 1996).

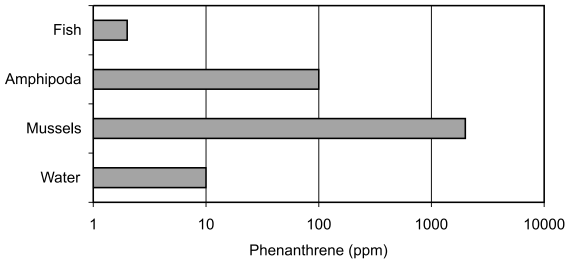

Fig. 12 Transfer of phenanthrene through three trophic levels of marine organisms (from Ba-Akdah, 1996).

quantities of phenanthrene, a toxic component of crude oil, transferred from contaminated water to a bivalve (mussel), to an amphipod (sand hopper) and finally to a fish. The transfer values represent the maximum possible since no tissue depuration was permitted between one organism and the next. The reduction in tissue burden between trophic levels occurs partly because each animal transforms some of the phenanthrene through its own metabolic processes. These metabolic products are often polar and therefore soluble and can be quickly leached out of the animal's tissues. They may also be more toxic than their precursors. Relatively little is known about the environmental significance of these metabolites. However, because of their rapid dilution in the surrounding water, compared with their slow production, they are unlikely to be of significant ecological impact.

Prospects for full environmental recovery

Signatures of oil contamination may persist for many years after an oil spill; in exceptional cases, such as salt marshes and mangrove swamps, effects may be measurable for decades after the event. However, in most cases environmental recovery is relatively swift, being complete within 2–10 years. This is because for the most part the marine environment is continuous and the majority of the animals reproduce by means of pelagic larvae (forms that float free in the water). If an area is denuded of its flora and fauna it can be restored by recruitment from nearby populations. The intertidal habitat is a harsh one. Exposed rocky shores are subject to natural mass mortality of their inhabitants through severe weather every year (Lewis, 1982). Even seabirds (e.g., murres) suffer similar periodic kills when adverse conditions persist offshore for extended periods (Bailey & Davenport, 1972) It could be argued that such species are pre-adapted to deal with periodic mass mortality and this is why they appear to recover so readily. Where oil has been eliminated from the scene, long-term impacts are generally confined to community structure anomalies that persist because of the longevity of the component species.

A cautionary note

These arguments hold true where there is a reservoir of species that can replace those lost by oiling. However, the recent oil spill resulting from the wreck of the *Jessica* off San Cristóbal on the Galapagos islands has focused attention on the fact that species lost as the result of an oil spill may not always be replaceable. The Galapagos had a lucky escape. The *Jessica* spilled around 1000 tonnes of oil about 600 tonnes of diesel, and 400 tonnes of bunker fuel oil. Fortunately wind and currents took the oil away from San Cristóbal giving time for the diesel to evaporate and the fuel oil to disperse before it could do major damage to the other islands. Nevertheless some oiling took place. Had the oil slick not broken up the world may have suffered its first true ecological disaster in which entire animal species could have been wiped out. About 40% of the species found on the Galapagos are unique to the archipelago. Amongst these are the lava gull (only 400 breeding pairs known to exist), the Galapagos penguin and the flightless cormorant (more or less confined to a single island), and the marine iguanas. A few tonnes of fuel oil in the wrong place at the wrong time have the potential to extinguish these species forever.

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