

Effects and Management of Oil Spills in Marsh Ecosystems

**A Review Produced from a Workshop
Convened July 1996 at McNeese State University**

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Editor

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PREFACE

This document was produced by participants of a Workshop held in July of 1996 at McNeese State University and sponsored by the U.S. Minerals Management Service. It is a follow-up document to the Proceedings of a Symposium held in New Orleans on July 14-15, 1994 entitled *Gulf of Mexico and Caribbean Oil Spills in Coastal Ecosystems: Assessing Effects, Natural Recovery, and Progress in Remediation Research*. A previous workshop held August 1995 addressed mangrove ecosystems and a report from that workshop was published by MMS as well. The symposium and workshops were supported under a cooperative agreement between MMS and McNeese State University. The sections in this report have been reviewed editorially, but have not been subjected to peer review.

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Effects of Oil on Marsh Macrophytes

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INTRODUCTION

U.S. Gulf Coastal marshes contain productive diverse habitats that are important for many reasons including protection of shoreline from wave actions (Webb 1977), providing fish and wildlife habitats, and improving water quality (Mitsch and Gosselink 1993). Throughout the region, significant petroleum exploration, refining, storing, and transportation activities are conducted on a routine basis and these marshes are therefore subject to occasional oil spills. Field and laboratory studies of the effects of oil on coastal marsh vegetation are numerous (Tables 1, 2, 3) but our ability to predict the effects of oil on marsh vegetation is limited because no single study has, or likely ever will, address the many factors controlling vegetation responses. Laboratory studies must limit their scope to allow detailed study of one to several factors under a small range of conditions but provide limited application to field conditions because of their limited scope. On the other hand, data gathered from oil spills in the field are often difficult to interpret or are of limited predictive value because of the lack of pre-spill site characterization, difficulties in establishing post-spill control or reference sites, and differences in the cleanup methodologies employed (Mendelsohn et al. 1993a, 1995). Furthermore, some important questions regarding the mechanisms of oil actions at the suborganismal level remain unanswered. The objective of this review is to synthesize the existing information in a manner that may help understand how oil affects macrophytes in coastal systems with emphasis placed on U.S. Gulf coastal marshes.

PHYSICALLY INDUCED EFFECTS

Physical impacts act primarily through the coating of the plant and soil surfaces. Direct contact of oil with the leaf surface appears to have more immediate effects than oiling the sediment surface, which generally exerts its negative effects over a longer time period as newly emergent shoots contact the sediment oil, thereby potentially limiting regeneration (Mendelssohn et al. 1990, Mendelssohn et al. 1993a, Webb 1995). Although leaf coating may result in more immediate response, the marsh may be more sensitive to soil coating. Mendelssohn et al. (1993b) reported that under greenhouse conditions an oiling rate of 8 L m⁻² of South Louisiana Crude to the sediment of *Spartina alterniflora* was required to significantly reduce photosynthesis, whereas only 4 L m⁻² was required to significantly reduce vegetative regrowth of new tillers through the oiled sediment. Death of *S. alterniflora* has been reported when high levels of crude oils accumulate in the sediment or remain in the marsh for extended periods of time (Holt et al. 1978, Alexander and Webb 1987, Krebs and Tanner 1981a,b).

When oil coats plant leaves, temperature stress occurs in leaves because of blocked transpiration pathways (stomata) and photosynthesis is also reduced because of restricted entry of CO₂ (Webb 1995, Pezeshki et al. 1995). The degree to which transpiration and photosynthesis are reduced by physical blockage of stomata depends on the amount of plant covered by oil, which in turn varies with the oil amounts, the water conditions, oil type and the dispersion of oil. Stomatal blockage can lead to plant mortality or can be followed by recovery of gas exchange activity and regrowth of new shoots as has been reported for several marsh species including *S. alterniflora* (Pezeshki and DeLaune 1993, Webb 1995) and *Juncus roemerianus* (Pezeshki and DeLaune 1993).

The transport of atmospheric oxygen from the leaves to roots in wetland plants is well documented as a mechanism of reducing oxygen stress in plant roots growing in flooded environments where soil oxygen is limited or essentially absent (Armstrong 1979). Therefore, the blockage of leaf stomata with oil may restrict oxygen diffusion to the roots and increase root oxygen stress, which is a primary factor limiting plant growth in wetlands. Similarly, oil covering the marsh sediment surface restricts the movement of oxygen into the sediment and can result in more anaerobic sediment conditions, thereby exacerbating oxygen stress on plant roots (Ranwell 1968, Cowell 1969).

CHEMICALLY INDUCED EFFECTS

Oil that sometimes fouls coastal marshes can cover a wide range of chemical compositions from light, refined oils to heavy, crude oils and the chemical impacts of oil on vegetation vary greatly among different oils. For instance, certain crude oils such as Arabian Crude, Libyan Crude, Mexican Crude, No. 6 fuel appeared to have few short-term effects on *S. alterniflora* (Tables 1, 2, and 3). In contrast, refined, light oils and Bunker C apparently penetrate into plants and subsequently prevent leaf and shoot regeneration (Pezeshki et al. 1995, Webb 1995). A further consideration of the impact of oil on salt marsh plant species was raised by Gilfillan et al. (1989), who reported that in some salt-tolerant plants, petroleum hydrocarbons may damage root membranes, thereby adversely affecting the ionic balance of the plants and their ability to tolerate salinity. The chemical effects of oil can be classified as short-term and long-

term. The adverse effects of oil on plants range from short-term reductions in transpiration and carbon fixation to plant mortality (Baker 1970, DeLaune et al. 1979, Alexander and Webb 1985, Pezeshki and DeLaune 1993). The long-term effects range from no visible effects to plant mortality. Chemical effects can also be classified on the basis of single and chronic exposure to oil.

Short-Term Vs. Long-Term Response To Oiling

Shortly after oiling, *S. alterniflora* plants had reduced stomatal conductance and no detectable photosynthetic activity (Pezeshki et al. 1995). This finding indicated the potential breakdown of photosynthetic apparatus in leaves directly subjected to oil application (Pezeshki et al. 1995). Such breakdown of leaf structure and/or chlorophyll system may occur because of blocked leaf transpiration leading to dramatic leaf temperature increases and/or direct adverse effects of oil penetrating into the leaf tissue destroying cellular integrity. In *S. alterniflora*, oiling led to leaf death for those leaves that were subjected to oiling up to 40 days after oiling (Pezeshki et al. 1995).

Although initial, short-term adverse effects of oil on plants are often dramatic, plants may recover in the long-term. For instance, complete oiling of *S. alterniflora* plants with 33% weathered South Louisiana crude initially caused rapid death of all existing leaves (Pezeshki et al. 1995). However, new leaf production began within two weeks, and two months after oiling, the gas exchange measurements conducted on leaves that had emerged after oiling showed that the new leaves had similar gas exchange rates to that of control plants. This finding is in agreement with previous work by DeLaune et al. (1979), Smith et al. (1984), and Pezeshki and DeLaune (1993) who also found that *S. alterniflora* and *Juncus roemerianus* plants recovered from oiling with South Louisiana Crude.

These findings suggest that the adverse effects of leaf oiling on photosynthesis of *S. alterniflora* may be a short-term response. Although plant survival is possible, survival may be species specific and may depend on several factors such as the plant species being oiled, the type and amount of oil and the mode of delivery. For instance, *S. alterniflora* plants oiled with Bunker C oil did not produce new leaves and the plants died (Pezeshki et al. 1995). The different effects of South Louisiana Crude and Bunker C on *S. alterniflora* probably resulted from differences in toxicity. Information on the relative toxicity of other petroleum hydrocarbons on marsh vegetation is lacking.

Single Vs. Chronic Exposure To Oil

Short-term recovery from a single application of oil does not necessarily represent plant responses to chronic oil spills. Chronic oil spill results in penetration and accumulation of oil in the sediment, which may coat newly regenerated shoots, damage plant regeneration processes, and poses long-term adverse effects on plant growth and productivity (Mendelsohn et al. 1993b, Webb 1995). Substantial mortality of *S. alterniflora* stands has been reported when high levels of crude oils accumulated in the sediment or remained in the marsh for extended period of time (Holt et al. 1978, Alexander and Webb 1987, Krebs and Tanner 1981a,b). Such adverse long-term effects on plants may impact the associated aquatic habitats because marsh vegetation

provide detritus to food webs (Mitsch and Gosselink 1993).

SEASON OF SPILL

The season during which an oil spill occurs may play an important role in influencing the impact of oil on vegetation (Ranwell and Hewett 1964, Baker 1971, Getter et al. 1984, Webb 1995). Ranwell and Hewett (1964) observed that during the period of senescence, even relatively fresh oil did not cause significant mortality in salt marsh vegetation. This suggests that plants are more sensitive to oil application during their active growing period than other periods. Alexander and Webb (1985) reported that No. 2 fuel oil applied to the sediment and the entire *Spartina alterniflora* shoot at a rate of 2 L m⁻² caused a greater reduction in live biomass in May (during the growth season) than in November (at the end of the growth season). The adverse effects of oil application to *S. alterniflora* were more severe during the spring season than the fall season (Webb 1995). A recent study (Lin and Mendelssohn, unpublished data) showed that application of 8 L m⁻² of south Louisiana crude oil to the soil substrate caused much greater reduction of photosynthetic rate, aboveground biomass and regrowth biomass of *S. alterniflora* and *Sagittaria lancifolia* in June than in late October, supporting the hypothesis that plants are more sensitive to oil in the active growing season. Baker (1971) indicated that a marked reduction of flowering can occur if plant aboveground are oiled when flower buds are developing, and flowers, if oiled, rarely produce seeds. Additionally, oiling of seeds may reduce germination.

INTERSPECIFIC SENSITIVITY TO OIL SPILLS

U.S. Gulf coastal marshes are composed of diverse plant species occupying various ecological zones including salt, brackish and freshwater habitats. The saltmarsh, brackish and freshwater marshes differ in plant species and tidal regimes and therefore differ in functional capabilities. For instance, freshwater marshes generally support a more diverse plant and wildlife community whereas saltmarshes generally support more commercially important estuarine fish species. Investigation of oil effects on wetland vegetation, up to date, was largely conducted in salt marsh (DeLaune et al., 1979, Ferrell et al., 1984, Alexander and Webb, 1985 and 1987, Li et al., 1990, Mendelssohn et al., 1990 and 1993a, Lin and Mendelssohn, 1996). Oil concentrations in the soil greater than 2-10.5 mg g⁻¹ caused decreased live stem density of *S. alterniflora* and led to long-term impacts (Krebs and Tanner 1981a,b, Alexander and Webb 1987). Application of south Louisiana crude oil at rates of 4 L m⁻² and higher reduced stem density, biomass and regrowth of *S. alterniflora* and *S. patens*. Plant mortality occurred at high oil dosages of 8 L m⁻² and above (Lin and Mendelssohn 1996). In a comparative study conducted on two saltmarsh species, *J. roemerianus* was initially less sensitive than *S. alterniflora* as was evident from photosynthetic responses. However, both species recovered rapidly (Pezeshki and DeLaune 1993).

The risk of oil spills in the coastal freshwater marshes is also high because of exploration, production, transportation, refinery, and storage of petroleum oil in or near these marshes. However, less information is available on the effects of oil on freshwater marsh plants compared with salt marsh. Generally, the species diversity is greater in freshwater zone (Mitsch

and Gosselink 1993). These species have different foliage characteristics and thus respond to oiling. This sensitivity difference is likely to be of greater consequence in freshwater marshes due to greater species diversity than salt and brackish marshes. In a comparative investigation of the effect of oil on marsh vegetation, Lin and Mendelsohn (1996) recently reported that the four fresh marsh plant species, *S. lancifolia*, *Eleocharis quadrangulata*, *Cyperus odoratus*, and *Ammania teres*, occurred in the sods of the fresh marsh receiving no oil, but no *C. odoratus* and *A. teres* survived in any of the oil treated sods. *Eleocharis quadrangulata* could only exist at oil levels up to 8 L m⁻² but experienced reduced biomass with increasing oil dosage up to that level. *S. lancifolia* occurred at all oil dosages and formed monospecific communities at 16 and 24 L m⁻² of oil, exhibiting a high oil tolerance and even an enhancement in growth with higher oil dosage. An oil spill in a freshwater marsh (Burk 1977) eliminated 18 plant species, reduce 14 species in relative abundance, and increased or unaffected 23 species in relative abundance following the spill, showing very different response of freshwater species to the oil spill.

Changes in plant community composition may also become evident following an oil spill and subsequent cleanup efforts because of the different sensitivities displayed to oils displayed by different plant species. For instance, in a spill of South Louisiana Crude Oil in a brackish/saline marsh in south Louisiana, Mendelsohn et al. (1990, 1993a) noted that *Distichlis spicata* became more abundant over a period of several years following the spill in areas of the marsh thought to have been previously dominated by *Spartina patens*. In areas dominated by *S. alterniflora*, increased cover by *D. spicata* was less pronounced, and generally of shorter duration than in the more brackish areas of the marsh.

INTRASPECIFIC SENSITIVITY TO OIL SPILLS

Recently, Hester et al. (in prep.) investigated the effects of oiling on genotypes collected from ten different Gulf coast populations of *Spartina patens*, a brackish marsh dominant. Significant intraspecific (within species) variation in sensitivity to oiling was evident when South Louisiana Crude oil was applied at the rate of 5 L m⁻² to the sediment surface. Genotypes from the different populations displayed significant differences in the degree to which photosynthesis and vegetative regrowth were impacted. Therefore, in addition to the other factors such as type and amount of oil, site characterization, and season, it may be that some of the apparent inconsistencies in the reported responses of certain marsh macrophytes to oiling can be partially explained by within species variation in oil tolerance.

EFFECTS OF CLEANUP ACTIVITIES ON MARSH VEGETATION

Although some plant species apparently tolerate being coated by some crude oils, refined oils on vegetation and high sediment concentrations of crude oil spills can destroy marsh plant communities (Hershner and Lake 1980, Hampson and Moul 1978). Thus, in cases where refined oils or large amounts of crude oil are involved, cleanup may be desirable but it is not clear what cleanup operations are useful in wetlands. The present techniques of dealing with oil spill in wetlands can be classified as mechanical or chemical methods. The effect of burning as a cleanup technique is considered in a separate section. Determining a proper strategy involves considerations of trade-off balancing damage to a marsh and short-term and long-term effects

of oil toxicity (Johnson and Pastorok 1985).

Oil can be collected and skimmed but this may greatly damage plants (OTA 1990). Some on-scene coordinators have cut and removed all oiled marsh vegetation to prevent contamination of wildlife, but this has caused permanent plant loss and soil erosion (Baca et al. 1985). Cutting is therefore not a valuable tool in Louisiana's coastal marshes where marsh loss is already severe (Gagliano et al. 1981). Mendelssohn et al. (1990) found that physical disturbance of vegetation and soil associated with clean-up activities had detrimental and long lasting effects on marsh vegetation. Hoff et al. (1993) found that human foot traffic caused greater mortality to *Salicornia/Distichlis* marsh than North Slope crude. It appears that physical responses, other than gentle flushing of water through the oiled marsh, are not useful in Gulf Coast marshes because cleanup activities will likely kill marsh vegetation and create shallow ponds that will not revegetate. Thus, chemical responses are more likely than physical responses. Chemical responses to oil spills are also available. Dispersants are becoming less toxic and their use may increase (Cunningham et al. 1991; Daniels 1995) but they will not likely be deployed directly in marshes where there is little water to dilute the dispersed oil (OTA 1990). Instead, dispersants will likely be used only in deep water with good circulation. However, marsh plants could still be exposed to dispersants and to dispersed oil present in adjacent rivers, bayous, lakes, or bays. Unfortunately, no data are available to evaluate the effects of dispersants or dispersed oil on marsh vegetation.

A new chemical alternative is a cleaner rather than a dispersant (Fiocco et al. 1991), it does not disperse oil but allows oil to be washed from surfaces such as rocks or vegetation back into the water where it can be collected. Cleaners might someday be used to clean marsh vegetation fringing rivers, bayous, and lakes where wildlife use is concentrated because fringing marshes are heavily utilized by wildlife even though they are small in area. Oiled fringing marshes have caused significant bird mortality in previous oil spills (Alexander et al. 1979). Teas et al. (1993) recently showed that cleaning prevented mortality of oiled red mangroves (*Rhizophora mangle*) by removing oil that otherwise suffocated roots, and Pezeshki et al. (1995) showed that cleaning prevented mortality of *S. alterniflora* coated with Bunker C. Cleaning South Louisiana Crude from *S. alterniflora* prevented leaf death but was not needed to prevent plant death. The use of this method, however, requires more information regarding the toxicity of cleaners to various organisms (Fingas et al. 1989, Fiocco et al. 1991).

A third chemical response is the application of nutrients to oiled marshes to speed bacterial consumption of the oil. Nutrients could be applied to spilled oil in water bodies before it reaches the marsh. Nutrient additions are also the only response that could conceivably be applied on a wide scale basis to marshes that have already been fouled with oil. However, some plant communities may be sensitive to nutrient additions, as indicated by the effects of chronic nutrient additions to the Florida Everglades (Davis 1994). Furthermore, the fate of added nutrients is unknown but should be determined to prevent eutrophication of adjacent water bodies. Phosphorus added to marshes is more likely to be transported to adjacent water bodies than nitrogen because wetlands promote denitrification (Mitsch and Gosselink 1993), but it is not known which fertilizer formulations simultaneously maximize oil consumption and denitrification.

Another response to spilled oil may be no action, which has been the case for some rocky shorelines (Mearns 1993). This is because oil evaporates and naturally degrades in wetland soils

(DeLaune et al. 1980, Hambrick et al. 1980), and because marsh plants can recover from fouling with some oils even though some leaf death may occur. No action might be the most used approach because physical cleanup activities is so damaging to vegetation and because of uncertainty regarding cleaner and dispersant toxicity and uncertainty regarding the fate of added nutrients (OTA 1990, Mearns 1993).

Although oiled vegetation may return to normal without cleanup operations in areas of the marsh where little oil accumulates on the soil surface, recovery is not likely where significant oil accumulation on the soil surface causes plant mortality, prevents regeneration, and causes loss of surface elevation. In such areas, sediment stripping might be useful. Sediment stripping results in complete plant mortality and eliminates the potential for recovery but plant recovery is unlikely in such areas anyway (Krebs and Tanner 1981a, b). Following stripping, vegetation can return to normal if the original elevation is restored by filling sediments (Krebs and Tanner 1981b, Vandermulen et al. 1981). Stripping without restoration of the original elevation not only prevents revegetation of the stripped area because of excessive flooding, but also causes erosion of adjacent, healthy areas because of changes in tidal prism (see Krebs and Tanner 1981b, Vandermulen et al. 1981).

INDIRECT EFFECTS

The failure of certain areas to revegetate following an oil spill may be linked to increased flooding stress resulting from erosion of the marsh substrate following plant stress and death from the initial oil impact. In the absence of healthy vegetation to trap and bind marsh sediments, marsh surfaces generally erode to a lower elevation, resulting in the formation of small dieback ponds. Elevation may also be lost upon plant mortality as the peat network decays (DeLaune et al. 1994). Once elevation is lost, vegetation rarely again colonizes the open water. Rather, small dieback ponds often coalesce to form larger, shallow open water bodies. In a south Louisiana brackish/saline marsh that had experienced localized death of the vegetation following an oil spill of South Louisiana crude, Mendelsohn et al. (1993a) found that increasing the substrate elevation by only 10 - 15 cm had a significant effect on whether transplants of *Spartina alterniflora* grew vigorously or were stressed to the point of not surviving. Other studies have similarly found marsh elevational differences to have a significant impact on plant stress and productivity (Mendelsohn and McKee 1988, Burdick and Mendelsohn 1990, Wilsey et al. 1992). Therefore, indirect effects from oil spills, such as subsequent lowering of the marsh surface resulting from sediment erosion following localized plant death, may need to be considered in decisions concerning suitable restoration of oiled marshes.

Oil may also affect soil microbial communities (Alexander and Schwarz 1980), which are important in regulating the flow of energy from plants to food webs and in control of nutrient regeneration in marsh soils that influences plant productivity (Knox 1986). Thus, if toxic components of oil inhibited bacterial decomposition of soil organic matter and the associated nutrient remineralization, plant growth would be slowed. However, the only study to address this issue found that Louisiana and Arabian Crude oils increased rather than decreased decomposition of soil organic matter in fresh marsh soils (Nyman and Patrick 1995). This would suggest increased nutrient remineralization rates, and might explain observations of enhanced plant growth following oil application to *S. alterniflora* (Hershner and Moore 1977,

Krebs et al. 1981b, Li et al. 1990) and *S. lancifolia* (Lin and Mendelssohn 1996). Additional data is needed regarding the effects of other oils and the responses of other marsh types before cause and effect can be assumed however.

CONCLUSIONS

As was pointed out, U.S. Gulf Coastal marshes are composed of diverse macrophyte species occupying various ecological zones. Such species diversity requires species specific and oil-specific data to assess the effects of oil on various species as well as the potential differences among dominant species to different oil types that are being explored, refined, stored or transported in the region. More research is needed to assess the effects of oil on non-fresh marsh plant species. In addition, data are needed on the effectiveness of methods used in removing oil from vegetation in different marsh habitats and the potential sensitivity of various species to such approaches.

The effects of oil spills on marshes are complex and need to be considered at several scales of resolution and modes of impact. It is generally recognized that lighter weight oils are more immediately toxic to plants and other organisms than heavier oils. However, many of the modes of impact to marsh macrophytes involve effects related to smothering of the gas exchange surfaces of the plant, or of limiting gas exchange into an oil-coated sediment. For these types of impacts, heavier weight oils can be as detrimental to vegetation health as lighter weight oils acting at the cellular level by altering membrane permeability or disrupting various facets of the plants' metabolism. Direct effects of oiling of marsh macrophytes tend to be most severe on aboveground tissue and often act via direct tissue toxicity or blockage of gas exchange in transpiration and photosynthesis. The effects oil on and in the marsh sediment can lead to increased oxygen stress in belowground tissues due to reduced gas exchange, disrupt root membranes and ion selectivity, and may adversely affect vegetative regrowth as new, sensitive shoots contact the oil as they emerge.

Differences in the sensitivity to oiling are evident at the level of the community, species, and individual. For instance, *Sagittaria lancifolia*, a fresh marsh dominant has recently been shown to highly resistant to oiling with South Louisiana Crude. Within *Spartina patens*, a brackish marsh dominant, genotypes collected from different Gulf coast populations have been recently shown to display significant variation in their response to oiling. Future research is needed that addresses the mechanisms underlying these differences between species and within species in their susceptibility or tolerance to oiling. In addition, more research is needed to study the effects of oil on fresh marsh due to the likelihood of greater different response of highly diverse species to oiling.

One time oil spills, depending on oil type and amount may not need extensive cleanup. In fact, activities associated with cleanup that drive oil into the sediment or destroy the plant root network, such as marsh buggy traffic and human foot traffic, may cause permanent plant mortality. Indirect effects on the microbial community and nutrient cycling, as well as possible loss of marsh surface elevation following plant stress and/or death from oiling, need to be considered when assessing oil impacts and formulating management and restoration plans. Cleanup activity might only be beneficial only in areas subject to large oil accumulations on the soil surface such as occur in some areas affected large spills or chronic spills.

LITERATURE CITED

- Alexander, M.M., P. Longabucco, and D.M. Phillips. 1979. The impact of oil on marsh communities in the St. Lawrence River. In, Proc. 1979 Oil Spill Conf., Amer. Petrol. Inst. Washington, D.C., pp. 333-340.
- Alexander, S.K., and J.R. Schwarz. 1980. Short-term effects of South Louisiana and Kuwait crude oils on glucose utilization by marine bacterial populations. *Applied and Environmental Microbiology*. 40:341-345.
- Alexander, S.K., and J.W. Webb, Jr. 1985. Oil in the salt marsh: what have we learned? Pages. 49-62. In, C.F. Bryan et al. (eds.). Proceedings of the Fourth Coastal Marsh and Estuary Management Symposium. Louisiana State University Printing Office. Baton Rouge, Louisiana .
- Alexander, S.K., and J.W. Webb, Jr. 1987. Relationship of *Spartina alterniflora* to sediment oil content following an oil spill. Pages 445-449. In, Proc. 1987 Oil Spill Conf., Amer. Petrol. Inst. Washington, D.C. .
- Armstrong, W. 1979. Aeration in higher plants. *Adv. Bot. Res.* 7:225-332.
- Baca, B.J., C.D. Getter, and J. Lindstedt-Siva. 1985. Freshwater oil spill considerations: protection and cleanup. Pages 385-390. In, Proceedings of the 1985 Oil Spill Conference. .
- Baker, J.M. 1970. The effects of oil on plants. *Environmental Pollution*. 1:27-44.
- Baker, J.M. (1971). Seasonal effects. Pp. 44-51 In, E.B. Cowell (Ed). *The Ecological Effects of Oil Pollution on Littoral Communities*. Applied Science Publishers LTD., Barking, Essex, England.
- Burdick, D.M. and I.A. Mendelsohn. 1990. Relationship between anatomical and metabolic responses to soil waterlogging in the coastal grass *Spartina patens*. *Journal of Experimental Botany* 41:223-228.
- Burk, C.J. 1977. A four year analysis of vegetation following an oil spill in a freshwater marsh. *J. appl. Ecol.* 14: 515-522.
- Cowell, E. B. 1969. The effects of oil pollution on salt-marsh communities in Pembrokeshire and Cornwall. *Journal of Applied Ecology* 6: 133-142.
- Cunningham, J.M., K.A. Sahatjian, C. Meyers, G. Yoshioka, and J.M. Jordan. 1991. Use of dispersants in the United States: perception or reality? Pages 289-292. In, Proceedings of the 1991 Oil Spill Conference.

- Davis, S.M. 1994. Phosphorus inputs and vegetation sensitivity in the Everglades. pages 357-378 In, S.M. Davis and J.C. Ogden (eds.). Everglades: the ecosystem and its restoration. St. Lucie Press, Delray Beach, Florida.
- DeLaune, R.D., W.H. Patrick, Jr., and R.J. Buresh. 1979. Effect of crude oil on a Louisiana *Spartina alterniflora* salt marsh. Environmental Pollution. 1979, pp. 21-31.
- DeLaune, R.D., G.A. Hambrick, and W.H. Patrick, Jr. 1980. Degradation of hydrocarbons in oxidized and reduced sediments. Marine Pollution Bulletin. 11:103-106.
- DeLaune, R.D., C.J. Smith, W.H. Patrick, Jr., J.W. Fleeger, and M.D. Tolley. 1984. Effect of oil on salt marsh biota: methods for restoration. Environmental Pollution (A) 36:207-227.
- DeLaune, R.D., J.A. Nyman, and W.H. Patrick, Jr. 1994. Peat collapse, ponding, and wetland loss in a rapidly submerging coastal marsh. J. Coastal Research 10:1021-1030.
- Ferrell, R.E., E.D. Seneca, and R.A. Linthurst. 1984. The effect of crude oil on the growth of *Spartina alterniflora* Loisel. and *Spartina cynosuroides* (L.) Roth. J. Exp. Mar. Biol. Ecol., 1984, 83: 27-39.
- Fingas, M. F., G. Stoodley, G. Harris, and A. Hsia. 1989. Evaluation of chemical beach cleaners. Cleanup Technology Workshop, Anchorage, Alaska, November 28-30.
- Fiocco, R.J., G.P. Canevari, J.B. Wilkinson, H.O. Jahns, J. Bock, M. Robbins, and R.K. Markarian. 1991. Development of COREXIT 9580 - a chemical beach cleaner. Pages 395-400. In, Proc. 1991. Oil Spill Conf. American Petroleum Institute, Washington D.C.
- Gagliano, S.W., K.J. Meyer-Arendt, and K.M. Wicker. 1981. Land loss in the Mississippi River Deltaic Plain. Trans. Gulf Coast Assoc. Geol. Soc. 31:295-300.
- Getter, C. D., G. Cintron, B. Dicks, R.R. Lewel, and E.D. Seneca. 1984. The recovery and restoration of salt marshes and mangroves following an oil spill. Pages 65-114. In, J. Cairns and A.L. Buikema (Eds.). Restoration of Habitats Impacted by Oil Spills. Butterworth publishers, Stoneham, MA.
- Gilfillan, E. S., D. S. Page, A. E. Bass, J. C. Foster, P. M. Fickett, W. G. H. Ellis, S. Rusk, and C. Brown. 1989. Use of Na/K ratios in leaf tissues to determine effects of petroleum on salt exclusion in marine halophytes. Marine Pollution Bulletin 20:272-276.
- Hambrick, G.A., R.D. DeLaune, and W.H. Patrick, Jr. 1980. Effect of Estuarine Sediment pH and oxidation-reduction potential on microbial hydrocarbon degradation. Applied and Environmental Microbiology. 40:365-369.

- Hampson, G.R., and E.T. Moul, 1978. No. 2 fuel oil spill in Bourne, Massachusetts: Immediate assessments of the effects on marine invertebrates and a 3 year study of growth and recovery of salt marsh. *J. Fish. Res. Board of Canada* 35:731-734.
- Hershner, C., and K. Moore. 1977. Effects of the Chesapeake Bay Oil Spill on salt marshes of the lower bay. Pages 529-533. In, Proceedings of the 1977 Oil Spill Conference, American Petroleum Institute, Washington D.C.
- Hershner, C. and J. Lake. 1980. Effects of chronic pollution of a saltmarsh grass community. *Marine Biology* 56: 163-173.
- Hester, M.W., Q. Lin, and I.A. Mendelssohn. In prep. Intraspecific variation in tolerance to South Louisiana Crude oil in *Spartina patens*.
- Hoff, R.Z., G. Shigenaka, and C.B. Henry. 1993. Salt marsh recovery from a crude oil spill: vegetation, oil weathering, and response. 1993 Oil Spill Conference. 1993:307-311.
- Holt, S., S. Rabalais, N. Rabalais, S. Cornelius, and J.S. Holland, 1978. Effects of an oil spill on salt marshes at Harbor Island, Texas. I. Biology. Pages 344-352. In, Proc. Conf. Assessment of Ecol. Impacts of Oil Spills. Amer. Inst. Biol. Sci.
- Johnson, T.L., and R.A. Pastorok. 1985. Oil spill cleanup! Options for minimizing adverse ecological impact. American Petroleum Institute. Publication No. 4435.
- Knox, G.A. 1986. Estuarine ecosystems: a systems approach. Volume II. CRC Press, Inc. Boca Raton FL.
- Krebs, C.T., and C.E. Tanner, 1981a. Cost analysis of marsh restoration through sediment stripping and *Spartina* propagation. Pages 375-385. In, Proc. 1981 Oil Spill Conf. Amer. Petrol. Inst. Washington, DC,
- Krebs, C.T., and C.E. Tanner. 1981b. Restoration of oiled marshes through sediment stripping and *Spartina* propagation. Pages 386-390. In, Proc. 1981 Oil Spill Conf. Amer. Petrol. Inst., Washington, DC.
- Li, Y., J.T. Morris, and D.C. Yoch. 1990. Chronic low level hydrocarbon amendments stimulate plant growth and microbial activity in salt-marsh microcosms. *J Appl. Ecol.* 27: 159-171.
- Lin, Q. and I.A. Mendelssohn. 1996. A comparative investigation of the effects of South Louisiana Crude oil on the vegetation of fresh, brackish, and salt marshes. *Marine Pollution Bulletin* 32: 202-209.

- Mearns, A.J. 1993. Recovery of shoreline ecosystems following the Exxon Valdez oil spill and subsequent treatment. Pages 466-479. In, O.T. Magoon, (ed.), Coastal Zone '93 Volume I. American Society of Civil Engineers, New York.
- Mendelssohn, I.A. and K.L. McKee. 1988. *Spartina alterniflora* dieback in Louisiana: time-course investigation of soil waterlogging effects. *Journal of Ecology* 76: 509-521.
- Mendelssohn, I.A., M.W. Hester, C. Sasser, and M. Fischel. 1990. The effect of Louisiana crude oil discharge from a pipeline break on the vegetation of a southeast Louisiana brackish marsh. *Oil and Chemical Pollution* 7:1-15.
- Mendelssohn, I.A., M.W. Hester, and J.M. Hill. 1993a. Effects of oil spills on coastal wetlands and their recovery: OCS Study MMS 93-0045. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans, LA. 46 pp.
- Mendelssohn, I.A., K.L. McKee, and T. Kong. 1993b. An evaluation of indicators of wetland vegetation stress and their relationship to biological endpoints. Office of Exploratory Research, US EPA, Washington, D. C.
- Mendelssohn, I. A., M. W. Hester, and J. W. Pahl. 1995. Environmental effects and effectiveness of in-situ burning in wetlands: Considerations for oil spill cleanup. Louisiana Oil Spill Coordinator's Office/Office of the Governor, Applied Oil Spill Research and Development Program, Baton rouge, LA. 57 pp.
- Mitsch, W.J., and J.G. Gosselink. 1993. *Wetlands*. Van Nostrand Reinhold Co. New York.
- Nyman, J.A., and W.H. Patrick, Jr. 1995. Effects of oil and chemical responses on fresh marsh function and oil degradation: response implications. Louisiana Oil Spill Coordinator's Office/Office of the Governor, Louisiana Applied Oil Spill Research and Development Program, Baton Rouge, Louisiana. 68 pp.
- OTA. 1990. Coping with an oiled sea. U.S. Congress, Office of Technology Assessment. OTA-BP-O-63. U.S. Government Printing Office, Washington D.C.
- Pezeshki, S.R., and R.D. DeLaune. 1993. Effect of crude oil on gas exchange functions of *Juncus roemerianus* and *Spartina alterniflora*. *Water, Air, and Soil Pollution* 68: 461-468.
- Pezeshki, S.R., R.D. DeLaune, J.A. Nyman, R.R. Lessard, G.P. Canevari. 1995. Removing oil and saving oiled marsh grass using a shoreline cleaner. Pages. 203-209. In, International Oil Spill Conf., Amer. Petrol. Inst., Publ. No., 4620.

- Ranwell, D.S. 1968. Extent of damage to coastal habitats due to the Torrey Canyon incident. Pages 39-47. In, The biological effects of oil pollution on littoral communities. J. D. Carthy and D. R. Arthur (eds.), Field Studies Council, London, England.
- Ranwell, D.S. and D. Hewett. 1964. Oil pollution in Poole Harbour and its effects on birds. *Bird Notes*, 31:192-197.
- Smith, C.J., R.D. DeLaune, W.H. Patrick, Jr., and J.W. Fleeger. 1984. Impact of dispersed and undispersed oil entering a Gulf Coast salt marsh. *Environmental Toxicology and Chemistry* 3:609-616.
- Teas, H.J., R.R. Lessard, G.P. Canevari, C.D. Brown, and R. Glenn. 1993. Saving oiled mangroves using a new non-dispersing shoreline cleaner. Pages 147-151. In, Proc. 1993. Oil Spill Conf. American Petroleum Institute, Washington D.C.
- Vandermeulen, J.H., B.F.N. Long, and L. D'Ozouville. 1981. Geomorphological alteration of a heavily oiled saltmarsh (Ile Grande, France) as a result of massive cleanup. Pages 347-351. In, Oil Spill Conf. American Petroleum Institute, Washington D.C.
- Webb, J.W. 1977. Establishment of vegetation for shoreline stabilization in Galveston Bay, Texas. Ph.D. Dissertation, Texas AandM Univ., College Station, Texas, pp. 136.
- Webb, J.W., 1995. Effects of oil on saltmarshes. Pages. 55-61. In, C.E. Proffitt and P.F. Roscigno (Eds.). Symposium Proc. Gulf of Mexico and Caribbean Oil Spill in Coastal Ecosystems: Assessing Effects, Natural Recovery, and Progress in Remediation Research. OCS Study/MMS 95-0063. U.S. Dept. of the Interior, Minerals Management Service. New Orleans, LA, .
- Wilsey, B. J., I. A. Mendelsohn, and K. L. McKee. 1992. Effects of increased elevation and macro- and micronutrient additions on *Spartina alterniflora* transplant success in salt-marsh dieback areas in Louisiana. *Environmental Management*. 16:505-511.

Table 1.

Effects of Louisiana Crude Oil (unless otherwise noted) on US Gulf coastal marsh species.
Table adapted from a workshop handout by C.E. Proffitt.

Exposure	Species	Effects	Reference
0.25 L/m spill in marsh	<i>S. alterniflora</i>	Little damage to existing stocks and new colonizers	de la Cruz et al. 1981
0.028 L/m spill in marsh	<i>S. alterniflora</i> and <i>S. patens</i>	64% decrease in cover in mixed species assemblage	Mendelssohn et al. 1990
1 L/m ² exp. marsh	<i>S. alterniflora</i>	No significant difference in above ground biomass	DeLaune et al. 1979
2 L/m ² oil in marsh	<i>S. alterniflora</i>	No significant difference in above ground biomass CO ₂ fix. decreased in 6 and recovered. in 13 days	Smith et al. 1984
2 L/m ² on foliage, 5 week study	<i>S. alterniflora</i>	100% oil cover: No photosyn. Partial oil: Photosyn. decreased 50 - 80%	Pezeshki and DeLaune 1993
Mexico Sour Crude			
8 L/m ²	<i>S. alterniflora</i>	No significant difference in above ground biomass	Crow et al. 1976
Oil (undetermined)	<i>S. alterniflora</i>	Decreased production early but on long-term effects	Lytle 1975
32 L/m ² greenhouse	<i>S. alterniflora</i>	No significant difference in above ground biomass	DeLaune et al. 1979

8 L/m ² and higher of south Louisiana crude oil	<i>S. alterniflora</i>	No regrowth in the year following oil application	Lin and Mendelsohn 1996
8 L/m ² and higher of south Louisiana crude oil	<i>S. patens</i>	Significant reduction in photosynthetic rate, aboveground biomass and no regrowth in the year following oil application	Lin and Mendelsohn 1996
Up to 24 L/m ² of south LA crude	<i>Sagittaria lancifolia</i>	Significant increase in biomass and stem density	Lin and Mendelsshon 1996

Table 2.

The Effect of Crude Oil and Dispersants on *Spartina Alterniflora*. Table Adapted from a Workshop Handout by C.E. Proffitt.

Exposure	Effects	Reference
2 L/m ² oil in marsh	No significant difference in above ground biomass	Smith et al. 1984
	CO ₂ fixation decreased in 6 and recovered in 13 days	Smith et al. 1984
2 L/m ² oil+dispersant in marsh	No significant difference in above ground biomass	Smith et al. 1984
2 L/m ² field experiment	No significant difference in biomass or CO ₂ fixation	DeLaune et al. 1984
Oil+water flushing	No significant difference in biomass or CO ₂ fixation	DeLaune et al. 1984
Oil+mechanical cleaning	No significant difference in biomass or CO ₂ fixation	DeLaune et al. 1984
Oil+conc. dispersant	75% decrease in biomass and some decr. in CO ₂ fixation	DeLaune et al. 1984
Oil+vegetation removal	Significant decrease in biomass and slow recovery (>2 years)	DeLaune et al. 1984

Table 3.

The Effects of Refined Oil on *Spartina Alterniflora*. Table Adapted from a Workshop Handout by C.E. Proffitt.

Exposure	Effects	Reference
No. 2 fuel oil (1 L/m ²)	Complete-partial loss of above ground biomass	Webb et al. 1985 Burger 1994
No. 6 fuel oil in marsh	Increased growth of oiled vegetation	Hershner and Moore 1977, Stebbins 1970
No. 6 fuel oil in marsh	Total loss of above ground biomass. Resprouted in 4 months.	Proffitt and Devlin unpubl.

Effects of Petroleum Hydrocarbons on Coastal Marsh Biogeochemical Processes

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REVIEW

The soil microbial community continually releases nutrients from organic matter in marsh soils to adjacent water; this continual nutrient release appears extremely important in maintaining high productivity of aquatic habitats (Knox 1986 pages 111-112). In addition to regulating nutrient cycling, the soil microbial community governs soil Eh, which influences plant growth, and also degrades petroleum hydrocarbons. The recovery of fouled marshes may therefore depend partly on biodegradation rates and how petroleum hydrocarbons affect soil conditions, and petroleum hydrocarbons may have long term effects on wetland functions even after plant growth resumes. Thus, whereas short-term effects of spills in marshes are dominated by effects on plants, the long-term functioning of the marsh greatly depends on how petroleum hydrocarbons affect soil bacteria and the biogeochemical processes they control. None-the-less, little attention has been paid to the effects of oil on the marsh soil microbial community or biogeochemical processes.

Some workers found no or little effects of oil on structure of the soil microbial community (DeLaune et al. 1979, DeLaune et al. 1984) but others have found adverse effects of oil on soil organisms (Alexander and Schwarz 1981). Burns and Teal (1979) found oil in marsh soil 7 years after a spill, which indicates the potential for long term effects. Weathering may be more rapid and toxicities higher in fresh marshes than in saline marshes because the solubility of petroleum hydrocarbons decreases as water salinity increases (Robotham and Gill 1989) but this has not been examined. Although weathered petroleum hydrocarbons are believed to be less toxic than freshly released ones, weathered crude oils can become near irreversible sinks for other, often more deleterious pollutants. These enriched carbonaceous sites can scavenge other point source and surface runoff chemicals such as pesticides, PCB's, and organometallic compounds that are loosely bound to suspended solids. As a result, naturally occurring remedial processes such as dispersion by hydraulic transport, volatilization, photodegradation, and biodegradation, are suppressed (personal observations, M. Wood). High organic carbon sediments can also become toxic hotspots for hydrophobic pollutants through equilibrium with the water column. Ultimately, such areas can require sediments removal or other remediation due to the acquired toxic burden unrelated to the original petroleum spill event. Otherwise, these toxic sediments can be moved into formerly unpolluted areas by maintenance dredging, navigation, and storms. Also, toxins can enter the food chain by way

of particle feeders. Thus, cleanup of crude oil spills is especially critical in marshes and other shallow water habitats.

Metal components of crude oil and petroleum hydrocarbons are prone to accumulate in marshes because marsh soils generally contain large amounts of silts, clays, and organic matter. These fine textured particles have a greater affinity for all classes of contaminants than sand particles (EPA 1991). Organic matter in the form of humic and fulvic acids greatly increases the affinity of sediments for some metals and nonpolar organics (EPA 1991, Robotham and Gill 1989). Fresh, intermediate, brackish, and saline marsh soils have different amounts of mineral and organic matter Nyman et al. 1990) and Lin and Mendelssohn (1996) found that soil organic matter content was positively correlated with the amount of crude oil persisting in soil plugs after 4 months.

Few studies have examined the effects of petroleum hydrocarbons on marsh biogeochemical cycling. Crude oil can have dramatic effects on soil Eh when it prevents oxygen from entering the water (DeLaune et al. 1979), and Nyman and Patrick (1985) found temporary Eh decreases in fresh marsh soils incubated for 6 months with South Louisiana crude and Arabian crude oils. Nyman and Patrick (1995) also found that those crude oils greatly but temporarily stimulated soil respiration, which would imply increased nutrient remineralization rates. Li et al. (1990) found that chronic exposure of Atlantic coast salt marshes to a selected set of hydrocarbons stimulated soil respiration. Similar data are lacking from intermediate, brackish and more organic saline marshes typical of the Gulf coast and no data are available on the effects of refined hydrocarbons on marsh soil respiration or nutrient remineralization rates.

The balance between nitrogen fixation and denitrification is an especially critical aspects of ecosystem function. Petroleum hydrocarbons sometimes stimulate nitrogen fixation in lake and stream sediments (Shales et al. 1989) and might support eutrophication but there has been only one study in using coastal marsh soils. Li et al. (1990) simulated chronic exposure of Atlantic coast type salt marsh to petroleum hydrocarbons and found that both nitrification and denitrification were stimulated at low levels, but inhibited both at high levels; actual effects on N fluxes could not be estimated however. No similar studies on nitrogen cycling have been conducted with higher soil organic matter salt marshes typical of the Gulf Coast or with fresh, intermediate, and brackish marshes.

A research program to understand the long-term effects of petroleum hydrocarbons on nutrient cycling in the different marsh types is needed. Information on the effects of different petroleum hydrocarbons and response activities on soil respiration, nitrogen cycling, phosphorus cycling, and soil Eh in the different marsh types is needed as is information on the effects of different marsh types on the persistence and toxicity of different petroleum hydrocarbons following different response activities. Also, in situ or off-site chemical techniques are needed to treat highly weathered crude oils and highly organic soils that have scavenged other pollutants from the water column.

LITERATURE CITED

- Alexander, S.K., and J.R. Schwarz. 1980. Short-term effects of South Louisiana and Kuwait crude oils on glucose utilization by marine bacterial populations. *Applied and Environmental Microbiology*. 40:341-345.

- Burns, K.A., and J.M. Teal. 1979. The West Falmouth oil spill: hydrocarbons in the salt marsh ecosystem. *Estuarine and Coastal Marine Science*. v8, pp. 349-360.
- DeLaune, R.D., W.H. Patrick, Jr., and R.J. Buresh. 1979. Effect of crude oil on a Louisiana *Spartina alterniflora* salt marsh. *Environmental Pollution*. 1979:21-31.
- DeLaune, R.D., C.J. Smith, W.H. Patrick, Jr., J.W. Fleeger, and M.D. Tolley. 1984. Effect of oil on salt marsh biota: methods for restoration. *Environmental Pollution (A)*. 36:207-227.
- EPA. 1991. Handbook Remediation of Contaminated Sediments. Center for Environmental Research Information, Office of Research and Development, U.S. Environmental Protection Agency. EPA/635/6-91/028. Cincinnati, Ohio.
- Knox, G.A. 1986. Estuarine ecosystems: a systems approach. Volume II. CRC Press, Inc. Boca Raton FL.
- Lin, Q. and I.A. Mendelssohn. 1996. A comparative investigation of the effects of South Louisiana Crude oil on the vegetation of fresh, brackish, and salt marshes. *Marine Pollution Bulletin* 32: 202-209.
- Li, Y., J.T. Morris, and D.C. Yoch. 1990. Chronic low level hydrocarbon amendments stimulate plant growth and microbial activity in salt marsh microcosms. *J. Applied Ecology* 27:159-171.
- Nyman, J.A., R.D. DeLaune, and W.H. Patrick, Jr. 1990. Wetland soil formation in the rapidly subsiding Mississippi River Deltaic Plain: mineral and organic matter relationships. *Estuarine, Coastal and Shelf Sci.* 31:57-69.
- Nyman, J.A., and W.H. Patrick, Jr. 1995. Effects of oils and chemical responses on fresh marsh function and oil degradation: response implications. Louisiana Oil Spill Coordinator's Office/Office of the Governor, Louisiana Applied Oil Spill Research and Development Program, Baton Rouge, Louisiana. 68pp.
- Robotham, P.W.J. and R.A. Gill. 1989. Input, behaviour and fates of petroleum hydrocarbons, pages 41-79 In J. Green and M.W. Trett (eds.) *The Fate and Effects of Oil in Freshwater*. Elsevier Applied Science. New York. 316pp.
- Shales et al. 1989. Biological and ecological effects of oils, pages 81-171 In J. Green and M.W. Trett (eds.) *The Fate and Effects of Oil in Freshwater*. Elsevier Applied Science. New York. 316pp.

Use of Cleaners in Removing Oil from Marsh Plants: Reponse of Selected U.S. Gulf Coast Species

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INTRODUCTION

U.S. Gulf Coastal marshes, composed of diverse and productive macrophyte species, are important components of riverine, estuarine, and coastal ecosystems. In addition, coastal marshes are important in shoreline protection from wave actions (Webb 1977), provide fish and wildlife habitats, and improve water quality (Mitsch and Gosselink 1993). Thus, there is generally great public attention and pressure to minimize negative impacts of oil in these ecosystems. However, a significant amount of petroleum is refined, stored, or transported through these marshes thus some marshes are subject to occasional fouling with oil.

The adverse effects of oil on marsh vegetation range from short-term reductions in photosynthesis to mortality (Baker 1970, DeLaune et al. 1979, Alexander and Webb 1985, Pezeshki and DeLaune 1993). This may in turn affect adjacent aquatic habitats because marsh vegetation provides detritus to food webs (Mitsch and Gosselink 1993). Oil may also adversely affect soil microbial communities. Burns and Teal (1979) found that oil persisted in saltmarsh sediments even seven years after an oil spill. The microbial community is important because it regulates the flow of energy from plants to food webs and also controls nutrient regeneration in marsh soils, which affects plant growth (Knox 1986). Thus, oil may have long-term effects on marsh functions even after plant growth resumes.

Mechanical and chemical methods are available to minimize negative effects of oil in wetlands. Oil can be physically removed from the wetland or concentrated with absorbent materials or burned. But wetlands are particularly vulnerable to mechanical damage during removal operations (OTA 1990). Determining a cleaning strategy therefore involves considerations of trade-offs balancing physical damage to the marsh and oil toxicity. Short-term damage to wetland ecosystems can be acceptable when it prevents long-term ecological impacts (Johnson and Pastorok 1985). Under certain circumstances, no action may be the best approach because physical damage and toxicity problems associated with the available cleaning techniques may be greater than allowing the oil to remain in the wetland (OTA 1990, Mearns 1993). However, the need exists for techniques that reduce adverse impacts of oil on wetlands without causing additional impacts, toxicity problems, or adversely affecting adjacent ecosystems.

EFFECTS AND EFFECTIVENESS OF CLEANERS

Cleaners and dispersants have been proposed as means of removing oil from affected wetlands and a number of commercial cleaners are available. The use of this method; however, require careful considerations since certain cleaners and dispersants may be toxic to various organisms (Fingas et al. 1989, Daniels 1994). COREXIT 9580 shoreline cleaner, developed during the cleanup in Alaska of the Valdez spill (Fiocco et al. 1991), is a low toxicity, low dispersion cleaner. The cleaning effectiveness and low toxicity of COREXIT 9580 have been reported by Environment Canada (see Fingas et al. 1989 for detail). The cleaner has been previously used to remove oil from plants. Teas et al. (1993) showed that COREXIT 9580 prevented mortality of oiled red mangroves (*Rhizophora mangle*) by removing oil that otherwise suffocated roots. Pezeshki et al. (1995) studied the effectiveness of COREXIT 9580 in removing oil from *Spartina alterniflora* foliage. The cleaner was effective in removing oil from the leaf and shoot surfaces. The overall responses of gas exchange in *S. alterniflora* (Figure 1) shows that the cleaner was effective in removing different types of oil and improved short-term plant functioning as indicated by the greater stomatal conductance. Similar findings were reported for stomatal conductance and net photosynthesis in *S. alterniflora* as compared to plants that were oiled and not cleaned (Pezeshki et al. 1995). The cleaner also appeared to have a delayed, temporary adverse effect on plant photosynthetic functions. Application of cleaner alone did not affect leaf conductance in *S. alterniflora* but resulted in significant reductions in net photosynthesis. However, the authors noted that while there were reductions in net photosynthesis in response to cleaner application, plants treated with “cleaner only” or “oiled and cleaned” did not show massive leaf death as seen in the “oiled” plants. Similar results were reported for use of COREXIT 9580 on *S. alterniflora* plants after oiling with with 33% weathered South Louisiana Crude and Bunker C oil. Even though the Bunker C formed an extremely thick coating on *S. alterniflora* plants, the cleaner was effective in removing the oil from plant foliage. Plants in the “oil only” treatment had massive leaf death and did not recover during the study. On the other hand, plants in “oiled and cleaned” treatment recovered and there were no apparent differences between them and the control plants after 8 weeks.

SPECIES SENSITIVITY DIFFERENCES

U.S. Gulf Coastal marshes are composed of diverse macrophyte species occupying various ecological zones including salt, brackish and freshwater habitats. Generally, the species diversity is greater in freshwater zone. These species have different foliage characteristics and may respond to the chemicals in oil and cleaners differently. Thus information is needed on the potential differences among various U.S. Gulf coast species to different oil types that are being transported in the area. In addition, data is needed on the effectiveness of cleaners in removing oil from vegetation and the potential sensitivity of various species during different seasons particularly during the growing season, to the cleaners. In a recent study, Pezeshki et al. (1995) used a 13% weathered South Louisiana Crude Oil on *S. alterniflora*. The oiling appeared to have toxic effects on plants but new leaves quickly appeared. The cleaner removed almost all visible traces of oil from the foliages. The application of cleaner after 1 day and 2 days had similar effects on plant gas exchange but cleaning after 1 day resulted in significant improvement

on the recovery rates of plant photosynthesis relative to plants cleaned after 2 days. Thus the timely use of cleaner had minimized the initial adverse effects of oiling in *S. alterniflora*.

The effects of COREXIT 9580 in removing oil from leaf surfaces thus restoring stomatal conductance pathway of oiled *S. alterniflora*, *Spartina patens*, and *P. hemitomon* were studied in a greenhouse. Marsh soil-plant plugs were collected from Louisiana coastal region and placed in a greenhouse. Plant leaves were coated with South Louisiana crude oil. One day following the oiling treatment, plants were sprayed with COREXIT 9580 solution and flushed with water. Using COREXIT 9580 helped restore stomatal functions in all of the study species (Figure 2). The data reflects the improvement in stomatal functions of those leaves that existed and were subjected to the treatments. It does not reflect the functioning of new leaves developed from regeneration of new tillers that germinated during post-treatment period. Significant recovery was observed under oiled treatments as was evident from stomatal conductance measurements on newly developed leaves, regeneration of new shoots, and leaf sheaths elongation rate. Similar results were obtained using COREXIT 9580 to remove Bunker C oil from *S. alterniflora* plants (Figure 3). Plant photosynthetic rates were significantly greater in "Oiled+Cleaner" treatment than "Oiled" treatment. While the results demonstrate the beneficial effects of using COREXIT 9580 for oil removal in study species, additional test is needed to evaluate the overall effects of this cleaner on other plant species and the associated organisms under field conditions.

SHORT-TERM vs. LONG-TERM RESPONSES TO OILING AND CLEANER APPLICATION

Although the initial, short-term adverse effects of oil on plants appear to be dramatic, plants may recover in the long-term. Such recovery may be species specific and may depend on the type of oil, the mode of delivery, the timing, the amount of oil, etc. For instance, oiled *S. alterniflora* plants initially showed a high percentage of mortality but recovered two months after oil application. Natural shoot regeneration and leaf development replaced dead foliages and no differences in biomass among the treatments were found (Pezeshki and DeLaune 1993, Pezeshki et al. 1995). Complete oiling of *S. alterniflora* plants with 33% weathered South Louisiana Crude initially caused massive, rapid death to all existing leaves (Pezeshki et al 1995). Leaf death in the "oiled and cleaned" plants did not appear as extensive as in the "oiled only" plants. Preventing death of oiled leaves resulting from cleaner application is significant because the living tissues continued to photosynthesize and function, albeit at a slower rate than unoiled vegetation, as was evidenced from the live above-ground biomass accumulation (Figure 4). This continued functioning had likely enhanced production of new leaves that replaced oiled leaves. In addition, photosynthetic rates of cleaned leaves were significantly greater than in uncleaned leaves. However, during the second month, the gas exchange measurements conducted on leaves that had emerged after the treatment initiation showed that the newly emerged leaves had similar gas exchange rates to that of control plants. This finding indicated that the adverse effects of oiling on photosynthesis of *S. alterniflora* may be short-term. After two months, plants in "oiled" treatment appeared to recover as was evidenced from production of new leaves by the existing shoots and regeneration of new shoots. This finding is in agreement with previous work by DeLaune et al. (1979), Smith et al. (1984), and Pezeshki and DeLaune (1993) who also found that under greenhouse conditions *S. alterniflora* and *Juncus roemerianus* plants recovered from oiling with South Louisiana Crude. However, this was not the case when *S. alterniflora*

plants were oiled with Bunker C. The treatment resulted in complete plant mortality and no apparent recovery (Pezeshki et al 1995). Such response further underlined the fact that various crude oils may have different impacts on a given species.

RESPONSE IMPLICATIONS

In responding to oil spills in U.S. Gulf coast marshes, the responding agency should consider a number of important variables including the amount and the type of oil involved, vegetation types, the season, the habitat sensitivity to physical impacts of cleaning operations, and the porportion of plant canopy that is covered by the oil. Proper considerations given to these variables is critical. For instance the timing of oil spill is critical. The adverse effects on *S. alterniflora* was more severe during the spring than fall or during the dormant season (Webb 1994). This is because plants are growing actively during the spring season whereas in the fall, most plants are undergoing dormancy. Similar difference in seasonal effects are expected for other marsh species.

As was pointed out elsewhere in this manuscript, the oil type is also important. For instance, *S. alterniflora* marshes oiled with South Louisiana Crude may recover without cleaning (Pezeshki et al. 1995). On the other hand, the same species oiled with Bunker C may require cleaning to survive. In general, light oils appear to kill plant tissue on contact while crude oil effectively prevent plant gas exchange (Pezeshki and DeLaune 1993, Webb 1994). Regardless of the type of oil to be cleaned, it appears that if the use of the cleaner is feasible, then it should be applied as soon as possible following an oil spill to minimize oil penetration into the sediment, to prevent massive plant tissue death, and to speed up the recovery of plant normal gas exchange functioning. Marsh plants fouled with South Louisiana Crude and Bunker C benefited from cleaning with COREXIT 9580, but the variations in the level of toxicity of the different oils suggests different response strategies when resources are limited. For example, when *S. alterniflora* marshes are fouled with South Louisiana Crude, limited resources might best be spent on other aspects of cleaning because the marsh plants will recover as shown by the previous studies (DeLaune et al. 1979, Smith et al. 1984). However, when *S. alterniflora* marshes are fouled with Bunker C, limited resources might best be spent on cleaning the marsh because the marsh may not recover otherwise.

Specific data are needed to determine the toxicity of various oils and cleaners to other important US Gulf coastal marsh plant species under field conditions before response strategies can be formulated for other marsh types and other oil types. Recognizing the need, we have established field plots in fresh, brackish, and salt marsh habitats at the Pointe aux Cheins Wildlife Refuge Management Area in Louisiana coastal marshes. In these experimental oil spill plots, we plan to evaluate the reported results from previous laboratory and greenhouse studies under natural field conditions. When these field studies are complete, protocols will be developed for the use of cleaners in various marsh communities which may become fouled with different types of crude oil.

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REFERENCES

- Alexander, S.K., and J.W. Webb, Jr. 1985. Oil in the salt marsh: what have we learned?. In C.F. Bryan et al. (eds.) Proceedings of the Fourth Coastal Marsh and Estuary Management Symposium. Louisiana State University Printing Office. Baton Rouge, Louisiana, pp. 49-62.
- Baker, J.M. 1970. The effects of oil on plants. *Environmental Pollution*. v1, pp. 27-44.
- Burns, K.A., and J.M. Teal. 1979. The West Falmouth oil spill: hydrocarbons in the salt marsh ecosystem. *Estuarine and Coastal Marine Science*. v8, pp. 349-360.
- Daniels, C.B., 1994. Toxicity of dispersants. Symp. Proc. Gulf of Mexico and Caribbean Oil Spill in Coastal Ecosystems: Assessing Effects, Natural Recovery, and Progress in Remediation Research. US Dept. Interior, Minerals Mgt. Ser. OCS Study/MMS 95-0063, New Orleans, LA, pp. 240--242.
- DeLaune, R.D., W.H. Patrick, Jr., and R.J. Buresh. 1979. Effect of crude oil on a Louisiana *Spartina alterniflora* salt marsh. *Environmental Pollution*. 1979:21-31.
- Fingas, M. F., G. Stoodley, G.Haris and A. Hsia. 1989. Evaluation of chemical beach cleaners. Cleanup Technology Workshop, Anchorage, Alaska, November 28-30.
- Fiocco, R.J., G.P. Canevari, J.B. Wilkinson, H.O. Jahns, J. Bock, M. Robbins, and R.K. Markarian. 1991. Development of COREXIT 9580 - a chemical beach cleaner. Pages 395-400. In, Proc. 1991. Oil Spill Conf. American Petroleum Institute, Washington D.C
- Johnson, T.L., and R.A. Pastorok. 1985. Oil spill cleanup! Options for minimizing adverse ecological impact. American Petroleum Institute. Publication No. 4435.
- Knox, G.A. 1986. Estuarine ecosystems: a systems approach. Volume II. CRC Press, Inc. Boca Raton FL.
- Mearns, A.J. 1993. Recovery of shoreline ecosystems following the Exxon Valdez oil spill and subsequent treatment. Pages 466-479. In O.T. Magoon, (ed.), Coastal Zone '93 Volume I. American Society of Civil Engineers, New York.
- Mitsch, W.J., and J.G. Gosselink. 1993. Wetlands. Van Nostrand Reinhold Co. New York.
- OTA. 1990. Coping with an oiled sea. U.S. Congress, Office of Technology Assessment. OTA-BP-O-63. U.S. Government Printing Office, Washington D.C.

- Pezeshki, S.R., and R.D. DeLaune. 1993. Effect of crude oil on gas exchange functions of *Juncus roemerianus* and *Spartina alterniflora*. *Water, Air, and Soil Pollution* 68: 461-468.
- Pezeshki, S.R., R.D. DeLaune, J.A. Nyman, R.R. Lessard, G.P. Canevari. 1995. Removing oil and saving oiled marsh grass using a shoreline cleaner. Pages. 203-209. In, Proc. of the International Oil Spill Conf., Amer. Petrol. Inst., Publ. No., 4620.
- Smith, C.J., R.D. DeLaune, W.H. Patrick, Jr., and J.W. Fleeger. 1984. Impact of dispersed and undispersed oil entering a Gulf Coast salt marsh. *Environmental Toxicology and Chemistry* 3:609-616.
- Teas, H.J., R.R. Lessard, G.P. Canevari, C.D. Brown, and R. Glenn. 1993. Saving oiled mangroves using a new non-dispersing shoreline cleaner. Pages 147-151. In, Proc. Oil Spill Conf. American Petroleum Institute, Washington D.C.
- Webb, J.W., 1977. Establishment of vegetation for shoreline stabilization in Galveston Bay, Texas. Ph.D. Dissertation, Texas A&M Univ., College Station, Texas, pp. 136.
- Webb, J.W., 1994. Effects of oil on saltmarshes. pp. 55-61. In, C.E. Proffitt and P.F. Roscigno (eds.). Symp. Proc. Gulf of Mexico and Caribbean Oil Spill in Coastal Ecosystems: Assessing Effects, Natural Recovery, and Progress in Remediation Research. US Dept. Interior, Minerals Mgt. Ser. OCS Study/MMS 95-0063, New Orleans, LA.

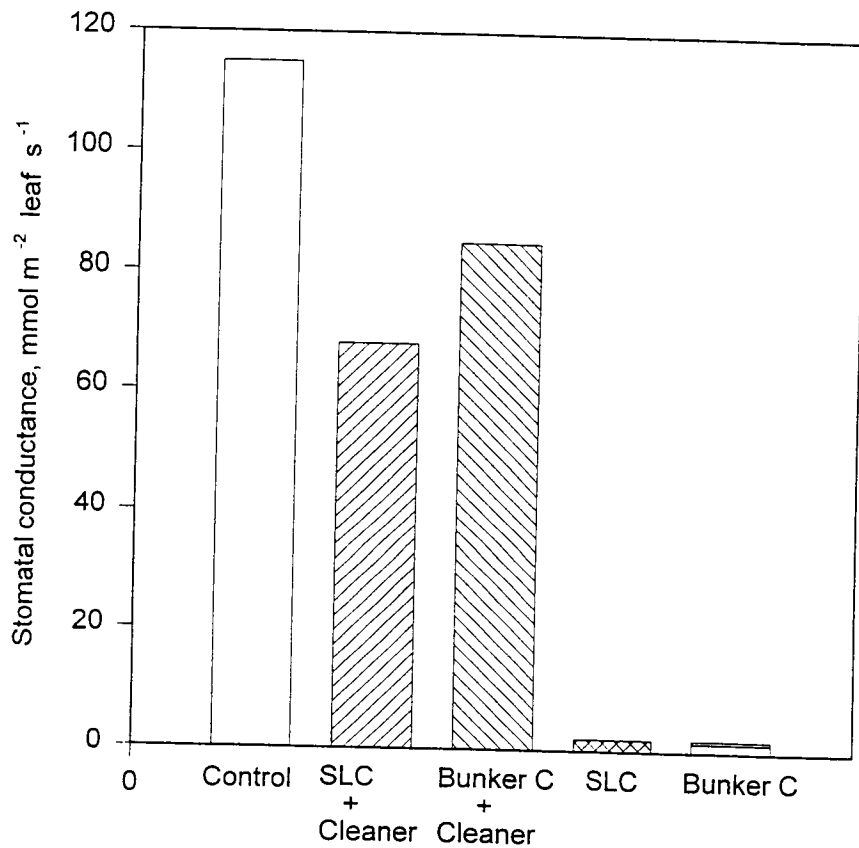


Figure 1. Responses of stomatal conductance in *Spartina alterniflora* to various oil types, oil+cleaner (COREXIT 9580), and control. The oil types included South Louisiana Crude oil (SLC) and Bunker C oil. The leaves were initially coated with oil. Stomatal data were collected on leaves that existed at the time of treatment initiation and were initially coated with oil. Stomatal measurements were conducted 28 days after treatment initiation. Values are the mean for six replications.

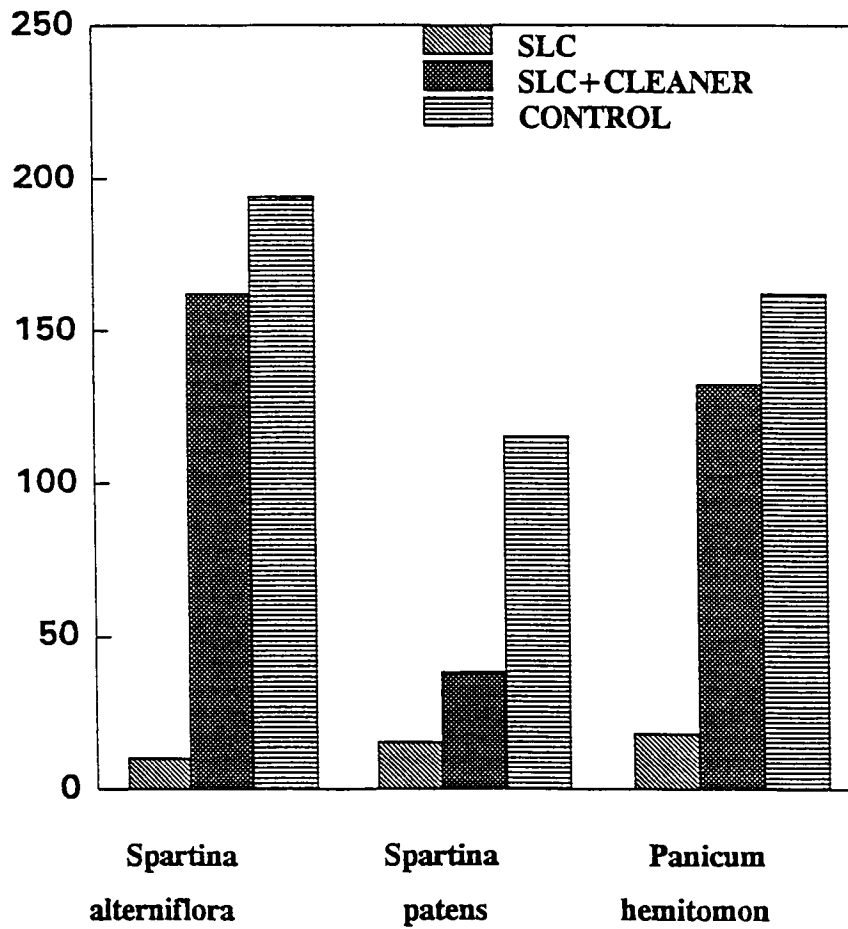


Figure 2. Effect of COREXIT 9580 on restoring stomatal conductance of oiled *Spartina alterniflora*, *S. patens*, and *Panicum hemitomon*. Data were collected on leaves that existed at the time of treatment initiation and were coated initially with oil. The leaves were coated with South Louisiana Crude oil. Stomatal measurements were conducted 58 days after initial treatment. Values are the mean for five replicated measurements.

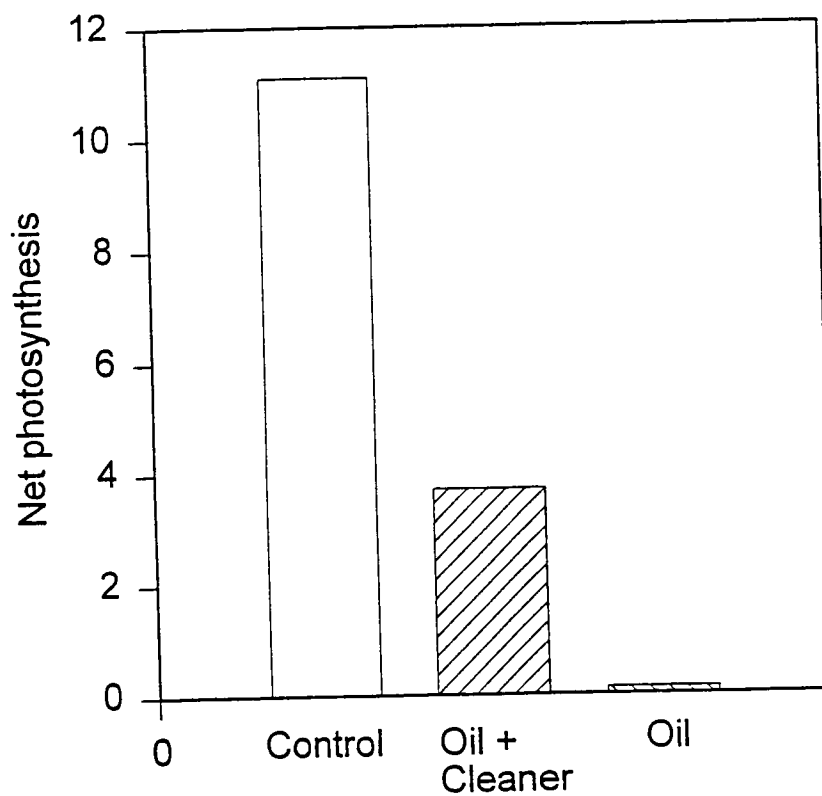


Figure 3. Responses of net photosynthesis ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ leaf area s}^{-1}$) in *Spartina alterniflora* to Bunker C oil, oil+cleaner (COREXIT 9580), and control. The leaves were initially coated with oil. Photosynthetic measurements were conducted on leaves that existed at the time of treatment initiation. Photosynthetic measurements were conducted 14 days after treatment initiation. Values are the mean for six replications.

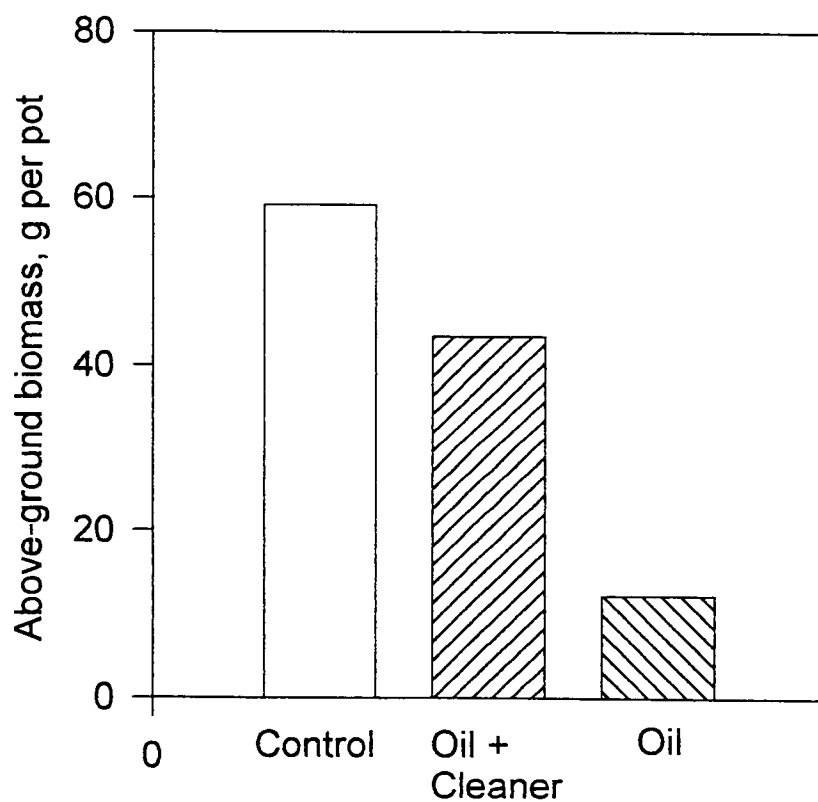


Figure 4. Above-ground live biomass accumulation in *Spartina alterniflora* eight weeks after treatment. Data were collected on plants coated with Bunker C oil. The cleaner, COREXIT 9580, was applied to plants one day after initial oiling. Values are the mean for six replicated pots (Redrawn from Pezeshki et al. 1995).

In-situ Burning of Oiled Wetlands as a Cleanup Technique

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INTRODUCTION

In-situ burning of oil in sensitive wetland environments provides a potentially attractive alternative to other oil spill cleanup methods that often result in substantial habitat damage beyond the impact of the oil. Recently, Mendelssohn et al. (1995) examined the environmental effects and effectiveness of in-situ burning in oiled wetlands by reviewing existing literature and conducting field samplings of in-situ burn sites in different marsh plant communities. They concluded that in-situ burning in oiled wetlands does represent a viable alternative to other oil spill cleanup techniques under some, but not all circumstances. Mendelssohn et al. (1995) recommend that in-situ burning as an oil spill cleanup technique should be considered on a case by case basis and that careful consideration be given to biotic and abiotic factors at the spill site that can influence the success of this technique. It has become apparent that many of the factors that influence successful burning of marshes as a management tool directly relate to the success of in-situ burning of oil in wetlands (Mendelssohn et al. 1995, Nyman and Chabreck 1995).

In this section, we have provided a brief overview of burning in wetlands with emphasis placed on the plant community and the most important factors to consider when contemplating in-situ burning as an oil spill cleanup technique. This information is largely based on documents by Mendelssohn et al. (1995), who, as mentioned above, recently evaluated the environmental effects and effectiveness of in-situ burning of oiled wetlands as a cleanup technique, and Nyman and Chabreck (1995), who recently reviewed the role of fire in Gulf coast marshes. Additional, general information on the effects of fire on ecosystems can be found in a book edited by Kozlowski and Ahlgren (1974) and in an annotated bibliography by Kirby et al. (1988) on fire in wetland ecosystems.

Fire is an important part of coastal marsh ecosystems and is also a traditional management tool (Nyman and Chabreck 1995). Prescribed burning is used in some tidal fresh marshes to prevent invasion by shrubs, and in some intermediate and brackish marshes to increase the production of preferred wildlife food plants. Export of litter by tidal action often prevents accumulation of sufficient fuel to carry a fire in saline marshes (Nyman and Chabreck 1995). Furthermore, salt marshes have generally not been as intensively managed as fresh marshes, resulting in progressively less information on the effects of burning along the gradient from fresh to brackish to salt marshes (Mendelssohn et al. 1995). Although prescribed burning

is only beginning to be critically evaluated as an oil spill cleanup technique, it appears that burning can enhance oil removal and allow plant recovery if the normal guidelines for prescribed burning in coastal marshes are followed in conjunction with site-specific considerations at the spill site. However, it should be kept in mind that critical evaluations of the effects and effectiveness of in-situ burning in oiled wetlands are often compromised due to absence of data on the pre-spill plant community and/or lack of appropriate (oiled, but not burned) controls at the site (Mendelsohn et al. 1995).

Although all burning results in an immediate short-term reduction in plant cover, favorable recovery of herbaceous wetland plant species often takes place within one to five years. However, recovery rates can be quite variable and "complete" recovery may take as long as a decade (Mendelsohn et al. 1995). In general, in-situ burning of forested (or shrub) wetlands should be avoided due to the long recovery time required to re-establish mature stands. Poor recovery of herbaceous wetland vegetation following burning is often related to fire damage to the roots (root burns) or to the roots and soil (peat burns) if the marsh surface is not flooded (or at least saturated) at the time of the burn (Mendelsohn et al. 1995, Nyman and Chabreck 1995). Another important factor that can adversely affect vegetative recovery is a post-burn increase in water level above the burnt stubble, which limits air transport to the belowground tissues and can cause oxygen stress and potentially death during periods of prolonged post-burn inundation (Mendelsohn et al. 1995, Nyman and Chabreck 1995).

Although there is much variation in the effect of season and the success of in-situ burning of oiled marshes, it seems that summer is consistently the worst time to burn (Mendelsohn et al. 1995). Therefore, as a general recommendation, spring and summer burns should be avoided (Mendelsohn et al. 1995; Nyman and Chabreck 1995). For optimal plant recovery, burning should only be done during periods of plant dormancy (or low growth), such as fall and winter, with moderate steady wind, and when water is on the marsh surface (Mendelsohn et al. 1995, Nyman and Chabreck 1995). Furthermore, late fall burns may be better than early fall burns, simply because plants will have more time to translocate nutrients and carbohydrate reserves to their belowground tissues before senescing (or being burned), thereby ensuring sufficient belowground reserves for vigorous regrowth the following spring (Mendelsohn et al. 1995). Below we have provided an abbreviated guideline and rationale for when to burn, or not to burn, an oiled wetland based on the criteria of wetland type, season, water level, and wind speed.

ABBREVIATED GUIDELINES FOR IN-SITU BURNING OF OILED WETLANDS

I. Wetland Type

- A. Herbaceous wetlands (marshes) are the best candidates for in-situ burning.
- B. Forested (or shrub) wetlands are not recommended for in-situ burning.

Rationale - very long recovery times for recovery of mature plant community in forested, wooded wetlands.

II. Season

- A. Late fall and winter burns are best for in-situ burning.
- B. Periods of new growth (spring) and active or non dormant growth (summer) are not recommended.

Rationale - Periods of plant dormancy or of little plant growth are best. Belowground plant reserves for regrowth are generally highest in the late fall and winter. Also, spring and summer often correspond to periods of wildlife nesting and young, vulnerable offspring.

III. Water Level

- A. In-situ burning should be done only when water levels in the marsh are several centimeters above the marsh surface, or at least at the marsh surface.
- B. Never burn during drought conditions.
- C. Never burn when a substantial rise in water levels is expected within a few weeks of the burn.

Rationale - Inadequate water levels at the time of burning may result in heat damage to the plant roots (and belowground storage organs). Low water levels can result in burning of the marsh substrate (peat burns), resulting in loss of marsh surface elevation and increased flooding stress on vegetation. A substantial rise in post-burn water levels can result in stress and/or death of emerging vegetation due to insufficient oxygen transport to belowground tissues.

IV. Wind Speed

- A. A moderate steady wind is preferred for in-situ burning.
- B. Never burn during strong, gusty winds.
- C. Never burn during dead calm conditions.

Rationale - During high winds, the fire may be difficult to control, especially where fuel loads are high, or parts of the marsh may fail to burn where fuel loads are low. During calm conditions, root damage can result where fuel loads are high, or the fire may fail to carry or burn incompletely where fuel loads are low.

More research is needed to adequately evaluate the effectiveness of in-situ burning in oiled wetlands and to further assess potential environmental consequences of utilizing this technique in the cleanup of oil-impacted marshes. Our knowledge on this subject may best be enhanced through controlled field burns with (1) pre-spill site characterization (vegetation, soil, elevation), (2) adequate controls (unoiled/unburned and oiled/unburned), and (3) time series monitoring of plant responses, soil variables, and oil degradation rates and by-products.

LITERATURE CITED

- Kirby, R.E., S.J. Lewis, and T.N. Sexton. 1988. Fire in North America wetland ecosystems and fire-wildlife relations: an annotated bibliography. U.S. Fish and Wildlife Service, Biological Report 88(1).
- Kozlowski, T.T. and C.E. Ahlgren, eds. 1974. Fire and ecosystems. Academic Press, New York, NY.

Mendelssohn, I.A., M.W. Hester, and J.W. Pahl. 1995. Environmental effects and effectiveness of in-situ burning in wetlands: Consideration for oil spill cleanup. Louisiana Oil Spill Coordinators Office/Office of the Governor, Louisiana Applied Oil Spill Research and Development Program, Baton Rouge, Louisiana, 57 pp.

Nyman, J.A., and R.H. Chabreck. 1995. Fire in coastal marshes: history and recent concerns. Pages 143-141. In, S.I. Cerulean and R.T. Engstrom, eds. Fire in wetlands: a management perspective. Proceedings of the Tall Timbers Fire Ecology Conference, No. 19. Tall Timbers Research Station, Tallahassee, FL.

Phytoremediation: A Bioremediation in the Rhizosphere

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REVIEW

Bioremediation is a low-impact technology that attempts to accelerate the natural degradation process by overcoming factors that limit microbial hydrocarbon degrading activities. Generally, the factors having the greatest influence on oil degradation in the sediment are soil water content, inorganic nutrient supply, pH, concentration of the pollutants, the sorption and water solubility of the pollutants, and the presence of an acclimated microbial population (Alexander 1989, Balba et al. 1991, Mahaffey et al. 1991). In the bioremediation operation, the most common agents used to enhance oil degradation are fertilizers, aeration, and microbial seeding. Bioremediation has been applied to treat various contamination, such as cleanup for hazardous waste sites, underground water contaminants, and oil spill in coastal environments (Alexander 1989, Balba et al. 1991, Lindstrom et al. 1991, Lantz 1991, Fayad et al. 1992, Altas 1993, Bragg et al. 1993, Hicks and Caplan 1993, Cerniglia 1993, Kennedy and Hutchins 1993). Recent research (Mendelssohn et al. 1995) has shown the positive effects of addition of fertilizers and soil oxidant on oil bioremediation in salt marsh mesocosms. Application of nitrogen and phosphorus increased soil microbial respiration. Addition of fertilizers and soil oxidant significantly increased soil microbial respiration rate, the numbers of petroleum hydrocarbon degraders, and enhanced biodegradation of the petroleum hydrocarbons in the salt marsh sediment. However, so far, little investigation has been conducted to study the influence of vegetation present on oil bioremediation.

Phytoremediation, the use of vegetation for the in-situ treatment of contaminated soil and sediment, is an emerging technology that promises effective and inexpensive cleanup of certain hazardous wastes (Stomp et al. 1993, Schnoor et al. 1995). Phytoremediation applies to all plant-influenced biological, chemical, and physical processes that aid in remediation of contaminated substrates (Cunningham and Breti 1993). The phytoremediation technology has already been shown to be effective for the removal of both inorganic (Dierberg et al. 1987, Jain et al. 1989, Mo et al. 1989, Brown et al. 1995, Salt et al. 1995 and others) and organic pollutants (Anderson and Walton 1992, Bell 1993, Nair and Schnoor 1994), including polycyclic aromatic hydrocarbons (PAHs) (Wild et al. 1992, Banks and Schwab 1993).

One of the major fates of the spilled petroleum oil in the coastal environment is its incorporation into sediments (Alexander and Webb 1987). Microbial activities in rhizosphere could be important in biodegradation of oil in the wetland sediment. However, the knowledge of interaction between soil microbes and plant rhizosphere in bioremediation for the coastal marsh oil spill is limited. Critical evaluation of the influence of vegetation

present on oil biodegradation, especially the influence of the plant rhizosphere on microbial degradation of oil in the wetland sediment is lacking in the published literature. To maximize the efficacy of bioremediation, the gap of lacking the knowledge of phytoremediation for oil spill in wetland is necessary to fill. Therefore, the investigation of phytoremediation for oil spill in wetlands is needed to be included in the future MMS research plan.

REFERENCES

- Alexander, S.K. and J.W. Webb. 1987. Relationship of *Spartina alterniflora* growth to sediment oil content following an oil spill. Pages 445-449. In, Proceeding of the 1987 Oil Spill Conference, American Petroleum Institute, Washington, D.C.
- Alexander, M. 1989. Biodegradation of Chemicals at Trace Concentrations. Army Research Office, Research Triangle Park, NC. Report No. ARO-23543.19-LS, 28 pp.
- Anderson, T.A. and B.T. Walton. 1992. Comparative plant uptake and microbial degradation of trichlorethylene in the rhizospheres of five plant species-implications for bioremediation of contaminated surface soils. Oak Ridge, TN: Oak Ridge National Laboratory. Environmental Science Division, Pub.3809. ORNL/TM-12017, 1992.
- Atlas, R.M. 1993. Bacteria and bioremediation of marine oil spills. *Oceanus*, 36:2:71-73.
- Balba, M. T., A.C. Ying and T.G. McNeice. 1991. Bioremediation of contaminated soil: strategy and case histories. Pages. 235-241. In, Proceedings of the HMC-South 91: Hazardous Waste, Hazardous Materials/Hazardous Materials Control (HWHM/HMC) Conference, April 24-26 1991, Houston, TX.
- Banks, K.M. and Schwab, A.P. 1993. Dissipation of polycyclic aromatic hydrocarbons in the rhizosphere. Page 246. In, Symposium on bioremediation of hazardous wastes: research, development and field evaluations, Washington, DC: Environmental Protection Agency, EPA/600/R-93/054.
- Bell, R.M. 1993. Higher plant accumulation of organic pollutants from soils. USEPA, Risk Reduction Engineering Lab. EPA/600/SR-92/138.
- Bragg, J.R., Prince, R.C., Harner, E.J and Atlas, R.M. 1993. Bioremediation effectiveness following the Exxon Valdez spill. Pages 435-446. In, Proceedings of the 1993 Oil Spill Conference - prevention, preparedness, response. Tampa, FL.
- Brown, S.L., Chaney, R.L., Angle, J.S. and Baker, A.J.M. 1995. Zinc and cadmium uptake by hyperaccumulator *Thlaspi caerulescens* grown in nutrient solution. *Soil Sci. Soc. Am. J.*, 59:125-133.

- Cerniglia, C.E. 1993. Oxidative biodegradation pathways of PAHs. Page 245. In, Proceedings of the Symposium on Bioremediation and Bioprocessing presented at the 205th National Meeting of the American Chemical Society, Denver, CO.
- Cunningham, S.D. and W.R.Berti. 1993. Remediation of contaminated soil with green plants: an overview. *In Vitro Cellular and Developmental Biology-Plant*. 29:207-212.
- Dierberg, F.E., T.A. DeBusk, and N.A. Goulet, Jr. 1987. Removal of copper and lead using a thin-film technique. Pages 497-504. In, Aquatic Plants for Water Treatment and Resource Recovery. Reddy, K.B. and Smith, W.H. (eds.). Magnolia Publishing Inc. FL.
- Fayad, Nabil M., L. Edora, H. El-Mubarik, and B. Polancos, Jr. 1992. Effectiveness of bioremediation product in degrading the oil spilled in the 1991 Arabian gulf war. *Bull. Environ. Contam. Toxicol.* 49:787-797.
- Hicks, B.N., and J.A. Caplan. 1993. Bioremediation: A natural solution. *Pollution Engineering (United States)*. 25:30-33.
- Jain, S.K., P. Vasudevan, and N.K. Jha. 1989. Removal of some heavy metals from polluted water by aquatic plants: Studies on duckweed and water velvet. *Biological Wastes*, 28:115-126.
- Kennedy, L.G. and S.R. Hutchins. 1993. Applied geologic, microbiological, and engineering constraints of in-situ btx bioremediation. *Remediation* 3:83-110.
- Lantz, R.M. 1991. Methods used to determine the efficacy of in-situ bioremediation at hazardous waste sites. Pages 257-261. In, Proceedings of Northeast Conference and Exhibition on Hazardous Materials Control (HMCRI) '91, July 10-12 1991, Greenbelt, MD.
- Lindstrom, J. E., R.C. Prince, J.C.lark, M.J .Grossman, T.R. Yeager, J.F. Braddock, and E.J. Brown. 1991. Microbial populations and hydrocarbon biodegradation potentials in fertilized shoreline sediments affected by the Exxon Valdez oil spill. *Appl. and Environ. Microb.*, 57: 2514-22.
- Mahaffey, W.R., M. Nelson, J. Kinsella, G. Compeau. 1991. Developing strategies for PAH and TCE bioremediation. *Water Environment and Technology*, 3:10:1044-9493.
- Mendelsohn, I.A., Q. Lin, C.B. Henry, P. Roberts, R.J. Portier, and M.M. Walsh 1995. Bioremediation: a tool for the initial restoration of oiled salt marshes. *International Conference, ERF '95*. Corpus Christi, Texas.

- Mo, S.C., D.S. Choi, and J.W. Robinson, 1989. Uptake of mercury from aqueous solutions by Duckweed: The effect of PH, copper and humic acid. *J. Env. Sci. Health A24*:135-146.
- Nair, D.R. and J.L. Schnoor, 1994. Effect of soil condition on model parameters and atrazine mineralization rates. *Wat. Res.* 28:1199-1205.
- Salt, D.E. M. Blaylock, N.P. Kumar, V. Dushenkuv, B.D. Ensley, I. Chet, and I. Raskin. 1995. Phytoremediation: A novel strategy for the removal of toxic metals from the environment using plants. *Biotechnology.* 13:468-474.
- Schnoor, J.L., L.A. Licht, S.C. McCutcheon, N.L. Wolfe, and L.H. Carreira. 1995. Phytoremediation of organic and nutrient contaminants. *Environmental Science and Technology*, 29:318A-323A.
- Stomp, A.-M., K.-H. Han, and M.P. Gordon. 1993. Genetic improvement of tree species for remediation of hazardous wastes. *In Vitro Cellular and Developmental Biology-Plant.* 29:227-232.
- Wild, S.R., M.L. Berrow, S.P. McGrath, and K.C. Jones. 1992. Polynuclear aromatic hydrocarbons in crops from long-term field experiments amended with sewage sludge. *Environ. Pollut.* 76:23-32.

Bioremediation Research and Development for Marine Oil Spills

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DEFINITIONS

Biodegradation is a natural process in which microorganisms chemically alter and breakdown organic molecules into other substances, such as carbon dioxide, fatty acids, and water, in order to obtain energy and nutrients. Because microbes capable of degrading hydrocarbons are commonly found in nature, most untreated oil spills eventually are removed from the environment by microbial degradation and other processes.

Bioremediation is a treatment technology that utilizes biodegradation to reduce the concentration and/or toxicity of chemical substances such as petroleum products and other hydrocarbons. It seeks to accelerate natural biodegradation processes by applying specially chosen nutrients (nutrient addition), microbes (bioaugmentation) and/or oxidants to environments contaminated by, for example, spilled oil.

BACKGROUND

Bioremediation of marine oil spills is an idea that has been around since at least the early 1970s (Ahearn 1973, Miget 1973). For nearly twenty years, however, the lack of scientific credibility precluded its acceptance by the governmental response community. In 1989 and 1990, things began to change. Three nationally significant oil spills highlighted the promise and pitfalls of the method. Scientific studies of shorelines impacted by the Exxon Valdez incident indicated that nutrient addition enhanced oil biodegradation rates (Pritchard and Costa 1991). Attempts at bioremediation during the Megaborg tanker and Apex barge spills along the Texas Gulf Coast emphasized the lack of credible science and adequate response planning for the technique. The 1990 Oil Pollution Act (OPA) provided incentives for development of innovative response technology, including bioremediation.

During 1990, the Administrator of the Environmental Protection Agency (EPA) met with representatives of industry to establish goals for the safe development and use of biotechnology. To follow up on recommendations from that meeting, a government- industry Bioremediation Action Committee (BAC) was formed. The BAC Subcommittee on National Bioremediation Response developed the Interim Guidelines for Preparing Bioremediation Spill Response Plans (EPA 1991). Using the scientific criteria and the response decision-making recommendations contained in the Guidelines, several federal Regional Response Teams have now developed their own regional protocols for response.

The BAC's Treatability Protocol Development Subcommittee prepared tiered

protocols for assessing the efficacy and toxicity bioremediation products: gathering of existing information about a product (base tier and tier I); laboratory scale protocols for estimating product efficacy and toxicity (tier II); laboratory mesocosms to simulate field testing (tier III); and field scale testing (tier IV). The base tier and tiers I & II are in Subpart J of the National Oil and Hazardous Substances Pollution Contingency Plan (NCP), 40 CFR Part 300, as a requirement for testing products seeking eligibility for use by Federal On-Scene Coordinators. Further development and utilization of tiers III and IV are areas of needed research.

The use of bioremediation to treat waters of the U.S. contaminated by spilled oil must follow the approval process outlined in Subpart J of the National Oil and Hazardous Substances Pollution Contingency Plan (NCP), 40 CFR Part 300. It is important that R&D objectives include meeting the needs of that process; critical end users of research data are the response community managers, planners and decision makers and the natural resource trustees.

Federal Responsibility for Bioremediation Research and Development

Title VII of OPA 90 established an Interagency Coordinating Committee on Oil Pollution Research, with a charge to coordinate a comprehensive program of research, technology development, and demonstration among Federal agencies in cooperation with industry, universities, research institutions, State governments, and other countries. In 1992, the Committee convened the First International Oil Spill R&D Forum (Sheehan 1992a) to provide an opportunity for the international community to promote cooperation on oil spill research. During the same year, the committee published its Oil Pollution Research and Technology Plan (Sheehan 1992b), which among other things identified agency roles and responsibilities and established research priorities and goals. EPA was given lead responsibility for oil spill bioremediation technologies. Prioritized research projects are listed for bioremediation on pages 3.3-31 and 32 in the plan and are reflected in the Research Recommendations section of this report.

Since 1971, the EPA Administrator has been responsible for reviewing and approving proposals to deliberately spill oil in waters of the U.S. for the purposes of research and development. Recent heightened interest in bioremediation research to meet the needs of the response community has resulted in the granting of permitted oil spills.

Status of Bioremediation in Coastal Marine Oil Spills

Bioremediation currently occupies a credible place in the national oil spill response program, and is among the options now routinely considered by federal and state response managers and Regional Response Teams. Spills in open water environments are not considered candidates for bioremediation (EPA 1992); appropriate applications are in the coastal marine shorelines and wetlands.

The present consensus within the response community does not view bioremediation as an "emergency" procedure but as a long term cleanup process to be considered after mechanical removal has been precluded or completed. The time scale for the biodegradation

processes, even enhanced, is weeks to months, not hours to days (Owen 1991).

While contingency planning for bioremediation rapidly progressed once credible scientific underpinnings started becoming available, there remains a considerable amount of research and development necessary. No where is that more evident than in the need for cost effective monitoring protocols to serve two separate groups. Early in a pollution incident, response managers have an operational need for real time monitoring of the efficacy and safety of bioremedial applications. Later, the natural resource trustees may elect bioremediation as a means to reduce the duration of pollutant impact or for environmental restoration and will need protocols for monitoring those projects. The extent of monitoring that must be incorporated is largely specific to the incident and the needs of the data user. While EPA has developed a comprehensive monitoring guidance, there remains a critical need to establish cost feasible, "minimumly adequate" monitoring protocols for operational use that can be incorporated in response pre-planning documents.

Until recently, credible scientific underpinnings meant the results of the Exxon Valdez nutrient addition bioremediation study. Research (Venosa et al. 1992) has also demonstrated the efficacy of nutrient additions during a coastal shoreline field study. The study demonstrated that inorganic mineral nutrient additions significantly enhanced the natural, or intrinsic, rate of oil biodegradation. An on-going field research effort at Parker Cove on the Texas coast (Bonner, 1996) will further clarify the role of nutrient additions in the biodegradation of crude oil. There have been no similarly scaled studies to evaluate the effects of microbe or microbe + nutrient additions (bioaugmentation). The evidence is lacking that such seeding will enhance biodegradation (Owen 1991). The present inclination of the response community is to favor the technique of nutrient addition rather than bioaugmentation.

RECOMMENDED RESEARCH

1. Conduct statistically credible field studies in a variety of marine coastal ecosystems utilizing EPA permitted intentional releases of oil or spills of opportunity to establish the efficacy and safety of biodegradation enhancement techniques, including nutrient addition and bioaugmentation.
2. Develop nutrient addition guidelines and protocols to include recommendations concerning selection of most effective nutrient formulations, determining background nutrient levels in water and sediment, how best to apply nutrients and how often, what detrimental effects may occur, etc.
3. Develop coastal mapping of locations where bioremediation would be considered in the event of contamination by oil and record the quantitative, seasonal baselines for background levels of nutrients and the numbers and activities of indigenous hydrocarbonoclastic microbial populations at critical locales. Such pre-planning would better enable the response manager to determine whether nutrient addition and/or bioaugmentation are advantageous for enhancement of the intrinsic biodegradation rate.

4. Determine bioremediation effects on microbial communities. The introduction of nutrients and organisms to promote the biodegradation of oil on shorelines may upset the ecological balance on indigenous microbial communities.
5. Develop guidelines for cost effective, "minimally necessary" monitoring protocols for use by response managers engaged in planning and implementing bioremediation projects of varied complexities and coastal locales. Such protocols and their data quality objectives need to be consistent with the operational responsibilities of the response manager.
6. Conduct studies utilizing tiers III and IV Product Treatability Protocols.
7. Develop protocols for conducting spill of opportunity studies, including strategies for coping with the difficult experimental design requirements and logistics associated with such short lead time events.

REFERENCES

- Ahearn, D.G. 1973. Microbial facilitated degradation of oil: a prospectus. Pages 1-2. In, The Microbial Degradation of Oil Pollutants. Center for Wetland Resources LSU-SG-73-01.
- Bonner, J. 1996. Verbal comm. Department of Environmental Engineering, Texas A&M University, College Station, Texas.
- EPA. 1991. Interim Guidelines for Preparing Bioremediation Spill Response Plans. Subcommittee on National Bioremediation Spill Response, Bioremediation Action Committee, USEPA, Wash., D.C.
- EPA. 1992. Region 6 Bioremediation Spill Response Plan. USEPA, Dallas, Texas.
- Miget, R. 1973. Bacterial seeding to enhance biodegradation of oil slicks. In: The Microbial Degradation of Oil Pollutants. Center for Wetland Resources LSU-SG-73-01. pp. 291-307.
- Pritchard, P.H. and C.F. Costa. 1991. EPA's Alaska oil spill bioremediation project. Environ. Sci. Technol. 25:372-379.
- Owen, D. 1991. Bioremediation of oil spills: scientific validity and operational constraints. Pages 119-127. In, Proc. 14th Arctic and Marine Oil Spill Program Technical Seminar. Vancouver, Canada.
- Sheehan, D. 1992a. Proceedings From The First International Oil Spill Research and Development Forum. McLean, Virginia.

Sheehan, D. 1992b. Oil Pollution Research and Technology Plan, prepared under authority of Title VII, OPA of 1990, Pp 101-380.

Venosa, A.D., J.R. Haines, and D.M. Allen. 1992. Efficacy of commercial inocula in enhancing biodegradation of weathered crude oil contaminating a Prince William Sound beach. *J. Industrial Microbiology* 10:1-11.



The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.



The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The **MMS Royalty Management Program** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.