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A REVIEW OF EXPERIMENTAL SHORELINE OIL SPILLS

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ABSTRACT: *Oil spill research and development has involved a large number of experiments to evaluate the effectiveness and the effects of marine shoreline protection and cleanup techniques. Considerable knowledge has accumulated from laboratory and wave tank studies, and there have also been a number of field experiments, in which oil was intentionally spilled on shorelines under controlled conditions. This review summarizes those field experiments, which are grouped in five major habitat types: rocky intertidal, cobble/pebble/gravel, sand/mud, saltmarshes, and mangroves/seagrasses. Tables included in the paper itemize the oil type and volume, location and substrate character, number and size of plots, response techniques tested, and referenced publications. This information is then used to combine understanding of the effectiveness of cleanup with understanding of the ecological effects of cleanup methods, compared with those of untreated oil. It is very difficult to achieve this type of information and understanding from toxicity testing or from spills of opportunity.*

At a time when permitting problems make it difficult to conduct controlled field experiments in North America in natural habitats, we considered it worthwhile to review the knowledge gained in experiments to date. Each section of this paper reviews international field experiments, including pertinent unpublished data. The paper is not an exhaustive review, however, because discussion of each combination of cleanup method and habitat type includes recommendations on the need for more research. Further API research into this topic is described by Owens, Gould, and Siva in these proceedings.[27]

Rocky intertidal (Table 1)

High pressure/hot water. Broman and colleagues used Russian crude and water at 90° C and 2,100 psi on exposed Baltic rocky shores with lichens and algae.[11] The system was efficient on rocky shores (but not on gravel shores) in freeing rocks from oil, but the treatment dramatically reduced shore vegetation. Offshore from the experimental site, mussels (*Mytilus edulis*) were placed in net bags 3 and 8 m from the shore. The mussels' hydrocarbon levels rose significantly following the shore treatment.[25]

There were some difficulties in determining exactly which treatments or combinations of treatments had been used at various sites affected by oil from the *Exxon Valdez*. Nevertheless, the picture from Alaska is consistent with evidence from the Scandinavian field experiments and with common sense: high-pressure hot water treatment is damaging to shore life. Some controversies remain. At what temperatures and pressures do significant adverse impacts begin to occur? How do we judge when it is justifiable to use this method to reduce threats to birds and mammals, even if algae and invertebrates are killed in the process?

Vegetation removal. Crapp oiled a sheltered rocky shore in Milford Haven, United Kingdom, dominated by the brown alga *Ascophyllum nodosum*, which he then cut.[16] This treatment led to a decrease of fauna because of the loss of habitat, and the bare surface was colonized by the algal opportunist *Enteromorpha*. Large brown algae are relatively resistant to oil pollution, partly because of their mucilage coatings.[3] They are also relatively slow-growing, so their wholesale removal is unnecessary in view of the loss of habitat.

Dispersant/surfactant. Field experiments with Kuwait crude and BP 1002 were carried out by Crapp on both exposed rocky shores (with mussels, limpets, barnacles, and winkles), and sheltered rock dominated by algae.[16] On the exposed shores, the greatest damage occurred in oiled plots cleaned using dispersant. Highest mortalities were recorded among the dominant mussels and limpets. However, on the sheltered rocky shore *Ascophyllum nodosum* was tolerant of a single treatment of BP 1002. This result is of interest because BP 1002 is a particularly toxic cleaning agent, and has not been used for oil spill cleanup for years. Limpets, barnacles, and winkles under the seaweed cover were killed, although rapidly replaced by immigrants from the surrounding area. Ganning and Billing tested the alga *Fucus vesiculosus*, an important habitat for many shore invertebrates, by keeping the algae in raft-mounted tubs in a shallow bay in the Baltic Sea.[24] Pollutants involved are given in Table 1. Dispersed oil was found to be more harmful than untreated oil.

Experiments in Somerset, U.K., are described by Baker and colleagues and Crothers.[4,5,17] Forties crude and BP 1100 WD were tested in two experiments (single and repeated treatments respectively) on an exposed rocky shore. Further experiments (single applications) were carried out with a range of dispersants (see Table 1), and all of these experiments demonstrated the efficiency of natural cleaning on exposed rocky shores. Dispersant cleaning did not add to the damage already done by the oil. Experiments were also done with Forties crude and BP 1100 WD on a more sheltered rock platform dominated by fucoid algae.[5] In this case, none of the treatments had any effect that could be disassociated from natural increases of fucoid cover.

Battershill and Bergquist investigated the effects of Maui condensate and the dispersant Shell SD LTX on the gastropod *Nerita atramentosa melanotragus* in cages attached to boulders in the littoral zone.[9] In the short term, condensate/dispersant mixtures were toxic, whereas weathered condensate and LTX, when applied separately, produced no significant mortality, although there were some long-term sublethal effects such as changes in wet and gonad weights with dispersant treatments.

There is evidence that some oil/dispersant treatments are more damaging than oil alone. Considering the good natural cleaning that has been documented for exposed rocky shores, further experiments with dispersants on exposed rock are not a high priority. The picture with sheltered shores dominated by algae is less clear. Larger algal species may be relatively resistant to dispersants, in which case dispersant cleaning may offer an advantage. If oil is killing the invertebrates

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Table 1. Field experiments on rocky intertidal habitats

Cleanup method	Location	Description of experiment
High pressure, hot water	Stockholm, Sweden	Russian crude, water at 90° C and 150 bars (2,100 psi) on exposed rock with lichens and algae; triplicate 1 × 0.25 m plots at four tidal levels; experimental offshore mussel bags[11,25]
Vegetation cropping	Milford Haven, U.K.	Kuwait crude, cutting of oiled algae, on sheltered rock dominated by *Ascophyllum nodosum;* unreplicated 5 × 5 m plots[16]
Dispersant	Milford Haven, U.K.	Kuwait crude and BP 1002 on exposed rock with mussels, limpets, barnacles, and winkles; unreplicated 1 × 1 m plots at three tidal levels[16]
Dispersant	Baltic Sea	Diesel, kerosene, No. 4 fuel oil, Corexit 7664, and BP 1100X in tubs with *Fucus vesiculosus*[24]
Dispersant	Milford Haven, U.K.	Kuwait crude and BP 1002 on sheltered rock dominated by algae; unreplicated 5 × 5 m plots[16]
Dispersant	Hurlstone Pt., U.K.	Forties crude and BP 1100 WD on exposed rock dominated by limpets and barnacles; duplicate 2 × 2 m plots[5]
Dispersant	Hurlstone Pt., U.K.	As above, but with repeated treatments[5,17]
Dispersant	Hurlstone Pt., U.K.	Heavily weathered Flotta crude, mousse, BP 1100X, Corexit 8667, Corexit 7664; duplicate 2 × 2 m plots[5]
Dispersant	Watchet, U.K.	Forties crude and BP 1100 WD on sheltered rock dominated by fucoid algae; duplicate 2 × 2 m plots[5,17]
Dispersant	New Zealand	Maui condensate and SD LTX on caged gastropods[9]

in any case, dispersant treatment could be viewed as cleaning the habitat (the algae) as a means of speeding up recolonization by invertebrates. Possibly the same effect could be obtained by low-pressure flushing. There is scope for an experiment comparing low-pressure flushing, with and without dispersants, on sheltered macroalgae-dominated rocky shores.

Cobble/pebble/gravel (Table 2)

High pressure/hot water. Broman and colleagues tested a Baltic gravel shore with plants and arthropods, using Russian crude and water at 90° C and 2,100 psi.[11] On this type of shore the method was not effective in cleaning the shore, in contrast to the effectiveness of the method on intertidal rock (described above). This is because of penetration of oil into the sediment. Shore vegetation and macrofauna were drastically reduced. Broman and colleagues do not recommend high-pressure hot water treatment on gravel shores, and this view is consistent with that of Houghton and colleagues.[11,30] However, removal of free oil reduces the tendency to form asphalt pavements, thus avoiding long-term modification of the habitat that could occur if the oil were left alone.

Low-pressure flush. Owens and colleagues carried out an experiment on a mixed sand and coarse sediment beach as part of the Baffin Island Oil Spill (BIOS) program.[49] Total hydrocarbon concentrations

Table 2. Field experiments on cobble/pebble/gravel habitats

Cleanup method	Location	Description of experiment
Mechanical removal	Half Moon Bay, California	North Slope crude, scraping and side-casting, screening using grader, scraper, and front-end loader on large (100 m^2) beach plots (Sartor and Foget, 1970; see authors)
High pressure, hot water	Stockholm, Sweden	Russian crude, water at 90° C and 150 bars (2,100 psi), on pebble/gravel shore with plants and arthropods; unreplicated 10 × 4 m plots[11]
Low-pressure flush, dispersant, tilling, visco-elasticizer, burning	Cape Hatt, Baffin Island, Canada (BIOS project)	Lagomedio crude, BP 1100X, Corexit 7664, Rototiller, BP solidifying agents, DREV incendiary devices on gravel beach; various related experiments[49]
Dispersant	Straits of Magellan, Chile	Magellan crude, Corexit 9527, on stony terrace dominated by mussels; duplicate 1 × 1 m plots (experiments by Guzman in progress)
Dispersant, mechanical removal/beach material washing	Newhaven, U.K.	Light, medium, and heavy fuel oils and emulsions, type 3 dispersant, several types of mechanical equipment, on pebble beach; various related experiments[45,58]
Bioremediation	Prince William Sound, Alaska	Prudhoe Bay crude accidentally spilled from the *Exxon Valdez*, Inipol EAP 22, Customblen; various related experiments[12]
Beach cleaning agent	Prince William Sound, Alaska	Prudhoe Bay crude accidentally spilled from the *Exxon Valdez*, Corexit 7664/9580, BP 1100X (unpublished source)
Water injection	Prince William Sound, Alaska	Prudhoe Bay crude accidentally spilled from the *Exxon Valdez*, warm water and air injection on an oiled beach (unpublished source)
Washing (cold and hot), tilling, beach cleaners, bioremediation	British Columbia, Canada	North Slope crude. Final design will include control, oiled, and treated plots to evaluate techniques and effects individually and on a comparative basis (experimental site selection in progress by Environment Canada)
Bioremediation	Spitsbergen, Norway	Statfjord crude, fuel oils, and Inipol EAP 22, on gravel shores[54]

were not reduced by low-pressure flushing, and the technique was labor-intensive. It was concluded that the method was unlikely to have significant application to Arctic or remote gravel environments.

Dispersant/surfactant. Morris tested dispersant on fuel oil applied to a U.K. pebble beach.[45] Dispersant treatments had no discernible effect on the contaminated area after five days. The shingle seemed able to absorb wave energy, so that dispersion did not occur. Owens and colleagues tested BP 1100X and Corexit 7664 on Baffin Island gravel beaches.[49] Both reduced surface oil on semi-exposed plots, but there was an increase in subsurface oil. Neither dispersant was effective on very sheltered plots. Magellan crude and Corexit 9527 treatments are included in the current field experiments of Guzman (personal communication). The experimental site is a coarse-sediment terrace, dominated by mussels, in the Straits of Magellan (Chile). Interim observations are that oil/dispersant mixtures are the most damaging, having led to a high mussel mortality, which has resulted in erosion because normally the byssus threads of the mussels help to stabilize the sediments. In conclusion, the available evidence suggests that dispersant treatment on cobble/pebble/gravel is not a promising approach.

Visco-elasticizer. Owens and colleagues tested a BP solidifying agent during the BIOS program.[49] Stranded oil was successfully encapsulated. The solidifying agent retarded sediment reworking in the intertidal zone, and the method is labor-intensive and expensive.

Tilling. Blaylock and Houghton concluded that tilling, meaning agitation to physically release oil, was beneficial in coarse sediments following the *Arco Anchorage* incident. Investigations to explore the wider applicability of this method would be useful.[10]

Burning. Owens and colleagues carried out small burning tests using incendiary devices, as part of the BIOS program.[49] The devices were not effective in igniting the beached oil.

Bioremediation. The Exxon Production Research Company conducted laboratory column tests using oiled beach gravels from Prince William Sound.[20] The tests showed a significant loss of oil residue to depths of at least 0.75 m, and that bioremediation was achieved using Inipol, Customblen, and water-soluble inorganic fertilizers. Chianelli and colleagues concluded that bioremediation made a strong contribution to the overall cleanup of the *Exxon Valdez* spill.[12] However, there was high variability in the field data. The possibility that fertilizer application might stimulate an algal bloom was assessed by monitoring chlorophyll in the nearshore water. There were no indications of algal blooms. Nearshore waters collected during the four days following fertilizer application showed no toxicity when tested with mysids. Samples from cobble surfaces treated with Inipol showed that more than 99 percent of the butoxyethanol had dissipated from treated shorelines within 24 hours. Time-lapse cameras, taking one frame every six minutes, recorded no wildlife on Inipol-treated areas while wildlife deterrents were present.[51] However, information on potential ecological effects is scarce. What are the effects of bioremediation on shore microalgae, interstitial micro- and meiofauna, and associated food chains?

Sand/mud (Table 3)

Low-pressure flush. A field experiment involving low-pressure flushing, carried out by Howard and Little, was about 85 percent effective in clearing fuel oil mousse from sheltered intertidal sand, and lugworm activity was greater in the oiled and flushed plots than in the oiled plots.[32] The technique was effective because the water table was raised and the surface 3 to 4 cm was sufficiently disturbed to liberate oil that had penetrated the sediment. The technique works with viscous oils on accessible sloping shores with thick, firm sediments. The technique is not likely to be successful on very coarse sand, gravels, and muds, because of erosion and mixing of sediments and oil. Use of a flowing film of water was found to protect a beach surface from oiling, but the coverage of water was uneven owing to channeling.[60]

Dispersant/surfactant. Levell, in the first of several U.K. sand/mud experiments, tested Kuwait crude oil and the dispersant BP 1100X on an intertidal flat of fine sand dominated by lugworms.[38] He concluded that crude oil, dispersant, and 1:1 and 5:1 mixtures of both all reduced the population density of *Arenicola*. Recolonization of the oiled sediment by juveniles was inhibited, although this inhibition decreased with time. Nigerian crude, Forties crude, and BP 1100 WD were used in experiments on waterlogged muddy sand.[5] During the first tidal immersion following treatment, both untreated and dispersant-treated oil were washed off the plots. The hydrocarbon content and *Arenicola* cast production were not significantly affected.

A series of experiments was then carried out on freely draining fine sand involving Forties crude, Nigerian crude, BP 1100WD and Corexit 7664.[1,5,39,40] In some cases the highest retention of oil was in disper-

Table 3. Field experiments on sand and mud habitats

Cleanup method	Location	Description of Experiment
Surface treatment agents	Arthur Kill, New Jersey	Arabian crude: No. 2 and No. 6 fuel oil, water flushing, xanthum gum, PVA, oil herder[59]
Mechanical removal	Half Moon Bay, California,	Arabian crude, scraping and side-casting, screening motor graders and elevator scrapers on large (100 m^2) sand beach plots (Sartor and Foget, 1970; see authors)
Surface treatment agents	Raritan Bay, New Jersey,	Iranian crude, PVA-borate gel, Corexit 7664: plot size varied from 30 m^2 to 125 m^2 on a sand-gravel beach[60]
Low-pressure flush	Milford Haven, U.K.	Thin layer of medium fuel oil mousse, saltwater flush (2 L/s); duplicate 7 × 2 m plots[32]
Dispersant	Milford Haven, U.K.	Kuwait crude and BP 1100X on fine sand with *Arenicola marina;* duplicate 5 × 5 m plots[38]
Dispersant	Searsport, Maine	Murban crude and Corexit 9527, released nearshore; intertidal study plots 60 × 100 m[50]
Dispersant	Bridgwater Bay, U.K.	Nigerian and Forties crude, BP 1100 WD; unreplicated 5 × 3 m plots[5]
Dispersant	Milford Haven, U.K.	Nigerian crude and BP 1100 WD; unreplicated 2 × 2 m plots[39]
Dispersant	Milford Haven, U.K.	Forties crude and BP 1100 WD; duplicate 5 × 5 m plots[5]
Dispersant	Milford Haven, U.K.	Nigerian crude, BP 1100 WD, and Corexit 7664; duplicate circular plots of 3 m diameter[1,5,40]
Dispersant	Milford Haven, U.K.	Nigerian crude, medium fuel oil mousse and Enersperse 1037[42]
Bioremediation	Rance Estuary, France	Arabian light crude, oleophilic and agricultural fertilizers; unreplicated 1 × 1 m plots[23]
Bioremediation	Spitsbergen, Norway	Statfjord crude, fuel oils and Inipol EAP 22, on sandy shores[54]
Bioremediation	Nova Scotia, Canada	Scotian Shelf condensate, Hibernia crude, Inipol EAP 22 and agricultural fertilizer[36]
Dispersant	Wadden Sea, FRG	Mesocosm enclosure over tidal flats[21]
Mechanical removal, dispersant	S. Wales, U.K.	Scrapers, gulley suckers, dispersants (aerial spraying)[45,46] (see authors for further references)

sant-treated plots, and in other cases there was no difference. The results highlighted the importance of local variations in factors such as sediment water table behavior. Little and Scales subsequently tested MA 1037 dispersant on crude and mousse.[42] Dispersant use did not dramatically alter the natural cleaning of most of the applied oil. However, after four months, residual concentrations of crude and mousse were generally less in dispersant-treated areas. After one year there was no difference with mousse due to dispersant treatment, whereas the dispersed crude oil was higher in concentration than untreated crude.[41]

A number of surfactants were tested on a sand/gravel beach.[59] Polyvinyl acetate (PVA) provided effective protection against oil, by decreasing penetration and allowing surface oil to be easily removed by flushing. Observations during a subsequent experiment in New Jersey indicated that the preapplication of Corexit 7664 did not reduce the amount of oil that stranded, but did appear to facilitate removal of the oil by waves.[60]

Page and colleagues released crude oil and dispersant-treated oil in nearshore Maine.[50] They found that oil retention by intertidal sediments and bivalves was less in areas exposed to dispersed oil than in areas exposed to untreated oil.

Morris and Thomas describe field experiments on a coarse sand beach at Folkestone, U.K., with three dispersants tested on fuel oils and fuel oil mousse.[46] Dispersants were an effective way of cleaning up residual amounts of oil and mousse left after other cleanup methods. These findings were compared with previous experiments at Pendine, Wales, where dispersants were less effective because of the lower wave energy there (Morris *et al.*, 1985, see author for complete reference).

Dispersant treatments in sand/mud habitats have been relatively well investigated and do not seem to offer very great advantages. In contrast, Page and colleagues' nearshore release indicates that sand/mud shores may benefit from efficient offshore dispersal.[50] Modern dispersants are also promising for coarser sands and gravel, but biological effects data are lacking.

Tilling. Land farming has been investigated by refineries in Europe and N. America as a disposal method for oily wastes.[13–15] Degradation rate was influenced by the amount of oily sludge, the fertilizers used, and climatic conditions, and in some experiments was clearly faster in summer than in winter. After two to three years, soil oil content had declined to a low level, and natural or sown vegetation grew well. In many cases it was noted that the density of vegetation was higher than in reference plots where oil had not been added. This approach should be evaluated in depauperate and/or bioturbated sand/muds where oil degradation is oxygen-limited. It could be combined with bioremediation where oil degradation is nitrogen- or phosphorus-limited.

Bioremediation. Fusey and Oudot tested bioremediation of crude oil in a sheltered sandy site in France.[23] They found that physical loss of oil dominated initially, and concluded that fertilizers should be applied only after oil contamination falls below a threshold value. Lee and Levy tested a waxy crude on fine and coarse sands in Nova Scotia.[37] Low concentrations of oil (0.3 percent) were degraded naturally within days. Higher concentrations (3 percent) were much more persistent, and bioremediation was found to be effective. Inipol was found to be less effective than agricultural fertilizer, because indigenous microorganisms used it preferentially over the oil. However, Sveum and Ladousse, using Inipol in Spitsbergen, found that the maximum enhancement of oil degradation during one Arctic summer (100 days) was approximately 90 percent for gas oil in sand/gravel, approximately 60 percent in sand, and insignificant in fine-grained sediments.[54] This result may be explained by the fertilizer's greater ability to penetrate coarse sediments.

The benefits of fertilizer application vary with sediment type and oil concentration. Immediate application of fertilizers alone is probably not the optimal approach for bioremediation of fine sand/mud habitats. Tilling combined with bioremediation is worthy of further investigation. Bioremediation is promising for coarse sands, but information on ecological effects is lacking.

Marsh (Table 4)

High-pressure flush. Owens and Foget reported on cleanup following a spill of No. 6 fuel oil which affected a marsh.[48] High-pressure flushing destroyed root systems and changed a firm substratum into poorly consolidated, waterlogged sediment, still containing oil that was incorporated into previously uncontaminated deeper sediments. High-pressure flushing is not a cleanup method seriously considered for marsh habitats, but it may be useful in marsh channels for preventing entry of oil into marshes.

Low-pressure flush. Kiesling and colleagues carried out field experiments with No. 2 fuel oil and Isthmus (Mexico) crude on *Spartina alterniflora* marsh.[34] There was no additional plant damage from low-pressure flushing with seawater. When oil remained on the sediment surface, flushing was effective, reducing levels of added oil by 73 to 83 percent. The method was not effective, however, after sediment penetration. Earlier, DeLaune and colleagues had found that flushing removed 36 percent of added oil.[19] Low-pressure flushing may be justified when large quantities of oil enter marshes, but it should be initiated prior to oil penetration into the sediment.

Sediment/vegetation removal. Cutting of *Spartina anglica* was carried out as a cleanup treatment on a marsh in Milford Haven, following a spill of light Arabian crude in November 1968. New growth occurred over most of the cut area, with shoot density slightly less than in an unoiled, uncut area. Following a spill in August 1969, the greatest mortality occurred in uncut, oiled *Spartina* in a waterlogged hollow. In well drained areas, oil and cutting did not have a long-term significant effect. With cut, unoiled *Spartina* at a control marsh there was a slight increase in shoot density compared with the unoiled, uncut area.[2]

In the tests by Kiesling and colleagues in a *Spartina alterniflora* marsh, cutting removed some oil but did not reduce plant damage or enhance recovery[34] (as was suggested by Mattson et al. 1977, who recommended cutting soon after a spill to reduce mortality; see authors for complete reference). Uncut plots it took up to one year for biomass to reach that of oiled and uncut plots. Damage to plants by foot traffic was noted.

Oiling and cutting experiments were carried out in a reed bed (*Phragmites australis*) by Baker and colleagues. The reed was resistant to up to 10 successive monthly applications of oil. Cutting led to a decrease of shoot height and destroyed the primary shoots when they were at a height of about 50 cm.

The cutting of oiled dominant marsh plants, notably *Spartina* and *Phragmites*, may be justified, for example, if there is a hazard to birds. These plants have a large biomass underground, and regrow provided that the sediments are not seriously oiled or severely compressed during the cleanup operation. The effects of cutting vary seasonally, with the least effect on subsequent yield if the cutting is done in autumn and winter.[33] Because there are already data, further field experiments on vegetation cutting alone should not have a high priority.

The picture is different when we consider combined vegetation and sediment removal, an extreme method for serious cases of either thick, smothering deposits on the surface of the marsh or substantial subsurface penetration of oil. Krebs and Tanner describe a stripping experiment on a *Spartina* marsh contaminated with heavy fuel oil.[35] Earth-moving equipment was used to strip oily sediments to just below the rhizome mat, a depth of 7 to 9 cm. Seeding and transplanting of *Spartina* were carried out to rehabilitate the plots. In untreated areas with sediment oil concentrations above 10,000 ppm, most of the rhizomes died, with little natural regrowth. *Spartina* densities in stripped plots and back-filled plots were similar to the density in the unoiled control by the end of the second growing season.

Removal of oily marsh surface was a controversial treatment following the *Amoco Cadiz* spill in Brittany.[43] Following the *Metula* spill of 1974, marshes near Punta Espora (Chile) were seriously contaminated by thick layers of oil and mousse. There was no cleanup. In December 1991, 17 years after the spill, there was still a thick layer of fresh mousse below the weathered crust on the surface of the marsh. There were areas with no biological recovery, but dead vegetation from 1974 was still preserved under the mousse.[6]

A number of questions, therefore, remain. How serious must the oiling be before this type of treatment is initiated? In other words, how much oil loading can different marsh types tolerate? Is there an alternative to sediment stripping if there is serious subsurface penetration and death of plants? Could tilling be an alternative approach, with transplants when the oil residues have been detoxified?

Dispersant/surfactant. Early experiments in the U.K. by Baker involved Kuwait crude and BP 1002.[2] All treated areas (oil, dispersant, and oil followed by dispersant) showed more dead vegetation than untreated areas, but there were no marked differences among the treatments. Three experiments were then conducted on *Spartina* marsh between 1978 and 1982.[5] The first involved single applications of

Table 4. Field experiments on saltmarsh habitats

Cleanup method	Location	Description of experiment
Vegetation cropping	Milford Haven, U.K.	Accidental spills of crude oils on *Spartina anglica* at two sites; pilot experiments with comparison of cut and uncut areas, 5 × 5 m plots[2]
Surface treatment agents	Arthur Kill, New Jersey	Arabian crude, No. 2 and 6 fuel, water flushing, xanthum gum, PVA, Oil Herder[59]
Vegetation cropping	Slapton Ley, U.K.	Forties crude and heavy fuel oil on *Phragmites australis;* duplicate 1 × 1 m plots cut[7]
Sediment removal	Potomac Estuary	Accidental spill of heavy fuel oil on *Spartina alterniflora;* experiment involved stripping to 7 to 9 cm, backfilling, seeding and transplants[35]
Dispersant	Milford Haven, U.K.	Kuwait crude and BP 1002 on *Spartina anglica* and *Puccinellia maritima;* duplicate 2 × 5 m plots in two main vegetation types[2]
Dispersant	Bridgwater Bay, U.K.	Forties crude and BP 1100 WD dispersant on *Spartina anglica;* pilot experiment with unreplicated 5 × 3 m plots[4,5]
Dispersant	Bridgwater Bay, U.K.	Forties crude and BP 1100 WD dispersant on *Spartina anglica*, two spills; duplicate 4.5 × 2.5 m plots[5]
Dispersant	Bridgwater Bay, U.K.	Forties crude, heavy Flotta residue, mousse, and Corexit 7664 on *Spartina anglica;* duplicate 2 × 2 m plots[5]
Dispersant	Bridgwater Bay, U.K.	Nigerian crude, medium fuel oil mousse, and Enersperse 1037 on *Spartina anglica*[42]
Burning	Milford Haven, U.K.	Kuwait crude and flame-thrower on *Spartina anglica;* pilot experiment with unreplicated 2 × 5 m plots[2]
Visco-elasticizer, solidification agents	Bridgwater Bay, U.K.	Forties crude, residue, mousse, and BP solidifying agents on *Spartina anglica* and *Puccinellia maritima;* pilot experiment with unreplicated 1 × 1 m plots in two vegetation types[47]
Bioremediation	Trondheim, Norway	Statfjord crude, oleophilic and water-soluble fertilizers; unreplicated 4 × 2 m plots[28]
Dispersant	Petpeswick, Nova Scotia, Canada	Alberta sweet blend crude, Corexit 9527, 21 0.4 × 0.4 m plots with replicated control, oil, and dispersant plots in various marsh zones[18]
Dispersant	Wisner Wildlife Refuge, Louisiana	South Louisiana crude applied at 2 L/m^2 to replicated 2.45 × 4.9 m plots; tested on *Spartina alterniflora* and meiofauna[52]
Flushing, flushing/dispersant pretreatment w/dispersant, vegetation cropping	Gulf Coast, USA	*Spartina* marsh; South Louisiana crude (2 L/m^2), flushing at 10 L/s for 5 minutes after 24-hours. Plots 2.4 × 2.4 m[19]
Bioremediation	Nova Scotia, Canada	*Spartina* marsh; Terra Nova waxy crude, agricultural and oleophilic fertilizers[37]

Forties crude, BP 1100 WD dispersant, or oil followed by dispersant. The same pollutants were used for the second experiment, but this time two applications were made, with a one-month interval, to simulate successive spills. The third experiment involved a wider range of oils (see Table 4), including mousse from the *Christos Bitas* incident, and Corexit 7664. It was concluded from these three experiments that, when applied alone, the dispersants had little effect on the *Spartina*. When used on oiled plots they were ineffective as a cleanup technique and did not consistently ameliorate damage caused by oil treatments. The dispersants were ineffective in these experiments because when the oils were applied to the marsh they were rapidly and strongly absorbed by the *Spartina* leaves.

Tests using a number of methods to protect a marsh from oiling showed that (a) polyvinyl acetate provided effective protection by decreasing penetration and facilitating washing, (b) xanthan gum was effective only for short-term protection, because it was easily removed by flushing, and (c) flowing water was not an effective protection method.[59,60]

Little and Scales tested MA 1037 with Nigerian crude and medium fuel oil mousse on the Steart saltmarsh.[42] Dispersant-treated oils were more damaging to the plant community in the short term than untreated oils. After heavy rain removed the oiled dead vegetation there was enhanced loss of the dispersant-treated oils from the marsh sediments, but with little overall difference after one year.[41] Kiesling and colleagues, in field experiments on a *Spartina* marsh, found that addition of dispersant (Corexit 7664) only slightly enhanced oil removal from the sediment surface, compared with low-pressure flushing.[34] Crowell and Lane found that following application of Alberta sweet blend crude oil, recovery on the creek edge (dominated by tall *Spartina*) was rapid compared with that at mid-marsh (dwarf *Spartina*), which showed minimal recovery over two growing seasons.[18] Application of Corexit 9527 initially resulted in more damage than crude oil; however, the toxic effects of the dispersant were short-lived, and most parameters recovered after one year.

Dispersant use on saltmarsh does not appear to be an option that merits further investigation. However, if the marsh is oiled such that the vegetation will die anyway, there may be some advantage in using a dispersant to reduce sediment oil concentrations. We do not yet have enough information to fully evaluate this possibility.

Visco-elasticizer/solidification agents. Use of visco-elasticizer is intended to increase the viscosity of the oil to reduce spreading and facilitate physical removal from the water. Use of gelling agents is a related technique, whereby oil is solidified by being mixed with a polymer and crosslinking agent.[44] Oldham and Baker experimented on various solidification treatments in marshes in 1982, using three types of oil (see Table 4).[47] Mixing in situ with a rake was successful but labor-intensive, and vegetation was damaged in the process. The application of gelling agents over oil, without mixing, proved ineffective and resulted in free oil being trapped below a mat of gelling agents. When solidification treatments were left on plots, there were large declines in *Spartina* cover and only partial recovery during the summer of 1982. When the solidified oil was removed, there was a relatively short-term disturbance.

Mixing difficulties preclude use of the method over large areas of wetland, but it might be useful locally where free oil is concentrated in pools. We have not found information for most other shore habitats, but the above comments probably would apply.

Sorbents. Kiesling and colleagues experimented with sorbent pad application on the sediment following cutting of oiled vegetation in a Texas *Spartina* marsh.[34] The sorbent pads (Type 157 oil sorbent, 3M Company) removed visible amounts of oil from the bare sediment surface. Following the 1989 *Worthy* spill in Southampton Water, horticultural peat was spread in oiled *Spartina* marsh to absorb free oil. The peat was left on the marsh and appeared to be useful in reducing oil mobility, but quantitative studies were not carried out. Rapid deployment of sorbents (including before the oil actually reaches the marsh) could reduce penetration of oil into sediments. Serious problems arise when there is substantial penetration of oil into marsh sediments.

Burning. In Milford Haven, neither April nor October burning of oiled *Spartina* significantly decreased shoot density during the following growing season. In February 1984 there was a spill of naphtha in the Martinshaven reed bed, which was covered with the dead aerial shoots of the previous year's growth. A fire started accidentally, and the reed shoots were burnt. Good regrowth occurred during the spring of 1984 from underground rhizomes which had not been damaged by the naphtha or the fire. A high water table in February probably helped the survival of the reed underground system. Following the *Sivand* spill (Humber estuary), good reed growth was possible in 1984 following the late 1983 oiling and an accidental fire in late May 1984.[7] Kiesling and colleagues found that live biomass in burned *Spartina* plots took up to one year to reach those of oiled and uncleaned plots. Burning increased the oil content of sediment.[34]

There are already enough data to show that burning may be a valid option for treating oiled marsh vegetation at certain times of the year. Burning in the winter has the advantage that much of the standing vegetation is dead, and the ground is likely to be relatively waterlogged, which will help protect underground rhizomes from damage. Because there is evidence that burning can increase sediment oil content, the method is likely to be more suitable for cases where the oil is firmly absorbed on dead marsh vegetation rather than pooled on the sediments.

Bioremediation. Halmo found that both oil-soluble and water-soluble fertilizers increased oil biodegradation in a Norwegian marsh.[28] Lee and Levy, testing a waxy Terra Nova crude in a Nova Scotia salt marsh, found that nutrient enrichment was effective for low concentrations of oil, where most of the oil was in the aerobic surface layer.[37] At higher concentrations, where the most of the oil penetrated into reduced sediments, little degradation was observed.

Bioremediation in marsh habitats could be further tested. Bioremediation combined with tilling might be an option in cases in which oxygenation is a problem, but this approach would need further assessment.

Mangrove/seagrass (Table 5)

High-pressure flush. In their field experiment in Florida, Teas and colleagues concluded that washing oiled mangroves apparently had no value for saving trees previously oiled by unweathered crude.[55] The oil would exert a rapid toxic effect before the wash treatment was applied. Perhaps high-pressure flushing would be of value in removing heavy, smothering oil types.

Dispersant/surfactant. Laboratory experiments by Getter and colleagues provided the first evidence that dispersed oil (bunker C) could be less toxic to mangroves than oil alone.[26] However, this result did not apply to some other oils, and the researchers also found differences in sensitivity between mangrove species. Hoi-Chaw and Meow-Chan investigated the effects of Arabian light crude and Corexit 9527 on mangroves in Malaysia.[29] The impact of undispersed oil was greater than that of the dispersed oil on mangrove saplings. Both naturally and chemically dispersed oils accumulated mainly in the upper 6 cm of the mangrove sediments, but weathered more quickly than undispersed oil.

Teas and colleagues tested dispersants and South Louisiana crude on *Rhizophora mangle* in field experiments in Florida.[55] Washes of water-based dispersant were found to have no value in saving oiled mangroves. Mangroves treated with predispersed oil (corresponding to a well-dispersed slick moving inshore) showed no greater mortality than was found in untreated control plots. Ballou and colleagues conducted field experiments on the Caribbean coast of Panama using Prudhoe Bay crude and a nonionic glycol ether-based dispersant.[8] Oil and dispersed oil were released in nearshore water within booms. Untreated oil had severe long-term effects on survival of mangroves; chemically dispersed oil had minor or no effects.

Seagrasses were also included in the experiment.[8] Untreated oil had relatively minor effects on seagrasses, and chemically dispersed oil had minor or no effects. However, Thorhaug and colleagues have emphasized that different dispersants have different toxicities to a range of seagrasses.[56,57]

Applications of pollutants (Forties crude, BP 1100X, and BP 1100 WD) were carried out on intertidal seagrass in Scotland by Steele.[53] There was a tendency for seagrass performance to be depressed by dispersants and oil-dispersant mixtures more than by oil alone. Baker and colleagues examined the effects of oil and dispersants on seagrass in the intertidal zone in Milford Haven.[5] Both single and successive applications of Forties crude, BP 1100 WD, oil followed by dispersant, or premixed oil and dispersant reduced the percentage cover. Howard and colleagues carried out further experiments with Nigerian crude and Dispolene 34.[31] Highest mortalities occurred in plots treated with premixed oil and dispersant, simulating the situation before the processes of offshore dispersion have been completed. Oil-only treatments, and treatments with oil followed by dispersant, appeared to arrest growth without causing mortality, and dispersant-only treatments behaved similarly to controls in that there was a summer increase in cover.

The mangrove evidence is consistent in indicating that oil dispersed offshore from the mangroves is less damaging than untreated oil. It appears that the same conclusion may apply to seagrasses, but dispersant type is important, and more evidence would be useful in this area. Nonetheless, oil that has been treated but not properly diluted is sometimes more damaging than oil. We conclude that further research on intertidal applications of pollutants to seagrass is of relatively low priority.

Conclusions

Shoreline field experiments are a highly effective and environmentally responsible method for improving our understanding of the ecological effects of cleanup of oiled habitats. Experiments have helped us to define the point at which an oiled habitat should be left alone, the most effective timing and dose rates of various treatments, and the conditions under which the method will be effective without increasing adverse ecological impacts. Because of this success, requirements for further experiments to fill important gaps in our knowledge are now fewer, but include the following:

- Sheltered, rocky intertidal and mangrove flushing with and without surfactants. At what temperature and pressure do adverse impacts occur?
- Cobble/pebble/gravel low-pressure flushing and tilling with and

Table 5. Field experiments on mangroves and seagrass habitats

Cleanup method	Location	Description of experiment
Dispersant	Milford Haven, U.K.	Forties crude and BP 1100 WD on *Zostera* seagrass bed; duplicate 1 × 1 m plots[5]
Dispersant	Milford Haven, U.K.	As above, but with repeated treatments[5]
Dispersant	Milford Haven, U.K.	Nigerian crude and Dispolene on *Zostera* seagrass bed; triplicate 1 × 1 m plots[31]
Dispersant	Pantai Acheh, Malaysia	Arabian light crude, Corexit 9527, on mangrove flora and fauna; various related experiments[29]
Dispersant, flushing	Turkey Point, Florida	South Louisiana crude, non-ionic water-based dispersant, glycol ether-based dispersant, on *Rhizophora mangle* mangroves; 3.0 m^2 plots[55]
Dispersant	Laguna de Chiriqui, Panama	Prudhoe Bay crude, glycol ether-based dispersant, on *Rhizophora mangle* mangroves, *Thalassia testudinum* seagrass beds, and seagrass bed fauna; Unreplicated study sites each 30 × 30 m, each comprising approx. 50% mangrove and 50% seagrass/coral[8]
Dispersant and surface collecting agent	Nigg Bay, U.K.	Forties crude, fuel oils, BP 1100X, BP 1100 WD, and BP Oil Marshal, on *Zostera* spp.; triplicate 0.25 m^2 plots[53]

without bioremediation. This is the objective of the proposed Environment Canada Pacific Coast Oil Spill.

- Marsh, sand/mud, and mangrove tilling and bioremediation. How could landfarming technology be transferred to the coastal zone?

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