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The effects of oil spill and clean-up on dominant US Gulf coast marsh macrophytes: a review

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"Capsule": *This review should be useful in guiding future research to improve oil spill response efficiency.*

Abstract

The objective of this review was to synthesize existing information regarding the effects of petroleum hydrocarbons on marsh macrophytes in a manner that will help guide research and improve spill-response efficiency. Petroleum hydrocarbons affect plants chemically and physically. Although plants sometime survive fouling by producing new leaves, even relatively non-toxic oils can stress or kill plants if oil physically prevents plant gas-exchange. Plant sensitivity to fouling varies among species and among populations within a species, age of the plant, and season of spill. Physical disturbance and compaction of vegetation and soil associated with clean-up activities following an oil spill appear to have detrimental effects on the US Gulf coast marshes. Other techniques, including the use of chemicals such as cleaners or bioremediation, may be necessary to address the problem. Clean-up may also be beneficial when timely removal prevents oil from migrating to more sensitive habitats.

Keywords: Bioremediation; Coastal marshes; Oil clean-up; Oil spill; Pollution; Plant stress

1. Introduction

Coastal marshes contain productive, diverse habitats that are important for reasons ranging from protection of shorelines from wave actions (Webb, 1977) to providing fish and wildlife habitats, and improving water quality (Mitsch and Gosselink, 1993). Field and laboratory studies of the effects of oil on coastal marsh vegetation are numerous (Tables 1–3), 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 generally allow detailed study of one to several factors under a relatively narrow range of conditions and, therefore, provide limited application to field situations. 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 clean-up methodologies employed (Mendelssohn et al., 1993a, 1995). Furthermore, many important questions regarding the mechanisms of oil actions at the suborganismal level, e.g. cellular level and process level remain unanswered. The objective of this review is to synthesize existing information in a manner that may help researchers and managers understand how oil affects macrophytes in coastal systems. Emphasis was placed on US Gulf coast marshes, where significant petroleum exploration, refining, storage, and transportation subject tidal marshes to occasional spills.

2. Plant response to fouling

The short-term, adverse effects of oil on plants range from reductions in transpiration and carbon fixation to plant mortality (Baker, 1970; DeLaune et al., 1979;

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Table 1
Effects of Louisiana crude oil (unless otherwise noted) on US Gulf coastal marsh species

Exposure	Species	Effects	Reference
0.25 l m ^{2} spill in marsh	*Spartina alterniflora*	Little damage to existing stocks and new colonizers	de la Cruz et al., 1981
0.28 l m ^{2} spill in marsh	*S. alterniflora* and *S. patens*	64% decrease in cover in mixed species assemblage	Mendelssohn et al., 1990
1 l m ^{2} exp. marsh	*S. alterniflora*	No significant difference in above-ground biomass	DeLaune et al., 1979
2 l m ^{2} oil in marsh	*S. alterniflora*	No significant difference in above-ground biomass CO_2 fixation decreased at 6 days and recovered at 13 days	Smith et al., 1984
2 l m ^{2} on foliage, 5-week study Mexico Sour crude	*S. alterniflora*	100% oil cover: no photosynthesis Partial oil: photosynthesis decreased 50–80%	Pezeshki and DeLaune, 1993
8 l m ^{2}	*S. alterniflora*	No significant difference in above-ground biomass	Crow et al., 1976
Oil (undetermined)	*S. alterniflora*	Decreased production early, but no long-term effects	Lytle, 1975
32 l m ^{2} greenhouse	*S. alterniflora*	No significant difference in above-ground biomass	DeLaune et al. 1979
8 l m ^{2} and higher in greenhouse	*S. alterniflora*	No regrowth in the year following oil application	Lin and Mendelssohn, 1996
8 l m ^{2} and higher in greenhouse	*S. patens*	Significant reduction in photosynthetic rate, above-ground biomass and no regrowth in the year following oil application	Lin and Mendelssohn, 1996
Up to 24 l m ^{2}	*Sagittaria lancifolia*	Significant increase in biomass and stem density	Lin and Mendelssohn, 1996
Chronic exposure to mixed hydrocarbons at a rate of 3.3–33.3 g C m ^{2} day ^{1}	*S. alterniflora*	Non-linear response; stimulated plant growth and microbial activity at low level, but inhibited at higher levels	Li et al., 1990
5 l m ^{2} to sediment only	*S. patens*	Significant reduction in photosynthesis, proportion dead above-ground tissue, and regrowth	Hester et al., 1998
8 l m ^{2} to sediment only	*S. alterniflora*	Significant intraspecific variation in these responses	

Table 2
The effect of crude oil followed by use of vegetation removal, dispersants, or cleaners on US Gulf coastal marsh plant species

Exposure	Species	Effects	Reference
2 l m ^{2} oil in marsh	*Spartina alterniflora*	No significant difference in above-ground biomass; CO_2 fixation decreased in 6 and recovered in 13 days	Smith et al., 1984
2 l m ^{2} oil + dispersant in marsh	*S. alterniflora*	No significant difference in above-ground biomass; CO_2 fixation not decreased	Smith et al., 1984
2 l m ^{2} field study	*S. alterniflora*	No significant difference in biomass or CO_2 fixation	DeLaune et al., 1984
Oil + water flush	*S. alterniflora*	No significant difference in biomass or CO_2 fixation	DeLaune et al., 1984
Oil + mechanical cleaning	*S. alterniflora*	No significant difference in biomass or CO_2 fixation	DeLaune et al., 1984
Oil + concentrated dispersant	*S. alterniflora*	75% decrease in biomass and some decrease in CO_2 fixation	DeLaune et al., 1984
Oil + cleaners	*S. alterniflora*	Temporary decrease in plant gas-exchange and growth	Pezeshki et al., 1995
Oil + cleaners	*S. alterniflora*	Improved plant gas-exchange and regeneration attributed to the use of cleaner	Pezeshki et al., 1997
Oil + vegetation removal	*S. alterniflora*	Significant decrease in biomass and slow recovery (> 2 years)	DeLaune et al., 1984

Alexander and Webb, 1985a; Pezeshki and DeLaune, 1993). Death of *Spartina alterniflora* has been reported when high levels of crude oils accumulated in the soil or remained in the marsh for extended periods of time (Holt et al., 1978; Alexander and Webb, 1987; Krebs and Tanner, 1981a, b). Direct effects of oil on plants result from physical effects and chemical toxicity. The effects vary depending on a number of variables including type of oil (Table 3). Specific gravity at a given temperature and other measures are used to compare density or weight of oils, but for general ecological uses oil may be classified into five categories: (1) very light oils such as jet fuels and gasoline; (2) light oils such as diesel, No. 2 fuel oil, and light crude oil; (3) medium oils including most crude oils; (4) heavy oils such as No. 6 fuel oils, Bunker C, and heavy crudes; and (5) very heavy oils

Table 3
The effect of refined petroleum hydrocarbons on coastal marsh plant species

Exposure	Species	Effects	Reference
No. 2 fuel oil	*Spartina alterniflora*	Complete–partial loss of above-ground biomass	Webb et al., 1985
No. 2 fuel oil, 1 l m ^{2}	*S. alterniflora*	Fast regrowth (1 year)	Burger, 1994
No. 2 fuel oil, 1 l m ^{2} to sediment	*S. alterniflora*	Decreased above-ground live biomass after 5 and 12 months	Alexander and Webb, 1985b
No. 2 fuel oil, 1.5 l m ^{2} to sediment and lower plant stem	*S. alterniflora*	Decreased live above-ground biomass after 1, 5, and 12 months	Alexander and Webb, 1985b
No. 2 fuel oil, 2 l m ^{2} to sediment and total plant coverage	*S. alterniflora*	No live above-ground tissue after 1 month; decreased live above-ground biomass after 5 and 12 months	Alexander and Webb, 1985b
No. 6 fuel oil in marsh	*S. alterniflora*	Increased growth of oiled vegetation	Hershner and Moore, 1977; Stebbings, 1970
No. 6 fuel oil in marsh ('banding')	*S. alterniflora*	Initial total loss of above-ground biomass but resprouted in 4 months	Proffitt and Devlin, unpublished data
No. 6 fuel oil, 2 l m ^{2} to sediment and total plant coverage	*S. alterniflora*	Temporarily (1 month) decreased live above-ground biomass	Alexander and Webb, 1985b
Continuous refinery discharge at oil concentration of 30 ppm	*Spartina anglica*	Mortality resulted from thin oil film that coated plants following high spring tides	Baker, 1971b

that may not float on water such as some heavy No. 6 oils. This classification is not precise, but can be used to address the effects of different oil types.

2.1. Physically induced effects

Physical impacts of oil on plants act primarily through the coating of the plant foliage and soil surfaces. When oil coats plant leaves, temperature stress may occur, e.g. temperature rises in leaves because of blocked transpiration pathways (Pezeshki and DeLaune, 1993). Leaf photosynthesis is also reduced because of restricted entry of CO_2 due to blocking of stomatal pores (Pezeshki and DeLaune, 1993; Webb, 1994; 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 (Table 1), which in turn varies with the amount of oil spilled, the hydrologic conditions (tides, winds), 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 *Spartina alterniflora* (Pezeshki and DeLaune, 1993; Webb, 1994) and *Juncus roemerianus* Sheele (Pezeshki and DeLaune, 1993).

The transport of atmospheric oxygen from the leaves to roots in wetland plants is well documented as a critical mechanism of reducing oxygen stress in plant roots growing in flooded environments where soil oxygen is limited or essentially absent (Armstrong, 1979). Therefore, if oil blocks leaf stomata, oxygen diffusion to the roots decreases and root oxygen stress increases, which is a primary factor limiting plant growth in wetlands (Mendelssohn and McKee, 1988; Pezeshki et al., 1989). Similarly, oil covering the soil surface restricts the movement of oxygen into the soil and can result in more anaerobic soil conditions, thereby exacerbating oxygen stress on plant roots (Ranwell, 1968; Cowell, 1969).

2.2. Chemically induced effects

The chemical impacts of oil on vegetation vary greatly among oils. For instance, certain crude oils such as Arabian Crude, Libyan Crude, Mexican Crude, and No. 6 fuel appeared to have few short-term effects on *Spartina alterniflora* (Tables 1, 2). In contrast, refined, light oils and Bunker C apparently penetrate into plants and subsequently prevent leaf and shoot regeneration (Webb, 1994; Pezeshki et al., 1995, 1997, see Table 3). 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. Chemical effects can also be classified on the basis of fouling of leaves and fouling of soil. Leaves, but not soil, can be fouled when oiled waters pass through a marsh during high or storm tides. Soil can be fouled when oil is stranded by falling waters; soil fouling is otherwise associated with chronic exposure to hydrocarbons.

2.3. Fouling of leaves versus fouling of soils

Fouling of leaves appears to have more immediate effects than fouling of the soil surface, which can lead to more persistent exposure of new shoots (Mendelssohn et al., 1990; Mendelssohn et al., 1993a; Webb, 1994; Lin and Mendelssohn, 1996). Shortly after leaf fouling, *Spartina alterniflora* plants have been observed to display reduced stomatal conductance and no detectable photosynthetic activity, which suggests the potential breakdown of photosynthetic apparatus in leaves directly subjected to oil application (Pezeshki et al., 1995). Such breakdowns of leaf structure and/or chlorophyll system may occur because of blocked stomata leading to reduced transpiration; thus, dramatic leaf temperature increases and/or direct adverse effects of oil penetrating into the leaf tissue destroying cellular integrity. In *Spartina alterniflora*, fouling has been reported to lead to death of leaves up to 40 days after fouling (Pezeshki et al., 1995).

Although initial, short-term adverse effects of oil on leaves are often dramatic, plants may recover in the long term. For instance, complete fouling of *Spartina alterniflora* plants with South Louisiana crude initially caused rapid death of all leaves (Pezeshki et al., 1995). However, new leaf production began within 2 weeks, and 2 months after fouling, new leaves showed similar gas-exchange rates to those of control plants. Similar conclusions have resulted from other experiments with *Spartina alterniflora* and *J. roemerianus* (DeLaune et al., 1979; Smith et al., 1984; Pezeshki and DeLaune, 1993). Refined products have a different effect on leaves than crude oils. For instance, *Spartina alterniflora* plants oiled with Bunker C oil did not produce new leaves and the plants died (Pezeshki et al., 1995). Information on the relative toxicity of other petroleum hydrocarbons on marsh vegetation under controlled conditions is lacking.

Chronic oil spills and spills that are stranded by high tides may allow oil to penetrate and accumulate in the soil. It appears that soil type (sand, loam, clay) and soil organic matter (SOM) play important roles in the fate of petroleum hydrocarbons in soil, the extent of damage to vegetation, and the rate of recovery of marsh plants. In general, oil impact on vegetation is most significant in highly organic soils. Labile SOM probably slows biodegradation because it can replace petroleum hydrocarbons as a substrate for hydrocarbon-consuming bacteria. Consumption of SOM can also lower nutrient availability if the organic matter has low nutrient content. For these two reasons, SOM might be expected to increase the time that plants are exposed to toxins. On the other hand, SOM may sorb toxins, thereby reducing their bioavailability. Thus, SOM may reduce the effects of hydrocarbons on plants. Most petroleum components, generally, are nonionic and, therefore, associate more readily with organic than with mineral particles in soil (Testa and Winegardner, 1991). In an experimental oil spill, Lin and Mendelssohn (1996) found that the oil concentrations in the soil were strongly associated with the SOM content. In the range of 4–24 l m ^{2} of oil dosages, the *Spartina patens* (Ait.) Muhl. marsh sods with higher SOM constantly had the higher oil concentration in the soil, while the low oil concentration was found in the *Spartina alterniflora* sods, which had the lower SOM. In addition, Lin and Mendelssohn (1996) found that the oil concentration was as high as 279 times greater in the marsh soil with 42% of organic matter, compared to the soil with same mineral compositions but organic matter removed. Given that the amount and quality of the SOM is likely to vary with dominant vegetation, it is possible that the influence of SOM on vegetative response to hydrocarbons varies with dominant vegetation. However, much work needs to done to determine how SOM influences plant responses to petroleum hydrocarbons. Results from a recent mesocosm study (Dowty, 1998) showed significantly less residual oil remaining 18 months after oiling (both at 5 and 10 l oil m ^{2}) in commercial topsoil (mineral) than in a mix of topsoil with 50% peat (by volume). When oiled, *Panicum hemitomon*, *Sagittaria lancifolia* L., and *Phragmites australis* displayed greater rates of photosyntheis and biomass production in the topsoil treatment. Overall, the best plant response and the lowest levels of residual oil (after 18 months) were obtained in the topsoil sediment planted with either *Panicum hemitomon* or *Sagittaria lancifolia*.

Some studies indicate that size fraction of soil mineral matter (i.e. sand, silt, clay) influences degradation rates such that clays slow degradation (e.g. Apitz and Myeteys-Schulte, 1996). Slower degradation rates might then increase the time that plants are exposed to toxins. However, saline marshes generally have more mineral matter (primarily clays) than fresh marshes (Nyman et al., 1990) but saline marshes have more oil-sensitive vegetation than fresh marshes (DeLaune et al., 1996). In addition to SOM, the soil texture could also affect the residual oil concentration in the soil and marsh vegetation. In comparing the effects of soil texture, Ferrell et al. (1984) reported that *Spartina alterniflora* grown in finer textured marsh substratum were less affected by the presence of oil in substratum than were those growing in coarser sand. The differential response to substratum type was probably due to the difference in pore space size. Large pore spaces in sandy substratum would allow deeper and more rapid penetration of oil, whereas smaller pore spaces in fine-textured marsh substratum would not be readily penetrated by oil. Therefore, it appears that sensitivity varies primarily among plant species, and that size fraction of soil mineral matter may play a secondary role in moderating the sensitivity within a plant species. However, much work needs to be done before the influence that size fraction of soil mineral matter plays in the response of vegetation to petroleum hydrocarbons can be accurately predicted.

The effect that oil in the soil has on plants also varies with the age of the plant. Mendelssohn et al. (1993b) reported that under greenhouse conditions a fouling rate of 8 l m ^{2} of South Louisiana Crude to the soil of *Spartina alterniflora* was required to significantly reduce photosynthesis of established shoots, whereas only 4 l m ^{2} was required to significantly reduce production of tillers (i.e. new shoots that emerge from the base of the plant) through the oiled soil. Therefore, oil concentrations in soil that established plants tolerate can prohibit tiller production. Preventing tiller production would prevent natural regeneration and may contribute the substantial mortality of *Spartina alterniflora* stands that has been reported when high levels of crude oils accumulated in the soil or remained in the marsh for extended periods of time (Holt et al., 1978; Krebs and Tanner, 1981b; Alexander and Webb, 1987). Such adverse long-term effects may impact overall system productivity because marsh vegetation contributes to the detritus-based food web of estuarine ecosystems (Mitsch and Gosselink, 1993).

3. Season of spill

The season during which an oil spill occurs influences the impact of oil on vegetation (Ranwell and Hewett, 1964; Baker, 1971a; Getter et al., 1984; Webb, 1994). Ranwell and Hewett (1964) observed that during the period of senescence, even relatively unweathered oil did not cause significant mortality in salt marsh vegetation, which suggests that plants are more sensitive to oil application during their active growing period than other periods. Alexander and Webb (1985b) reported that No. 2 fuel oil applied to the soil 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 *Spartina alterniflora* were more severe during the spring season than the fall season (Webb, 1994). Lin (1996) showed that South Louisiana crude oil applied to soil reduced photosynthesis, above-ground biomass and regeneration of *Spartina alterniflora* and *Sagittaria lancifolia* more when oil was applied in June than when oil was applied in late October. In much of these observations, it is clear that plants are more sensitive to oiling during the growing season than during the pre-dormancy or dormant season. During the growing season plants are active; thus, any interruption of plant physiological functions or damage to plant tissue can lead to obvious symptoms. Much of this sensitivity is due to the interruption of physiological functions that result from oiling. As previously stated, oil may cover leaf stomata, thereby subjecting leaves to overheating and death as a result of reduced transpiration and the added heat absorbed due to oiling (Pezeshki et al. 1995). Oil may also penetrate into the leaf tissue resulting in tissue damage. Baker (1971a) indicated that a marked reduction of flowering can occur if plant above-ground tissues are oiled when flower buds are developing; and flowers, if oiled, rarely produce viable seeds. Additionally, oiling of seeds may reduce germination. Clearly, more research is needed to address the physical and chemical effects of oil on plant tissue. However, the task is complicated due to variation in sensitivity of plant tissues to oiling as well as differences in chemical composition of oils.

4. Interspecific sensitivity to oil spills

Tidal marshes are composed of diverse plant species occupying various ecological zones including salt, brackish and freshwater habitats. The salt marsh, brackish, and freshwater marshes differ in plant species and hydrologic regimes and, therefore, differ in functions. For instance, tidal freshwater marshes typically support a more diverse plant and wildlife community, though salt marshes generally support more commercially important estuarine fish species. The majority of investigation on the effects of oil on wetland vegetation have been largely conducted in salt marsh plant communities (DeLaune et al., 1979; Ferrell et al., 1984; Alexander and Webb, 1985a, b, 1987; Li et al., 1990; Mendelssohn et al., 1990, 1993a, b; Lin and Mendelssohn, 1996). Lin and Mendelssohn (1996) found that *Spartina patens*, which dominates many brackish marshes, was more sensitive than *Spartina alterniflora* to South Louisiana crude but both suffered complete mortality at oil dosages of 8 l m ^{2} and above. Pezeshki and DeLaune (1993) found that *Jancus roemerianus*, which dominates many brackish and is common in saline marshes, was initially less sensitive than *Spartina alterniflora* although both species recovered rapidly (Pezeshki and DeLaune, 1993).

Tidal, freshwater marshes are also subject to oil spills because petroleum exploration, production, transportation, refining, occurs in and near these marshes. However, little information is available on the effects of oil on freshwater marsh plants. Lin and Mendelssohn (1996) studied four fresh marsh plant species, *Sagittaria lancifolia*, *Eleocharis quadrangulata* (Michx.) R.&S., *Cyperus ordoratus* L., and *Ammania teres* Raf. grown in sods of the fresh marsh. *C. ordoratus* and *A. teres* failed to survive in any of the oil-treated sods. *E. quadrangulata* could only persist at oil levels up to but not greater than 8 l m ^{2}. In contrast, *Sagittaria lancifolia* persisted at all oil dosages and formed monospecific communities at the higher oil dosages of 16 and 24 l m ^{2}, thereby exhibiting a high relative oil tolerance. In addition, it displayed enhanced growth in response to higher oil dosages. Burk (1977) reported that an oil spill in a freshwater marsh eliminated 18 plant species, reduced 14 species in relative abundance, and increased or did not affect the relative abundance of 23 other species. The results demonstrate the range of vastly different response of freshwater species to oil spills.

Changes in plant community composition may also become evident following an oil spill. The difference has been attributed to variations in species' sensitivities to fouling and the physical disturbance often associated with the clean-up. For instance, in a spill of South Louisiana crude oil in a brackish–saline marsh in South Louisiana dominated by a mixture of *Spartina patens*, *Distichlis spicata* (L.), and *Spartina alterniflora*, Mendelssohn et al. (1990, 1993a) noted that *Spartina patens* generally displayed poorer recovery than either *D. spicata* or *Spartina alterniflora*. *Spartina alterniflora* had the best recovery and showed some of the greatest increases in live cover following the spill, probably due to a higher tolerance to oiling than *Spartina patens* (Mendelssohn et al., 1990; Lin and Mendelssohn, 1996). On a more limited scale, *D. spicata* showed some localized increases in cover relative to *Spartina patens* (Mendelssohn et al., 1990, 1993a). Therefore, it is possible that species differences in oil sensitivity may interact with changes in the environment in determining plant species community composition following an oil impact.

5. Intraspecific sensitivity to oil spills

In addition to the interspecific variations in responses of plants to fouling mentioned previously, intraspecific differences in oil sensitivity also exist. Hester et al. (1998) investigated intraspecific variation to oiling in the widespread marsh macrophytes *Spartina patens* and *alterniflora*. Ecotypes from 10 Gulf coast populations of each species displayed significant intraspecific variation in photosynthesis, vegetative regrowth through the oiled sediment, and other plant growth variables when South Louisiana crude oil was applied at the rate of 5 l oil m^{-2} to the soil surface for *Spartina patens* and 8 l oil m^{-2} for *Spartina alterniflora*. Three months following oiling, the most oil-tolerant *Spartina patens* ecotypes displayed high net photosynthetic rates that were not significantly different from their controls, whereas other ecotypes still exhibited a 30–60% reduction in photosynthetic rates. Results were similar for *Spartina alterniflora* (Hester et al. 1998). Therefore, some of the apparent inconsistencies in the reported responses of certain marsh macrophytes to fouling may be explained, at least in part, by within-species variation in oil sensitivity. This line of research also shows promise for identifying oil-tolerant ecotypes that may be used in accelerating the restoration or phytoremediation of oil-impacted marshes, as well as in physiological studies of underlying mechanisms of oil tolerance in marsh macrophytes.

6. Effects of clean-up activities on marsh vegetation

Although some plant species apparently tolerate being coated by some crude oils, refined oils on vegetation and high soil concentrations of crude oils can destroy marsh plant communities (Hampson and Mouls, 1978; Hershner and Lake, 1980). Thus, in cases where refined oils or large amounts of crude oil are involved, clean-up may be desirable, but it is not clear what clean-up operations are most appropriate. The present clean-up methodologies of dealing with oil spills can be classified as mechanical, in situ burning, chemical, and bioremediation. Determining a proper clean-up strategy involves consideration of trade-offs between balancing the potential damage to a marsh during the clean-up with short- and long-term effects of oil toxicity in a particular environment (Johnson and Pastorok, 1985).

Mechanical techniques involve collection and skimming, cutting and removal of vegetation, and gentle flushing with clean water. However, oil collection and skimming may greatly damage plants (Kiesling et al., 1988; OTA 1990; Owens et al., 1993a). Some on-scene coordinators have cut and removed all oiled marsh vegetation to prevent contamination of wildlife, but this may cause permanent plant loss and soil erosion (Baca et al., 1985). Cutting followed by subsequent prolonged flooding of the marsh surface (via high tides or high riverine flow) can be especially devastating to the vegetation because the pathway of oxygen transport (plant foliage) to below-ground tissues (roots) is eliminated. Cutting is, therefore, not beneficial, particularly where marsh loss occurs and is largely attributed to subsidence and increased flooding, such as in Louisiana's coastal marshes (Gagliano et al., 1981; Mendelssohn and McKee, 1988). Mendelssohn et al. (1990) found that physical disturbance and compaction of vegetation and soil associated with clean-up activities (foot traffic and marsh buggies) had detrimental and long-lasting effects on an oiled brackish–saline marsh in Louisiana. Subsequent transplant experiments confirmed that failure of *Spartina alterniflora* to recover in the area heavily impacted during the clean-up was due to decreased soil elevation, not residual oil remaining in the soil (Mendelssohn et al., 1993a). Hoff et al. (1993) similarly reported that human foot traffic caused greater mortality to a *Salicornia*/*Distichlis* marsh than North Slope crude. In addition, foot traffic and other mechanical activity can drive hydrocarbons into the subsurface, where they degrade more slowly (Owens et al., 1993b). Thus, physical responses, other than gentle flushing of water through the oiled marsh, need to be carefully considered because clean-up activities can kill marsh vegetation and create shallow ponds that will not revegetate. Thus, chemical responses and other less intrusive clean-up methodologies appear viable alternatives to the physical removal of oil from fragile marsh environments.

Although oiled vegetation may return to normal without clean-up operations in areas of 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 with sediments (Krebs and Tanner, 1981b; Vandermeulen et al., 1981). Stripping without restoration of the original elevation not only prevents revegetation of the stripped area because of excessive flooding, but might also increase tidal prism and cause adjacent healthy areas to erode (Krebs and Tanner, 1981b; Vandermeulen et al., 1981).

In situ burning of oiled marshes is another alternative to physically impacting the marsh during oil spill clean-up (Allen and Ferek, 1993). In situ burning results in an immediate reduction of plant cover, which may take up to 3 years to recover, often with an accompanying temporal shift in species dominance (Mendelssohn et al., 1995; Pahl et al., 1997). For instance, in experimental oiled field plots, Pahl et al. (1997) reported that burning resulted in a shift in species composition enhancing site recolonization by *Scirpus robustus* replacing previously dominated *D. spicata* and *Spartina patens*. Guidelines for in situ burning are generally similar to those recommended for prescribed burns in managed marshes (Nyman and Chabreck, 1995) and may be more suitable for wetlands where fire is used as a management tool regularly (Pahl et al., 1997). In general, in situ burns are most successful during periods of low growth or dormancy (late fall and winter) and when the marsh surface is flooded by a few centimeters of water (Mendelssohn et al., 1995; Nyman and Chabreck, 1995). These conditions take advantage of periods of high below-ground reserves for adequate regrowth initiation and minimize fire and heat damage to below-ground roots and rhizomes. As is the case in cutting oiled vegetation, in situ burning should never be conducted immediately prior to an anticipated rise in water levels because of the potential for plant stress and/or death resulting from insufficient oxygen transport to below-ground tissues (Mendelssohn et al., 1995). Flooding following burning adversely affected plant growth in many species (Smith and Kadlec, 1985; Pezeshki and DeLaune, 1993; Kirkman and Sharitz, 1994; Nyman and Chabreck, 1995; DeLaune et al., 1997; Pahl et al., 1997).

Chemical responses to oil spills include use of dispersants, cleaners, and soil oxidizers. Dispersants are becoming less toxic and their use may increase (Cunningham et al., 1991; Owens et al., 1993a). However, dispersants are not likely to be deployed directly in marshes where there is little water to dilute the dispersed oil (OTA, 1990). Instead, dispersants are more likely to be used 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); cleaners do not disperse oil but allow 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. Fouling of fringing marshes has caused significant bird mortality in previous oil spills (Alexander et al., 1979). Teas et al. (1993) showed that cleaning prevented mortality of oiled red mangroves (*Rhizophora mangle* L.) by removing oil that otherwise suffocated roots. Pezeshki et al. (1995) showed that cleaning prevented mortality of *Spartina alterniflora* coated with Bunker C. Cleaning South Louisiana crude from *Spartina alterniflora* prevented leaf death, but was not needed to prevent plant death (Pezeshki et al., 1995). Other studies reported differences in response to oiling and commercial cleaners among marsh species (Pezeshki et al., 1998). The use of this method, however, requires more information regarding the potential toxicity of cleaners to various organisms (Fingas et al. 1989; Fiocco et al. 1991).

Another clean-up technique is known as bioremediation. Bioremediation is an emerging technology referred to as "the emerging oil spill countermeasure of the 1990s" (Boufadel and Suidan, 1997; Lee et al., 1997). It is defined as "the act of adding materials to contaminated environment to cause an acceleration of the natural biodegredation processes" (Mearns et al., 1997). Bioremediation agents include biostimulation, e.g. adding nutrient or oxygen and/or bioaugmentation, e.g. addition of oil-degrading microorganisms (Lee et al., 1997). The microorganisms may be indigenous or adapted microbial populations. The microbial activities lead to degradation of toxic petroleum products into carbon dioxide and water. Laboratory studies have demonstrated promising results from the addition of nutrients to stimulate microbial activities, as well as utilizing oil-degrading microorganisms to enhance the degradation of petroleum hydrocarbons although field results are much more limited (Venosa et al., 1991; Swannelle et al., 1996; Lee et al., 1997).

The application of nutrients to oiled marshes appears to accelerate bacterial consumption of the oil. Nutrients may be applied to spilled oil in water bodies before it reaches the marsh. Nutrient additions also are 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 often unknown and 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 wetland conditions may promote denitrification (Mitsch and Gosselink, 1993), but it is not known which fertilizer formulations simultaneously maximize oil consumption and denitrification. Results from a large-scale field study in Delaware Bay, USA, demonstrated that in certain areas nutrients were the predominant factor limiting biodegradation (Mearns et al., 1997). As was pointed out by the authors, the results are more applicable to sand beaches and not to other environments such as marsh ecosystems. The need for addition of oil-degrading microorganisms to an oiled sand beach has been questioned (Venosa et al., 1996; Lee et al., 1997; Mearns et al., 1997). In addition, other studies have demonstrated that bioaugmentation may not improve the results over biostimulation (Atlas, 1995), although there are studies that show otherwise (Aldrett et al., 1997). Since the main objective of bioremediation is to facilitate the removal of contaminant from the environment while minimizing ecosystem disturbance, additional research studies are needed to further test the efficiency, safety, and applicability of various bioremediation techniques under field conditions and across a wide range of ecosystems.

Another response to spilled oil may be no action, which is also known as natural attenuation and has been the response for some rocky shorelines and sensitive wetlands (OTA, 1990; Mearns, 1993). Natural attenuation reduces oil concentrations because oil evaporates and naturally degrades in marsh 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 (Pezeshki et al., 1995, 1997). Under certain conditions, natural attenuation may be the best approach because physical clean-up activities can be so damaging to vegetation and because of uncertainty regarding cleaner and dispersant toxicity and the fate of added nutrients (OTA, 1990; Mearns, 1993).

7. Indirect effects

Oil also may affect soil microbial communities (Alexander and Schwarz, 1980), which control nutrient remineralization and thereby regulate vegetative productivity and energy flow from plants through food webs (Knox, 1986). Thus, if toxic components of oil inhibited bacterial decomposition of SOM and the associated nutrient remineralization, then plant growth might be slowed. Burns and Teal (1979) found oil in marsh soil 7 years after one spill, which indicates the potential for long-term effects. However, Li et al. (1990) noted that low doses of an artificial mixture of 10 hydrocarbons stimulated microbial activity, and Nyman (1999) found that Louisiana and Arabian crude oils accelerated rather than slowed microbial activity in fresh marsh soils. Accelerated organic matter mineralization would suggest increased nutrient remineralization rates and might explain observations of enhanced plant growth following petroleum hydrocarbons application to *Spartina alterniflora* (Hershner and Moore, 1977; Krebs and Tunner, 1981b; Li et al., 1990) and *Sagittaria lancifolia* (Lin and Mendelssohn, 1996). However, additional data are needed regarding the effects of other oils and the responses of other marsh types before definitive cause and effect relationships can be established.

8. Concluding remarks and future research direction

Coastal marshes are composed of diverse macrophyte species occupying various ecological zones. Such species diversity requires species- and oil-specific data to assess the effects of oil on various plant communities, 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-saline marsh plant species. In addition, data are needed on the effectiveness of methods used in removing oil from vegetation including bioremediation, 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 soil. For these types of impacts, heavier weight oils can be as detrimental to vegetation health as lighter weight oils, which act at the cellular level by altering membrane permeability or disrupting various facets of the plants' metabolism.

Direct effects of fouling of marsh macrophytes tend to be most severe on above-ground tissue and often act via direct tissue toxicity or blockage of plant gas-exchange (transpiration and photosynthesis). The effects of oil on the soil can lead to increased oxygen stress in below-ground tissues due to reduced gas exchange between soil and atmosphere, thereby disrupting 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 fouling are evident at the level of the plant community, the species, and the individual. For instance, *Sagittaria lancifolia*, a dominant freshwater marsh species, is highly resistant to fouling and may even show enhanced photosynthetic rates subsequent to fouling with South Louisiana crude. In contrast, *Spartina patens*, a dominant brackish marsh species, is more sensitive to fouling than *Sagittaria lancifolia* and *Spartina alterniflora*. Furthermore, ecotypes of *Spartina patens* and *alterniflora* collected along the US Gulf coast displayed significant intraspecific variation in their response to fouling. Future research is needed that addresses the specific effects of oils on within-plant processes, the potential differences in plant response to fouling between healthy plants versus plants stressed by other environmental factors such as flooding, drought, nutrient deficiency and salinity stresses, and mechanisms underlying differences among various marsh species (and within a given species) in their susceptibility or tolerance to fouling. In addition, more research is needed to study the diverse effects of oil on fresh marsh plant communities due to the likelihood of greater species diversity and the resultant diverse mosaic of responses to fouling in these plant communities.

Small oil spills, depending on oil type and amount, may not require extensive clean-up. In fact, activities associated with physical clean-up (such as marsh buggy traffic and human foot traffic) may actually drive oil into the sediment or destroy the plant root and below-ground network, thereby causing plant mortality and delayed (if not permanently failed) recovery. 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 fouling, need to be considered when assessing oil impacts and formulating management and restoration plans. Clean-up activity may be beneficial in areas subject to large oil accumulations on the soil surface, such as occur in some areas affected by large spills or chronic spills, or when containment and timely removal are necessary to prevent oil from being transported to more sensitive wetland habitats. Given an inability to predict which portions of oiled wetlands will recover and which portions will experience long-term plant mortality, it may be impossible to determine which portions of the wetland require remediation at the time of a spill. Such determinations may require waiting a complete growing season following the spill.

References

Aldrett, S., Bonner, J.S., McDonald, T.J., Mills, M.A., Autenrieth, R.L., 1997. Degradation of Crude Oil Enhanced by Commercial Microbial Cultures (Publication No. 4651). American Petroleum Institute. Washington, D.C, pp. 995–996.

Alexander, S.K., Schwarz, J.R., 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., Webb Jr., J.W., 1985a. Oil in the salt marsh: what have we learned? In: Bryan, C.F. (Ed.), Proceedings, Fourth Coastal Marsh and Estuary Management Symposium. Louisiana State University Printing Office, Baton Rouge, LA, pp. 49–62.

Alexander, S.K., Webb Jr., J.W., 1985b. Seasonal response of *Spartina alterniflora* to oil. In: Proceedings, Oil Spill Conference (Prevention, Behavior, Control, Cleanup) American Petroleum Institute 25–28 February 1985, Los Angeles, CA, pp. 355–357.

Alexander, S.K., Webb Jr., J.W., 1987. Relationship of *Spartina alterniflora* to sediment oil content following an oil spill. In: Proceedings of the 1987 Oil Spill Conference. American Petroleum Institute, Washington, D.C, pp. 445–449.

Alexander, M.M., Longabucco, P., Phillips, D.M., 1979. The impact of oil on marsh communities in the St. Lawrence River. In: Alexander, M.M., Longabucco, P., Phillips, D.M. (Eds.), Proceedings of the 1979 Oil Spill Conference. American Petroleum Institute, Washington, D.C, pp. 333–340.

Allen, A.A., Ferek, R., 1993. Advantage and disadvantages of burning oil. In: Proceedings of the 1993 International Oil Spill Conference. American Petroleum Institute, Washington, D.C, pp. 765–772.

Apitz, S.E., Myeteys-Schulte, K.J., 1996. Effects of substrate mineralogy on the biodegradability of fuel components. Environ. Toxicol. Chem. 15, 1883–1893.

Armstrong, W., 1979. Aeration in higher plants. Adv. Bot. Res. 7, 225–332.

Atlas, R.M., 1995. Bioremediation. Chemical Engineering 73, 32–42.

Baca, B.J., Getter, C.D., Lindstedt-Siva, J., 1985. Freshwater oil spill considerations: protection and cleanup. In: Proceedings of the 1985 Oil Spill Conference. American Petroleum Institute, Washington DC, pp. 385–390.

Baker, J.M., 1970. The effects of oil on plants. Environmental Pollution 1, 27–44.

Baker, J.M., 1971a. Seasonal effects. In: Cowell, E.B. (Ed.), The Ecological Effects of Oil Pollution on Littoral Communities. Applied Science Publishers, Barking, UK, pp. 44–51.

Baker, J.M., 1971b. Refinery effluent. In: Cowell, E.B. (Ed.), The Ecological Effects of Oil Pollution on Littoral Communities. Applied Science Publishers, Barking, UK, pp. 33–43.

Boufadel, M.C., Suidan, M.T., 1997. tide-driven nutrient transport in a beach microcosm in the absence of waves (Publication No. 4651). American Petroleum Institute, Washington, D.C, pp. 713–718.

Burger, J., 1994. Before and After Oil Spill: the Arthur Kill, New Brunswick, NJ. Rutgers University Press, New Brunswick, New Jersey, USA.

Burk, C.J., 1977. A four year analysis of vegetation following an oil spill in a freshwater marsh. J. Appl. Ecol. 14, 515–522.

Burns, K.A., Teal, J.M., 1979. The West Falmouth oil spill: hydrocarbons in the salt marsh ecosystem. Estuarine and Coastal Marine Science 8, 349–360.

Cowell, E.B., 1969. The effects of oil pollution on salt-marsh communities in Pembrokeshire and Cornwall. Journal of Applied Ecology 6, 133–142.

Crow, S.A., Bavor, H.J., Hood, M.A., 1976. Toxicity of crude oil on marsh plants (App. VI. Sec. 13). In: Gosselink, J.G., Miller, R.R., Hood, M.A., Bahr Jr., L.M. (Eds.), Louisiana Offshore Oil Port: Environmental Baseline Study. Loop Inc., New Orleans, LA.

Cunningham, J.M., Sahatjian, K.A., Meyers, C., Yoshioka, G., Jordan, J.M., 1991. Use of dispersants in the United States: perception or reality? In: Proceedings of the 1991 Oil Spill Conference. American Petroleum Institute, Washington DC, pp. 389–393.

Davis, S.M., 1994. Phosphorus inputs and vegetation sensitivity in the Everglades. In: Davis, S.M., Ogden, J.C. (Eds.), Everglades: the Ecosystem and its Restoration. St. Lucie Press, Delray Beach, FL.

de la Cruze, A.A., Hackney, C.T., Rajanna, B., 1981. Some effects of crude oil on a *Juncus* tidal marsh. J. Elisha Mitchell Society 97, 14–28.

DeLaune, R.D., Patrick Jr., W.H., Buresh, R.J., 1979. Effect of crude oil on a Louisiana *Spartina alterniflora* salt marsh. Environmental Pollution 20, 21–31.

DeLaune, R.D., Hambrick, G.A., Patrick Jr., W.H., 1980. Degradation of hydrocarbons in oxidized and reduced sediments. Marine Pollution Bulletin 11, 103–106.

DeLaune, R.D., Smith, C.J., Patrick Jr., W.H., Fleeger, J.W., Tolley, M.D., 1984. Effect of oil on salt marsh biota: methods for restoration. Environmental Pollution 36A, 207–227.

DeLaune, R.D., Jugsujinda, A., Pezeshki, S.R., 1996. Evaluation of Habitat Sensitivity to Oiling: Use of Cleaners for Removing Oil from Vegetation. Louisiana Oil Spill Coordinator's Office/Office of the Governor, Louisiana Applied Oil Spill Research and Development Program, Baton Rouge, LA.

DeLaune, R.D., Lindau, C.W., Devai, I., Henry, C.B., 1997. Burning of oiled Louisiana coastal marsh: field evaluation (Publication No. 4651). International Oil Spill Conference. American Petroleum Institute, Washington, D.C, pp. 903–904.

Dowty, R.A., 1998. Wetland Restoration: the Bioremediation of Small-scale Oil Spills in Fresh Marsh Environments and Adventitious Rooting Response in Marsh Vegetation. Masters thesis, Southeastern Louisiana University, Hammond, LA.

Ferrell, R.E., Seneca, E.D., Linthurst, R.A., 1984. The effect of crude oil on the growth of *Spartina alterniflora* Loisel. and *Spartina cynosuroides* (L.) Roth. J. Exp. Mar. Biol. Ecol. 83, 27–39.

Fingas, M.F., Stoodley, G., Harris, G., Hsia, A. 1989. Evaluation of Chemical Beach Cleaners. Cleanup Technology Workshop, Anchorage, Alaska, November 28–30.

Fiocco, R.J., Canevari, G.P., Wilkinson, J.B., Jahns, H.O., Bock, J., Robbins, M., Markarian, R.K., 1991. Development of COREXIT 9580—a chemical beach cleaner. In: Proceedings of the Oil Spill Conference. American Petroleum Institute, Washington D.C, pp. 395–400.

Gagliano, S.W., Meyer-Arendt, K.J., Wicker, K.M., 1981. Land loss in the Mississippi River Deltaic Plain. Trans. Gulf Coast Assoc. Geol. Soc. 31, 295–300.

Getter, C.D., Cintron, G., Dicks, B., Lewel, R.R., Seneca, E.D., 1984. The recovery and restoration of salt marshes and mangroves following an oil spill. In: Cairns Jr., J., Buikema Jr., A.L. (Eds.), Restoration of Habitats Impacted by Oil Spills. Butterworth Publishers, Stoneham, MA, pp. 65–114.

Gilfillan, E.S., Page, D.S., Bass, A.E., Foster, J.C., Fickett, P.M., Ellis, W.G.H., Rusk, S., Brown, C., 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., DeLaune, R.D., Patrick Jr., W.H., 1980. Effect of Estuarine Sediment pH and oxidation–reduction potential on microbial hydrocarbon degradation. Applied and Environmental Microbiology 40, 365–369.

Hampson, G.R., Moul, E.T., 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 Canada 35, 731–734.

Hershner, C., Lake, J., 1980. Effects of chronic pollution of a saltmarsh grass community. Marine Biology 56, 163–173.

Hershner, C., Moore, K., 1977. Effects of the Chesapeake Bay Oil Spill on salt marshes of the lower bay. In: Proceedings of the 1977 Oil Spill Conference. American Petroleum Institute, Washington, D.C, pp. 529–533.

Hester, M.W., Lin, Q., Mendelssohn, I.A., DesRoches, D.J., 1998. The Potential for Accelerated Bioremediation and Restoration of Oil-impacted Marshes through the Selection of Superior Oil-tolerant Vegetation (Final Report). US Department of Interior, Mineral Management Service, Gulf of Mexico OCS Regional Office, New Orleans, LA.

Hoff, R.Z., Shigenaka, G., Henry, C.B., 1993. Salt marsh recovery from a crude oil spill: vegetation, oil weathering, and response. In: 1993 Oil Spill Conference. American Petroleum Institute, Washington DC, pp. 307–311.

Holt, S., Rabalais, S., Rabalais, N., Cornelius, S., Holland, J.S., 1978. Effects of an oil spill on salt marshes at Harbor Island, Texas. I. Biology. In: Proceedings, Conference on the Assessment of Ecological Impacts of Oil Spills. Amer. Inst. Biol. Sci., pp. 344–352.

Johnson, T.L., Pastorok. R.A., 1985. Oil spill cleanup! Options for minimizing adverse ecological impact (Publication No. 4435). American Petroleum Institute, Washington, D.C.

Kiesling, R.W., Alexander, S.K., Webb, J.W., 1988. Evaluation of alternative oil spill cleanup techniques in a *Spartina alterniflora* salt marsh. Environmental Pollution 55, 221–238.

Kirkman, L.K., Sharitz, R.R., 1994. Vegetation disturbance and maintenance of diversity in intermittently flooded Carolina bays in South Carolina. Ecol. Appplications 4, 177–188.

Knox, G.A., 1986. Estuarine ecosystems: a systems approach, Vol. II. CRC Press, Boca Raton, FL.

Krebs, C.T. Tanner, C.E., 1981a. Cost analysis of marsh restoration through sediment stripping and Spartina propagation. In: Proceedings of the 1981 Oil Spill Conference. American Petroleum Institute, Washington, D.C, pp. 375–385.

Krebs, C.T., Tanner, C.E., 1981b. Restoration of oiled marshes through sediment stripping and *Spartina* propagation. In: Proceedings of the 1981 Oil Spill Conference. American Petroleum Institute, Washington, D.C, pp. 386–390.

Lee, K., Tremblay, G.H., Gauthier, J., Cobanli, S.E., Griffin, M., 1997. Bioaugmentation and biostimulation: a paradox between laboratory and field results. American Petroleum Institute (Publication No. 4651). Washington, D.C.

Li, Y., Morris, J.T., Yoch, D.C., 1990. Chronic low level hydrocarbon amendments stimulate plant growth and microbial activity in saltmarsh microcosms. J. Appl. Ecol. 27, 159–171.

Lin, Q., 1996. Factors Controlling the Impact of South Louisiana Crude Oil on Vegetation and Revegetation of Coastal Wetlands. PhD thesis, Louisiana State University, Baton Rouge, LA.

Lin, Q., Mendelssohn, I.A., 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.

Lytle, J.S., 1975. Fate and effects of crude oil in an estuarine pond. In: Proceedings of the 1975 Conference on Prevention and Control of Oil Pollution, American Petroleum Institute, Washington, D.C, pp. 595–600.

Mearns, A.J., 1993. Recovery of shoreline ecosystems following the Exxon Valdez oil spill and subsequent treatment. In: Magoon, O.T. (Ed.), Coastal Zone '93 Volume I. American Society of Civil Engineers, New York, pp. 466–479.

Mearns, A.J., Venosa, A.D. Lee, K., Salazar, M., 1997. Field-testing bioremediation treating agents: lessons from an experimental shoreline oil spill. American Petroleum Institute (Publication No. 4651), Washington, D.C.

Mendelssohn, I.A., McKee, K.L., 1988. *Spartina alterniflora* dieback in Louisiana: time-course investigation of soil waterlogging effects. Journal of Ecology 76, 509–521.

Mendelssohn, I.A., Hester, M.W., Sasser, C., Fischel, M., 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., Hester, M.W., Hill, J.M., 1993a. Effects of Oil Spills on Coastal Wetlands and Their Recovery (OCS study MMS 93-0045). US Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans, LA.

Mendelssohn, I.A., McKee, K.L., Kong, T., 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., Hester, M.W., Pahl, J.W., 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 Govenor, Applied Oil Spill Research and Development Program, Baton Rouge, LA.

Mitsch, W.J., Gosselink, J.G., 1993. Wetlands. Van Nostrand Reinhold, New York.

Nyman, J.A., 1999. Effect of crude oil and chemical additives on metabolic activity of mixed microbial populations in fresh marsh soils. Microbial Ecology 37, 152–162.

Nyman, J.A., Chabreck, R.H., 1995. Fire in coastal marshes: history and recent concerns. In: Cerulean, S.I., Engstrom, R.T. (Eds.), Fire in Wetlands: a Management Perspective. Proceedings of the Tall Timbers Fire Ecology Conference, No. 19. Tall Timbers Research Station, Tallahassee, FL.

Nyman, J.A., DeLaune, R.D., Patrick Jr., W.H., 1990. Wetland soil formation in the rapidly subsiding Mississippi River Deltaic Plain: mineral and organic matter relationships. Estuarine, Coastal and Shelf Science 31, 57–69.

OTA, 1990. Coping with an Oiled Sea. US Congress, Office of Technology Assessment. OTA-BP-O-63. US Government Printing Office, Washington, D.C.

Owens, E.H., Gould, J.R., Lindstedt-Siva, J., 1993a. Field studies to determine the ecological effects of cleanup methods on oiled shoreline. In: Proceedings of the 1993 International Oil Spill Conference. American Petroleum Institute, Washington, D.C, pp. 401–406.

Owens, E.H., Taylor, E., Marty, R., Little, D.I., 1993b. An inland oil spill response manual to minimize adverse environmental impacts. In: Proceedings of the 1993 International Oil Spill Conference. American Petroleum Institute, Washington, D.C, pp. 105–109.

Pahl, J.W., Mendelssohn, I.A., Hess, T.J., 1997. The application of in situ burning to a Louisiana coastal marsh following a hydrocarbon product spill: preliminary assessment of site recovery (Publication No. 4651). International Oil Spill Conference. American Petroleum Institute, pp. 823–828.

Pezeshki, S.R., DeLaune, R.D, 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., DeLaune, R.D., Patrick Jr., W.H., 1989. Effect of fluctuating rhizosphere redox potential on carbon assimilation of *Spartina alterniflora*. Oecologia 80, 132–135.

Pezeshki, S.R., DeLaune, R.D., Nyman, J.A., Lessard, R.R., Canevari, G.P., 1995. Removing oil and saving oiled marsh grass using a shoreline cleaner (Publication No. 4620). International Oil Spill Conference. American Petroleum Institute, Washington, D.C, pp. 203–209.

Pezeshki, S.R., DeLaune, R.D, Jugsujinda, A., Canevari, G.P., Lessard, R.R., 1997. Major field test evaluates a shoreline cleaner to save oiled marsh grass (Publication No. 465). International Oil Spill Conference. American Petroleum Institute, pp. 397–402.

Pezeshki, S.R., Jugsujinda, A., DeLaune, R.D., 1998. Responses of selected U.S. Gulf coast marsh macrophyte species to oiling and commercial cleaners. Water, Air and Soil Pollut. 107, 185–195.

Ranwell, D.S., 1968. Extent of damage to coastal habitats due to the Torrey Canyon incident. In: The Biological Effects of Oil Pollution in Littoral Communities. Field Studies Council, London, pp. 39–47.

Ranwell, D.S., Hewett, D., 1964. Oil pollution in Poole Harbour and its effects on birds. Bird Notes 31, 192–197.

Smith, L.M., Kadlec, J.A., 1985. Fire and herbivory in a Great Salt Lake marsh. Ecology 66, 259–265.

Smith, C.J., DeLaune, R.D., Patrick Jr., W.H., Fleeger, J.W., 1984. Impact of dispersed and undispersed oil entering a Gulf Coast salt marsh. Environmental Toxicology and Chemistry 3, 609–616.

Stebbings, R.E., 1970. Recovery of salt marsh in Brittany sixteen months after heavy pollution by oil. Environmental Pollution 1, 163–167.

Swannelle, R.P.J., Lee, K., McDonagh, M., 1996. Field evaluations of marine oil spill bioremediation. Microbiological Reviews 60, 342–365.

Teas, H.J., Lessard, R.R., Canevari, G.P., Brown, C.D., Glenn, R., 1993. Saving oiled mangroves using a new non-dispersing shoreline cleaner. In: Proceedings of the Oil Spill Conference. American Petroleum Institute, Washington, D.C.

Testa, S.M., Winegardner, D.L., 1991. Restoration of Petroleum-contaminated Aquifers. Lewis Publishers, Chelsea, MI, pp. 51–80.

Vandermeulen, J.H., Long, B.N.F., D'Ozouville, L., 1981. Geomorphological alteration of a heavily oiled saltmarsh (Ile Grande, France) as a result of massive cleanup. In: 1993 Oil Spill Conference. American Petroleum Institute, Washington D.C, pp. 347–351.

Venosa, A.D., Haines, J., Nisamaneepong, W., Govind, R., Pradhan, S., Siddique, B., 1991. Protocol for testing bioremediation products against weathered Alaskan crude oil. In: Proceedings of the International Oil Spill Conference. American Petroleum Institute, Washington, D.C, pp. 563–570.

Webb, J.W., 1977. Establishment of Vegetation for Shoreline Stabilization in Galveston Bay, Texas. PhD thesis, Texas A&M University College Station, TX.

Webb, J.W., 1994. Effects of Oil on Saltmarshes. Symp. Proc. Gulf of Mexico and Caribbean Oil Spill in Coastal Ecosystems: Assessing Effects, Natural Recovery, and Progress in Remediation Research. US Department of the Interior, Minerals Management Service, OCS Study/MMS 95-0063, New Orleans, LA, pp. 55–61.

Webb, J.W., Alexander, S.K., 1985. Effects of autumn application of oil on *Spartina alterniflora* in a Texas salt marsh. Environmental Pollution 38A, 321–337.