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Sensitivity of US Gulf of Mexico coastal marsh vegetation to crude oil: Comparison of greenhouse and field responses

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Abstract

Greenhouse and field studies were conducted to evaluate the effect of crude oil on selected US Gulf of Mexico coastal marsh species. Species showed different levels of sensitivity to oiling between greenhouse and field conditions. In greenhouse studies, two crude oils were used: South Louisiana crude oil (SLC) and Arabian Medium crude oil (AMC). The majority of *Spartina patens* plants died within one month following oiling with little or no recovery after three months. *Panicum hemitomon* and *Spartina alterniflora* were also adversely affected by oiling under greenhouse conditions but to a lesser extent than *S. patens*. The SLC or AMC oiling led to biomass reductions in *S. alterniflora* and *S. patens.* The dry biomass was not affected by oiling in *P. hemitomon, Sagittaria lancifolia, Typha latifolia*, and *Scirpus olneyi*. Results showed that *S. patens* plants were more sensitive to SLC as compared to AMC oil. Gross CO_2-C fixation data collected in the greenhouse indicated no differences in recovery among species across oiling treatments for *S. lancifolia*, *S. olneyi*, and *T. latifolia*. Field studies with *S. alterniflora, S. patens* and *S. lancifolia* demonstrated initial sensitivity of these species to oiling, and recovery following oiling with SLC. Our data also showed that caution must be employed whenever results from greenhouse studies are extrapolated to predict oil impact on vegetation under field conditions. Development of any sensitivity index of plant responses to oiling should not be based on greenhouse experiments only. Field evaluations should be included which best depict plant responses to oiling. Thus, restoration measures of US Gulf of Mexico coastal marshes following oiling should rely primarily on field studies. The field research suggests that the US Gulf of Mexico coastal marsh vegetation are likely to recover from oil spills naturally without the need for remediation procedures.

Introduction

The US Gulf of Mexico coastal zone is a region characterized by continuous, widespread, and intense activities associated with oil and gas production. Such activities create the potential for oil spill, thus, impacting the productivity of estuarine organisms that support a rich fishery and diverse wildlife habitats (Pezeshki and DeLaune 1993). Reported effects of oil on marsh plants range from short-term depressions of photosynthesis to mortality (Baker 1970; Pezeshki and DeLaune 1993). Marsh vegetation provides detritus to food webs (Mitsch and Gosselink 1993). Oil affects plants by disrupting plant-water relations, metabolism, nutrient uptake (McCown and Denek 1972), cause cell death (Prendevolle and Warren 1977), and reduce gas exchange between atmosphere and the soil affecting root functioning (Stebbing 1970). Burns and Teal (1979) found that oil can persist in salt marsh sediments years after spill. Oil also affects soil microbial communities (Alexander and Webb 1985a). The important microbial community regulates the flow of energy in plant-dominated food webs and also controls nutrient regeneration in marsh soils, which affects plant growth. Thus, oil may have long-term effects on marsh functions even after plant growth resumes.

When South Louisiana crude oil was applied to a set of replicate field plots in a Louisiana *Spartina alterniflora* salt marsh, oiling caused no reduction in biomass production as compared with the non-oiled plots (DeLaune et al. 1984). Alexander and Web (1985b) reported that season did not influence *S. alterniflora* response to oil when applied to sediment and lower plant portions, but season did influence *S. alterniflora* response to oil when applied to entire plant canopy. They also concluded that oil damage to *S. alterniflora* varies with types of oil, oil concentrations, height of plant coverage, seasons and ecosystems. Each of these factors must be evaluated in assessing oil damage.

Studies of toxicity of crude oil to plant species found in U.S.Gulf of Mexico coastal marshes yielded interesting results. For example, Lytle (1975) found decreased production of *S. alterniflora* immediately following an oil spill, but the oil had no noticeable long-term effects on *S. alterniflora* biomass. Crow et al. (1976) observed little damage to living *Spartina alterniflora* or reduction in regeneration of new plants after the application of 250 ml m^{-2} of Arabian light crude oil to marsh plots. DeLaune et al. (1979) reported that *S. alterniflora* could tolerate a large amount of oil without a short-term decrease in aboveground biomass. Lin and Mendelssohn (1996) reported that photosynthesis of *Spartina patens* significantly decreased after one month of oil application, while the photosynthetic rate of *S. alterniflora* was not significantly reduced by oil application until three months, and *Sagittaria lancifolia* was not detrimentally affected by the oil treatments. There have been many studies of crude oil's effect on freshwater and brackish marsh plant species. However, comprehensive studies comparing responses of a diverse group of species to oiling is still lacking. Furthermore, comparison of field and greenhouse studies were needed to provide the necessary data to allow assessment of differences found in reported data in the literature.

The overall objective of this project was to compare relative responses of selected US Gulf of Mexico coastal marsh species (fresh, brackish, and salt) to petroleum hydrocarbons under greenhouse and field conditions. Gross fixation of CO_2-C and growth and biomass were used as determinants of overall physiological status and health of plants.

Materials and methods

Crude oils used in the studies

The petroleum crude oils used in this study were: 1) South Louisiana "sweet" crude oil (SLC) which is enriched with light aromatic hydrocarbons, paraffins, and olefins, and contains low levels of N-, O-, and S-containing heterocyclic compounds such as the quinolines, thiophenes, and furans; and 2) Arabian Medium crude oil (AMC) which is transported through the Louisiana's Offshore Oil Pipeline. The Oil analysis of the two crude oils sources used showed both SLC and AMC contained similar concentrations of hydrocarbon compounds and both did not contain anthracene, except perylene-d12 which was 10 times higher in concentration (1558.4 μg/ml) in AMC as compared with SLC (155.4 μg/ml). Other differences were that acenapthene, fluranthene, and indeno (1,2,3-cd) pyrene was not found in AMC but was found in SLC (Kinghorn 1983).

Greenhouse studies

Fifteen intact marsh soil/plant plugs per vegetative type of monoculture used in the study were collected from Louisiana salt, brackish and fresh water marshes and acclimated to greenhouse conditions. Vegetation included *Spartina alterniflora* (saltwater marsh), *Spartina patens* (brackish water marsh), *Panicum hemitomon*, *Sagittaria lancifolia* , *Scirpus olneyi* , and *Typha latifolia* (all freshwater marsh). Total number of plug collected was 90. The plugs were 15 centimeters in diameter and 30 centimeters deep; they contained rooted plants roughly 40 cm tall. A 30-cm long sharpened 15-cm diameter PVC tubing was inserted into the marsh. The tubing containing soil and plant were removed and a PVC cap fixed over the bottom of the plugs (each plug containing plants and the associated roots and sediment represented one pot). Plugs were brought to the greenhouse where they were watered with tap water as needed. Vegetation was also washed weekly with a mist of tap water to remove any salt that accumulated on the leaves.

After the plants were acclimatized to the greenhouse condition for sixty days, the plants were fouled with either SLC or AMC oils. The crude oils were weathered by storing the oil in uncovered pans prior to application. Oil was applied manually at the rate of 2 l m^{-2} by wearing a cotton glove that was dipped in oil. An oil-proof glove was worn under the cotton glove to prevent skin contact with the oil. Following treatments were applied: 1) oiled with SLC, 2) oiled with AMC, and 3) no oil, control.

Treatments were arranged in a randomized complete block design consisting of five replications per vegetation type. Plant responses to the treatments were evaluated by monitoring changes in photosynthesis and respiration using the following techniques:

Photosynthetic rates for each plug were estimated from the difference between the rates of CO_2 change in light and dark chambers (Smith et al. 1981). Light and dark chambers were randomly placed over the experimental area in standing water to make an airtight chamber. Chambers were 1-m tall and 25-cm in diameter. Light chambers were constructed of clear Plexiglas and equipped with a rubber stopper for withdrawing gas samples. Dark chambers were similar, but covered with aluminum foil to block sunlight. The initial air volume was determined from the chamber diameter, chamber height, and water depth. Air samples (15 ml) collected over a 15 min. period in the chamber were stored in 10-ml Vacutainers (Becton Dickinson and Company, Rutherford NJ, USA) and returned to the lab. Subsamples (1 ml) were analyzed for CO_2 content with a gas chromatograph (Shimadzu, model GC-14A) and thermal conductivity detector (TCD). Gas samples were collected at 1 and 8 weeks after oiling.

Plug respiration, which included vegetation and soil communities, was estimated from the CO_2 increase occurring when a plug was placed in the dark chamber. Measurements made during darkness reflect only respiration, which produces CO_2 (change in CO_2 in dark = respiration). Measurements made during light reflect CO_2 produced during respiration as well as CO_2 depletion by photosynthesis (change in CO_2 in light = photosynthesis-respiration). Gross CO_2-C fixation was calculated from the algebraic sum of the fluxes determined with the light and dark chambers (Smith et al. 1981).

Whole plug gas samples were collected one and eight weeks after applying crude oils. Whole plug photosynthesis and whole plug respiration data were analyzed as repeated measures. Stem count data were also collected prior to oiling, one and three months after oiling.

The aboveground biomass components were harvested three months after oiling and dry weight of live and dead materials was determined by drying the harvested biomass at 80 ^oC to a constant weight. Number of dead and live plants, weight of biomass and CO_2-C gross carbon fixation (photosynthetic activity) were used in assessing the impact of the two crude oil sources on the study species.

Field studies

A permit was obtained from the Louisiana Department of Wildlife and Fisheries to conduct field studies in which oil was applied to marsh. The study was part of an overall study of oil impacted Gulf Coast marsh evaluating burning and dispersant application as remediation methods for removing oil from Louisiana Gulf Coast marsh (Lindau et al. 1999, Devai et al.1998, Pezeshki et al. 2001). Following the greenhouse studies, three field studies were conducted at three different sites at Louisiana Department of Wildlife and Fisheries, Pointe aux Chiens Wildlife Management Area, Montegut, Louisiana, USA (90° 50' W, 29° 50' N). The first study was conducted in 1995 in a monotypic stand of *S. alterniflora* salt marsh. Plant responses were monitored at the end of first growing season (12 weeks after oiling) and again after the second growing season (1996) to evaluate residual effect of oiling. The second study was conducted in 1996 in a monoculture of brackish water marsh populated with *S. patens*. The third study was conducted in 1996 in a freshwater marsh populated with a pure stand of *Sagittaria lancifolia.* The second and third studies were monitored only over one growing season. *S. patens*' biomass including number of live and dead shoots were measured 16 weeks after oiling or at the end of growing season. Due to a fast rate of plant growth turnovers, changes in responses to oiling for *S. lancifolia* were measured on a more frequent basis (four and eight weeks after oiling) than for other study species.

Eight enclosures (240 × 240 cm each) were constructed using 240 × 60 cm plywood sheets for each vegetative type. The enclosures were driven down into the marsh surface at study site so that 45-cm remained above the surface. Absorbent boom was placed around plot to prevent oil from leaking out of the plots. SLC oil was applied manually at the rate of 2 l m^{-2} onto the plant canopy. SLC was used because our greenhouse studies showed that many species were most sensitive to this oil. The treatments used

Table 1. Effect of South Louisiana crude (SLC) oil and Arabian Medium crude (AMC) oil on number of live shoots per pot (plug) and weight of dry biomass (above ground portion) per pot (plug) of six marsh species at harvest (Greenhouse Evaluation). Values are means of five replications (SD values are given in parenthesis). Within the same species, column means followed by different letters are significantly different at 0.05 level (Duncan's Multiple Range test).

Treatment	Species *Spartina alterniflora* (Smooth Cordgrass)	*Spartina patens* (Wiregrass)	*Panicum hemitomon* (Maiden Cane)	*Sagittaria lancifolia* (Bull-tongue)	*Typha latifolia* (Cattail)	*Scirpus olneyi* (Three corner)
Number of live shoots (shoots/pot)						
Control	17.2 a (5.8)	112.0 a (11.9)	33.0 a (6.8)	5.2 a (0.8)	20.8 a (9.5)	31.0 a (7.3)
SLC	14.0 a (4.9)	3.2 b (0.8)	28.6 a (5.3)	6.2 a (1.0)	5.0 b (0.8)	39.6 a (8.6)
AMC	15.6 a (5.1)	76.2 a (7.8)	25.8 a (4.5)	5.8 a (1.1)	8.2 b (1.1)	13.0 b (3.9)
Weight of dry biomass (g/pot)						
Control	104.6 a (9.8)	136.5 a (8.4)	44.3 a (3.2)	8.1 a (1.2)	36.2 a (3.2)	36.3 a (4.1)
SLC	49.2 b (7.3)	2.5 c (0.3)	36.8 a (2.8)	6.8 a (0.9)	32.8 a (3.7)	45.9 a (5.2)
AMC	45.2 b (6.1)	61.8 b (4.5)	30.7 a (3.2)	10.7 a (1.1)	46.4 a (4.1)	45.0 a (5.1)

were (1) oiled, and (2) control, no oil. The treatments were arranged in a randomized complete block design consisting of four replications (plot).

Plant responses to the treatments were monitored at selected intervals throughout the study. These intervals were based on differences in growth characteristics of the study species. During the growing season, changes in photosynthetic carbon fixation were evaluated periodically. Photosynthetic rates were estimated using similar techniques described for the greenhouse studies mentioned above. In addition, data on number of live plants, dead plants, new shoots and plant height recorded. The aboveground biomass components were cut at the end of the growing season, and dry weights of live and dead materials were determined by drying the harvested biomass at 80 °C to a constant weight as mentioned above.

Data analyses

Analysis of Variance (ANOVA) and the Student's t-test procedures (SAS Institute, Inc, Cary, NC, USA) were used to test for differences in growth and CO_2-C gross fixation among the treatment means in both greenhouse and field studies. These results of tests were considered significant at the 5% level of probability.

Results

Greenhouse studies

Growth

The effect of SLC and AMC oils on marsh vegetation as represented by *S. alterniflora, S. patens, P. hemitomon*, *S. lancifolia, T. latifolia*, and *S. olneyi*, varied depending on plant species (Table 1). At harvest, number of live shoots recorded for study species showed a different response to the study oils. Number of live shoots was reduced for *S. patens* in response to SLC, for *T. latifolia* in response to SLC and AMC, and for *S. olneyi* in response to AMC at the end of three months. Biomass of the six marsh species was also affected by oiling. The SLC or AMC led to biomass reduction in *S. alterniflora* and *S. patens.* The dry biomass was not affected by oiling in *P. hemitomon, S. lancifolia, T. latifolia*, and *S. olneyi*. Results show that *S. patens* plants were more sensitive to SLC as compared to AMC oil.

Gross CO_2-C fixation

Gross (or whole plug) carbon fixation as affected by the treatment is shown in Table 2. *S. alterniflora* displayed a significant reduction in gross fixation one week following exposure to either SLC or AMC. Gross fixation did increase with time indicating recovery of carbon fixation of the plants. After eight weeks gross fixation approached or was equal to the control. The increase or recovery in fixation was also reflected in the number of live plant shoots at the end of three months (Table 1).

Table 2. Effect of South Louisiana crude (SLC) oil and Arabian Medium crude (AMC) oil on CO_2-C gross fixation by six marsh species (Greenhouse Evaluation). Values are means of five replications (SD values are given in parentheses). Within the same species, column means followed by different letters are significantly different at 0.05 level (Duncan's Multiple Range test).

	CO_2-C gross fixation of six marsh species (g CO_2-C per pot per hour)					
Treatment	*Spartina alterniflora* (Smooth Cordgrass)	*Spartina patens* (Wire-grass)	*Panicum hemitomon* (Maiden Cane)	*Sagittaria lancifolia* (Bull-tongue)	*Typha latifolia* (Cattail)	*Scirpus olneyi* (Three corner)
1 week after oiling						
Control	0.097 a (0.1)	0.139 a (0.01)	0.05 a (0.06)	0.006 a (0.001)	0.04 a (0.005)	0.039 a (0.004)
SLC	0.016 b (0.005)	0.067 b (0.008)	0.014 b (0.003)	0.006 a (0.002)	0.019 a (0.003)	0.030 a (0.006)
AMC	0.018 b (0.005)	0.081 b (0.008)	0.018 b (0.005)	0.013 a (0.002)	0.017 a (0.003)	0.028 a (0.005)
8 weeks after oiling						
Control	0.057 a (0.006)	0.086 a (0.008)	0.043 a (0.004)	0.006 a (0.002)	0.034 a (0.003)	0.021 a (0.004)
SLC	0.055 a (0.006)	0.019 b (0.005)	0.042 a (0.005)	0.002 a (0.001)	0.017 a (0.003)	0.020 a (0.003)
AMC	0.034 a (0.004)	0.032 b (0.003)	0.039 a (0.004)	0.010 a (0.003)	0.027 a (0.004)	0.009 a (0.003)

Table 3. Effect of South Louisiana Crude (SLC) oil on growth of *Spartina alterniflora* marsh 12 weeks after oiling in 1995 and at the end of the 1996 growing season (Field Evaluation). Values are means of four replications (SD values are given in parenthesis). * denotes significant differences for each measured variable between treatments at the 0.05 level.

	Weight of dry biomass (g/m^2)			
	1995		1996	
Treatment	Live shoots	Dead shoots	Live shoots	Dead shoots
Control	292.1* (124.4)	298.8 (96.8)	670.0 (180.0)	0 *
SLC	94.4 (57.7)	351.9 (75.4)	560 (150.0)	370 (220.0)

SLC was toxic to *S. patens* as evidenced by substantial reductions in CO_2 fixation (Table 2). Some recovery was noted after 8 weeks primarily by initiation of new shoots but fixation rates in exposed shoots did not recover.

After 8 weeks, neither SLC nor AMC had any adverse effects on gross CO_2 fixation by *P. hemitomon*. There was an initial reduction in fixation after one week but this species had the ability to recover (Table 2). This species was capable of producing new leaf sheaths from the oil-coated plants as noted by high number of live shoots that allow resumption of carbon fixation (Table 1).

Photosynthetic carbon fixation for *S. lancifolia*, *S. olneyi*, and *T. latifolia* indicated no significant differences for each species across treatments (Table 2). Furthermore, there were no significant differences in responses of these species to oil types. The carbon fixation rates of the studied species, except *S. patens*, appeared to have recovered from any initial adverse effects of oiling in a relatively short period (Table 2).

Field studies

Growth

Dry biomass of live shoots per unit area of marsh in *S. alterniflora* study plots was reduced in response to SLC oiling in 1995 (Table 3). However, no adverse effects of residual oiling on weight of live shoots remained detecTable during the second growing season (1996). The first biomass harvest conducted at the end of the 1995-growing season (Table 3) revealed that the dead aboveground biomass was not significantly different between the treatments, while live biomass was reduced under oiled treatments. The second harvest in the 1996 growing season one year after oiling (Table 3) indicated that live aboveground biomass had recovered and was not significantly lower than control plots representing about 84 percent of control. Unlike the 1995 data that showed comparable values for dead aboveground biomass across treatments, 1996 dead shoots weight was significantly different across treatments (Table 3). The oiled plots had higher dead shoots weight than control plots. The accumulation of dead materials in oiled plots further in-

Table 4. Effect of South Louisiana Crude (SLC) oil on growth of *Spartina patens* at harvest (16 weeks after oiling) in the 1996 growing season (Field Evaluation). Values are means of four replications (SD values are given in parenthesis). * denotes significant differences for each measured variable between treatments at the 0.05 level.

Treatment	Plant height, % of control	Total stem number, % of control	Number of stems/m^2		Weight of dry biomass (g/m^2)	
			Live	Dead	Live	Dead
Control	100 (6.1)	100 (5.5)	1333.3 (93.3)	415.3 (61.5)	1384.2* (235.7)	388.8 (83.3)
SLC	86.6 (5.3)	81.1 (7.2)	826.6 (106.6)	592.2 (46.1)	582.8 (78.5)	538.8 (199.9)

Table 5. Effect of South Louisiana Crude (SLC) oil on growth of *Sagittaria lancifolia* (bulltongue*)* freshwater marsh species during the 1996 growing season (Field Evaluation). Values are means of four replications (SD values are given in parenthesis). * denotes significant differences for each measured variable between treatments at the 0.05 level.

	Number of shoots/m^2		Number of leaves/m^2	
Treatment	4 weeks after oiling	8 weeks after oiling	4 weeks after oiling	8 weeks after oiling
Control	63.1 (3.1)	48.8 (5.3)	183.2 (33.3)	141.2 (36.1)
SLC	57.3 (9.4)	53.6 (9.8)	91.6 (11.0)	180.5 (36.1)

dicated that oiling resulted in slow decomposition and thus, accumulation of dead biomass under field condition.

In contrast to *S. alterniflora*, *S. patens* was monitored only after one growing season. At harvest at the end of the 1996 growing season (16 weeks after oiling), SLC oiling did not affect the number of live and dead shoots per unit area of marsh in *S. patens* (Table 4). However, the aboveground biomass was reduced in oiled plots as compared to control.

S. lancifolia response was monitored at four and eight weeks following oiling in 1996. New shoots and leaves of *S. lancifolia* quickly appeared after oil treatments (Table 5). The new leaves were originated primarily from the culms. The regeneration of new shoots and leaves was not affected by the treatments. The number of shoots in oiled plots as compared to the control plots during these periods was not significantly different.

CO_2-C gross fixation

Response of CO_2-C gross fixation of *S. alterniflora* under field conditions during the 12 weeks period in the 1995 growing season showed significant initial reductions in carbon fixation in response to the treatment. However, the rates in oiled plants improved with time after 8 weeks (Figure 1). When CO_2-C gross fixation (g CO_2-C per m^2 per hour) values were examined at the end of the first growing season (week no. 12), it was evident that no significant ($p < 0.05$) adverse effects of oiling on plant gas exchange was detecTable, values were 90 percent of control in oiled treatments. Despite this recovery of gas exchange, the CO_2-C gross fixation rates per unit area of marsh remained lower in oiled plots as compared to the control plots. This finding was attributed primarily to low plant density in oiled plots due to initial plant mortality. Fewer live plants and less aboveground live biomass (Table 3) per unit marsh area during the first growing season had contributed to lower gross fixation per unit area of marsh observed in the oil plots under field condition.

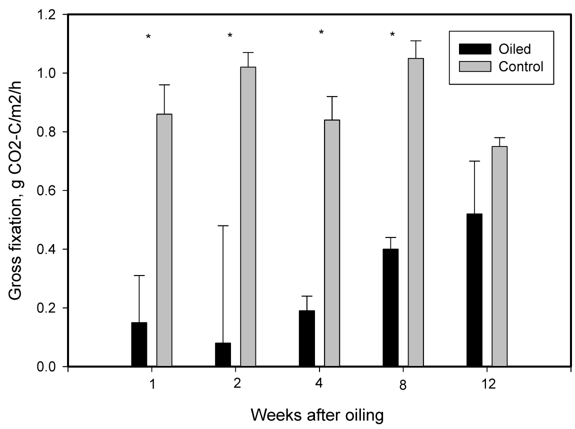

Figure 1. Effect of oiling by South Louisiana crude oil on gross fixation of CO_2-C by *Spartina alterniflora* (Smooth Cordgrass) saltwater marsh grass at different times after oiling (Field Evaluation, n = 4). * denotes significant differences between treatments at the 0.05 level.

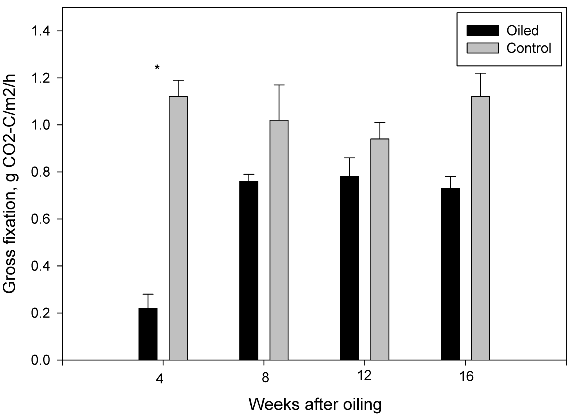

Figure 2. Effect of oiling with South Louisiana crude oil on gross fixation of CO_2-C by *Spartina patens* (Wiregrass) brackishwater marsh grass at different times after oiling (Field Evaluation, n = 4). *denotes significant differences between treatments at the 0.05 level.

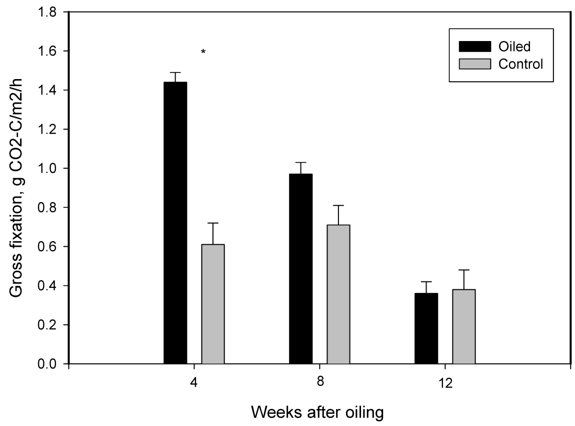

Figure 3. Effect of oiling with South Louisiana crude oil on gross fixation of CO2-C by *Sagittaria lancifolia* (Bulltongue) freshwater marsh grass at different times after oiling (Field Evaluation, n = 4). *denotes significant differences between treatments at the 0.05 level.

Time-course measurement of gas exchange of *S. patens* under field conditions showed significant reductions in CO_2-C gross fixation in response to the treatment (Figure 2). However, the rates improved in oiled plants within 8 weeks. From 8–16 weeks, CO_2-C gross fixation relative to control values were not significantly different representing 70–80 percent of control in oiled plants. These results indicated that there was a remarkable recovery of *S. patens* in oiled plots at harvest time under field condition.

A different response to oiling was shown by *S. lancifolia*. The photosynthetic carbon fixation measured 4 weeks after oiling was higher in the oiling treatment as compared to the control, most likely due to the production of a burst of new leaves and new shoots (Figure 3). After 8 weeks no significant differences between the treatments were observed. At 12 weeks, the CO_2-C gross fixation in all treatments was reduced following a tropical storm. Results indicated that gas exchange in *S. lancifolia* appeared to rapidly recover from any initial adverse effects of oiling.

Discussion

Greenhouse studies

Our data indicated that under greenhouse conditions the adverse effects of oiling on photosynthesis of *S. alterniflora* are short-term. After three months, oiled *S. alterniflora* plants had recovered as was evidenced from production of new leaves by the existing shoots and regeneration of new shoots (Table 2). Pezeshki et al. (1995) reported that during the second month following oil application to *S. alterniflora* canopy, gas exchange rates for the leaves that emerged after the treatment were similar to control plants under greenhouse conditions. Previous work by DeLaune et al. (1979), Smith et al. (1984), and Pezeshki and DeLaune (1993) found that under greenhouse conditions, *S. alterniflora and Juncus roemerianus* plants recovered from oiling with SLC.

In our greenhouse studies, *S. patens* exposed to SLC oil showed high sensitivity as few plants survived one month and three months after treatment. Lin and Mendelssohn (1998) found that under greenhouse condition *S. alterniflora* and *S. patens* plants were killed by SLC oil applied at the rate of 8 l m^{-2}. However, the residual oil in the soil did not significantly affect the biomass of both species two years after the application of the oil.

In this study, when *S. lancifolia*, a freshwater marsh species, was exposed to SLC oil under greenhouse conditions, the new leaves that emerged following oiling had photosynthetic rates similar to the control plants showing no detectable adverse effects of oiling.

Field studies

In our field study, after application of SLC oil, plants showed rapid recovery. Plants that were coated with oil died but the marsh vegetation recovered rapidly by regeneration of new shoots. The photosynthetic carbon fixation measurements also showed substantial recovery in the oiled treatments as a result of the regeneration and development of new shoots. As was evident in the greenhouse studies, the initial, short-term adverse effects of oil on plants were apparent. However, plants did recover. The speed and extent of such recovery appears to be species-specific and may depend on many factors including the type of oil, the mode of delivery, the timing of oiling and the amount of oil (Pezeshki et al. 2000). *S. patens*, a brackish marsh species, was very sensitive to oiling under greenhouse condition. When exposed to SLC, few plants survived at one month and at three months. When exposed to AMC oil, the plants recovered to some degree after three months. Under the field conditions, however, the impact of oil on this species was short-term. So, when given time, as shown in the field studies, this species also has the tendency to recover naturally.

The difference between the observed responses in the greenhouse, versus those noted in the field, reflect many factors that are different between these two environments. The response differences could be attributed to better rooting system of the plants in the field than in the greenhouse. The root growth of plants in the field usually is not confined to a small volume like potted plants (plugs) in the greenhouse. Therefore, the rooting system of the plants growing in the field is likely to be more extensive than in the potted plants. Thus, since the roots are major sinks and storage for carbohydrates (Barta 1988), there are larger pools of carbohydrate in the field-grown plants than in the greenhouse-grown potted plants. The *S. patens* plants fouled with SLC oil in the greenhouse mostly died and did not regenerate many new shoots. In contrast, the oiled plants in the field had the ability to regenerate from the underground rhizome vigorously. The photosynthetic carbon fixation showed substantial recovery in the oiled treatments with time in the field.

The work presented on marsh plant responses to oiling is a one-time episode representing only a portion of the potential responses. Plants such as *S. alterniflora* and *S. patens* have a substantial underground system of food reserves (rhizomes) and as a result, can withstand oil exposure and still produce vigorous new shoots (DeLaune et al. 1979; DeLaune et al. 1984; Pezeshki and DeLaune 1993; Webb 1994; Pezeshki et al. 1995; Proffitt et al. 1995). However, under chronic oil spill conditions, plants may respond differently with frequent spills resulting in stressed plants that are less likely to be capable of vigorous recovery. Gilfillan et al. (1995) compared two heavily oiled marsh systems after Amoco Cadiz oil spill (Brittany, France, 1978) and found that the marsh without clean-up recovered to its prior condition. The marshes, however, cleaned by removal of oiled sediment were extensively altered as a result of changes in intertidal height of the sediment surface.

Our studies showed different response or sensitivity to oiling under greenhouse as compared to field conditions. For example, under greenhouse conditions, *S. patens* died following exposure to SLC. *S. alterniflora* was also adversely affected. However, in the field studies these two important coastal marsh species recovered following oiling without long- term impact on growth.

Oil spill effects on coastal marshes are complex and thus, critical to be considered at various scales of resolution and modes of impact. It is known that much of the impacts to marsh vegetation involve adverse effects on the gas-exchange (transpiration and photosynthesis) surfaces of the plant due to blockage of stomata by oil. For these types of impacts, heavier weight oils may be as detrimental to vegetation as lighter weight oils that affect primarily at the cellular level by altering membrane permeability and disrupting plant metabolism (Pezeshki et al. 2000). Direct effects of oiling of marsh vegetation tend to be most severe on aboveground tissue, the tissue that comes in contact with the oil first. The effects of oil on marsh sediment can lead to increased oxygen stress in below-ground tissues due to reduced gas exchange between soil and atmosphere, disrupt root membranes affecting ion uptake and selectivity, and may adversely affect vegetative re-growth as newly germinated, sensitive shoots contact the oil as they emerge.

Conclusions

Our data demonstrated differences in sensitivity to oiling among the studied species. In addition, our data showed different responses or sensitivities to oiling under greenhouse as compared to field conditions. Based on our results, we conclude that: 1) Under field conditions, US Gulf of Mexico coastal marsh vegetation recovered following heavy oiling and presence of deposits or a layer of surface oil representing a typical shoreline oil pollution, 2) Greenhouse studies of oil impact on marsh vegetation could not always be extrapolated for predicting oil impact under field conditions, 3) Development of any sensitivity index for plant response to oiling should not be based on greenhouse data only as field evaluations would best represent plant responses to oiling, and 4) the best restoration strategy for coastal vegetation, following oil entering US Gulf of Mexico coastal marshes would be natural recovery without the need for any remediation or clean-up effort.

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