Dispersant Effects on Salt Marsh Vegetation: Toxicity Evaluation and Oil Remediation

Qianxin Lin
and
Irving A. Mendelssohn

Wetland Biogeochemistry Institute
School of the Coast and Environment
Louisiana State University
Baton Rouge, LA 70803

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Abstract

Oil spills in nearshore or estuarine environments may eventually be moved to shorelines by currents, tides, and winds. Coastal salt marshes are one of the most vulnerable habitats to oil impacts because spilled oils may strand inside the marshes and impact organisms. One strategy for coastal habitat protection and oil remediation may be to apply dispersants to the spilled oil before the oil drifts into the marshes. Our previous study indicated the potential of the dispersant JD-2000 for relieving the impacts of oil on fresh water marsh plants. The overall goal of this project was to determine the potential use of dispersants as an oil spill countermeasure in nearshore environments where spilled oil may move into coastal salt marshes and impact sensitive habitats. Specifically, the objectives of the project were to: (1) evaluate the toxicity of dispersants on coastal salt marsh plants by determining the dose-response of plants to different dispersants, (2) evaluate the toxicity of different dispersed diesel oils by determining the dose-response of coastal marsh plants to the dispersed oils, (3) compare the effects and effectiveness of dispersants applied in a simulated nearshore environment to counter the impact of oils (diesel and crude) on salt marsh plants.

The dose-response of the salt marsh plant *Spartina alterniflora* to the dispersants indicated that plant tolerance to this dispersant was relatively high. The marsh plant *S. alterniflora* was not impacted by the dispersants JD-2000 at dosages ≤ 12,000 ppm and Corexit 9500 in dosages between 4000 and 6000 ppm, based on plant live stem density, plant mortality rate, and plant aboveground biomass. In an experiment that determined the dose-response relationship and toxicity of dispersed oils to the salt marsh plant, live stem density, mortality rate, and live aboveground biomass of *Spartina alterniflora* were negatively affected by the JD-2000 and Corexit 9500 dispersed diesel at concentrations ≥ 12,500 ppm applied to the soil substrate. It appeared that the toxicity of dispersed oil to the salt marsh plants primarily resulted from the oil itself. Furthermore, dispersants greatly reduce impacts to vegetation if the oil is dispersed in nearshore environments before it comes in contact with coastal salt marshes. The dispersants JD-2000 and Corexit 9500 greatly relieved the adverse effects of both diesel and crude oil on the aboveground components of *S. alterniflora*. Without application of the dispersants, both diesel and crude oil significantly affected the salt marsh plants. One thousand ppm of diesel alone resulted in > 90% mortality of aboveground components of *Spartina alterniflora*; the salt marsh plant took a much longer time to recover from the diesel impacts than from the crude oil impacts. The present study indicates the potential of using dispersants as alternative countermeasures to oil spills in nearshore environments.

Dispersant Effects on Salt Marsh Vegetation: Toxicity Evaluation and Oil Remediation

1.0. Introduction

The risk of oil spills in Louisiana's coastal zone is high because of intensive oil-related activities in this area. Not only can spilled oil harm coastal habitats and associated organisms, but cleaning up oil in densely vegetated coastal marshes may do more damage than the oil itself. Preventing oil from stranding and coating sensitive coastal marshes is an important way to protect these habitats. Dispersants have received considerable attention for their usefulness in open, deep-water oil spills. Dispersants may also be helpful in coastal wetlands, pending further evaluation.

The use of dispersants for oil spill cleanup has attracted great attention since the Exxon *Valdez* oil spill in 1989. However, scientists disagree about dispersants' effectiveness and toxicities. These issues have been discussed since dispersants were introduced during the Torrey Canyon oil spill in 1967 (Cunningham et al. 1991; Venosa et al. 1999). Dispersants are chemicals that contain surfactants, or compounds that break liquid substances like oil into tiny droplets in the water column. This helps to remove oil from the water surface, making it less likely that an oil slick will reach or strand in sensitive habitats, such as coastal marshes. Dispersant use has been recommended as a way to disperse oil slicks in the sea before coastal habitats can be reached, although minimal guidelines have been outlined (Page et al. 2000). Therefore, studies examining the effects of dispersants have mainly focused on marine organisms, such as fishes and shrimp, and the larvae of fishes, crabs, and corals (Singer et al. 1994; Rhoton et al. 1999; Gulec and Holdway 2000; Epstein et al. 2000; Wolfe et al. 2001). Most of the studies on marine organisms were acute toxicity tests. However, decisions to use oil spill response chemicals should not be based solely on aquatic toxicity (George and Clark 2000).

A number of studies have examined dispersants' effects on plants from salt to fresh water marshes, although dispersant application is not pre-approved in Louisiana or Texas for water less than 10 m deep (RRT-6-OCS, 1996). Some studies indicated that dispersants, such as BP1100WD (Baker et al. 1984), Corexit 9527 (Lane et al. 1987), and BP Enersperse 1037 (Little and Scales 1987) were ineffective in cleaning an oiled salt marsh, and had greater detrimental impacts on *Spartina anglica*, *Salicornia* spp., *Spartina alterniflora* and *Aster spp*. than did oils without applied dispersants. In contrast, other studies (Smith et al. 1984) demonstrated that dispersants applied to Louisiana crude oil contaminated *Spartina alterniflora* provided short-term benefits to plant photosynthesis. However, these studies found that the dispersants did not have long-term effects on plant biomass.

Our recent study, which examined the effects of the dispersant JD-2000 on fresh water marsh plants (Lin and Mendelssohn 2003), indicated the potential for using dispersants as countermeasures during oil spills in nearshore environments. The dose-response of the fresh marsh plant *Sagittaria lancifolia* to the dispersant JD-2000 indicated that the plant's tolerance to this dispersant was relatively high (Lin and Mendelssohn 2003). The fresh water marsh plant

Sagittaria lancifolia was not impacted by the dispersant JD-2000 at dosages ≤ 4,000 ppm and was able to recover at dispersant dosages as high as 16,000 ppm, because the toxicity of the dispersant decreased during the 10-month experiment. In addition, in an experiment that simulated oil dispersed before coming in contact with marshes, the dispersant JD-2000 greatly relieved the adverse effects of both diesel and crude oil. Without the dispersant, both diesel and crude oil significantly decreased photosynthetic rates and increased mortality even at a 50 ppm dosage. Two thousand ppm of diesel without the dispersant resulted in > 60% mortality of aboveground components. In contrast, neither the dispersed crude nor the dispersed diesel significantly affected *S. lancifolia* compared to the no-oil control.

The dispersants used today are more effective and much less toxic than earlier products (NRC 1989). For example, a more recently marketed dispersant, Corexit 9500, contains the same surfactants as Corexit 9527 and an improved oliophilic solvent delivery system. The dispersant JD-2000, manufactured and marketed by Van Waters and Rogers in 2001, is especially effective for South Louisiana crude oil (EPA 2001) in both salt and fresh water. Both are high performance, biodegradable oil spill dispersants listed in the National Contingency Plan (EPA 2001). The efficacy of dispersants may vary with different spill scenarios. Dispersants generally are more effective in saltwater than in freshwater. They also work better on less viscous oil, and in warmer temperatures (NRC 1989; Guyomarch et al. 1999; EPA 2001). Thus, dispersant use may be effective in the near subtropical climate of Louisiana's coastal wetlands. However, little information is available about the toxicity and effects of dispersants on marsh habitats. This lack of information makes it difficult to develop useful strategies for using dispersants in the nearshore to protect sensitive coastal habitats.

1.1. Goal and Objectives

The overall goal of this project was to determine the potential use of dispersants as oil spill countermeasures in nearshore environments where spilled oil may move into coastal salt marshes and impact sensitive habitats. Specifically, the objectives of the project were to: (1) evaluate the toxicity of dispersants on coastal salt marsh plants by determining the dose-response of plants to different dispersants, (2) evaluate the toxicities of different dispersed diesel oils on coastal salt marsh plants by determining the dose-response of plants to the dispersed oils, (3) compare the effects and effectiveness of dispersants applied in a simulated nearshore environment to counter the impact of oils (diesel and crude) on salt marsh plants for habitat protection.

2.0. Materials and Methods

The experiments were conducted in two phases. Phase 1 involved a determination of the dispersants' toxicities and the effect of chemically dispersed diesel applied into the soil salt on marsh plants. Phase 2 involved determining if nearshore dispersant application protected habitats and promoted oil remediation of coastal salt marshes.

2.1. Phase 1. The Toxicity of Dispersant and Dispersed Oils Applied to the Soil on Salt Marsh Plants

2.1.1. Task 1. Dose-Response Relationship between Dispersants Applied to the Soil and the Growth of the Salt Marsh Plant, *Spartina alterniflora*

The salt marsh plant, *Spartina alterniflora,* was collected from coastal Louisiana and transplanted to the potting substrate, Jiffy Mix Plus. Plants were maintained in the greenhouse and grown until they reached a satisfactory size and health. The dispersants JD-2000 (a product of Van Waters and Rogers, Cincinnati, OH) and Corexit 9500 (a product of Exxon) are both listed in the National Contingency Plan (EPA 2001). These dispersants were applied in concentrations of 0, 1000, 2000, 4000, 6000, 8000, 12000, and 16000 ppm. The dispersants were applied to the soil substrate containing healthy *Spartina alterniflora* to determine the dose-response relationship between the chemical dispersants and growth of the marsh plant. This toxicity test was designed to provide reference data about the dispersants' toxicity to plants compared to the standard bioassay test on aquatic organisms. Each dosage was replicated three times. Short- and long-term toxicity and the effects of the dispersants on the plants were analyzed by measuring live stem density, plant leaf mortality rate, and aboveground biomass.

2.1.2. Task 2. Dose-Response Relationship between Chemically Dispersed Diesel Applied to the Soil and the Growth of the Salt Marsh Plant, *Spartina alterniflora*

As in Task 1, the salt marsh plant, *Spartina alterniflora,* was collected, transplanted, maintained in the greenhouse, and grown until it reached a satisfactory size and health. The dispersants JD-2000 and Corexit 9500 were pre-mixed with diesel at a ratio of 1:20 (within the manufacturer's recommended ratio of 1:10 to 1:50 of dispersant to oil). The dispersed diesel, ranging from 0, 800, 2000, 5000, 12500, and 31250 ppm of weathered diesel oil (25% weathered by v/v), was applied to the substrate containing healthy *Sagittaria lancifolia*. This was done to determine the dose-response relationship between chemically dispersed diesel and the growth of the salt marsh plant. This toxicity test provided reference data for environmental assessments. Each dosage was replicated three times. The dispersed diesel's toxicity was assessed by measuring the plants' live stem densities, plant leaf mortality rates, and live aboveground biomasses.

2.2. Phase 2. Potential and Effectiveness of Nearshore Dispersant Application on Habitat Protection and Oil Remediation

Oil spills in open water, nearshore environments, and estuaries may eventually move into coastal marshes. The oil may then strand and impact the marshes. It is extremely difficult to clean up oil stranded in marshes because the vegetation is highly sensitive to mechanical disturbance. Thus, one strategy may be to apply dispersants to the spilled oil before the oil comes in contact with salt marshes. We designed the following experiment to evaluate the effect of dispersed crude and diesel on marsh plant growth and oil remediation.

Intact soil sods (30 cm in diameter and 25 cm in depth) from a salt marsh dominated by *Spartina alterniflora* were extracted from coastal Louisiana. These sods were used in a mesocosm experiment conducted in the greenhouse.

The following treatments simulated the application of dispersants on oil spilled in nearshore environments, estuaries, and wetland canals before the oil drifted into marshes. Dispersed oil may move into the marsh with tides or currents, but most dispersed oil appears to move out with the ebbing tide because dispersed oil does not adhere to the surface of sediment particles or plant aboveground components.

The treatments were as follows:

- 1000 ppm weathered diesel fuel dispersed in the water column by the dispersant JD-2000
- 1000 ppm weathered diesel fuel dispersed in the water column by the dispersant Corexit 9500
- 1000 ppm weathered diesel fuel over the water column without applying any dispersants
- 1000 ppm weathered South Louisiana crude oil (SLC) dispersed in the water column by the dispersant JD-2000
- 1000 ppm weathered SLC dispersed in the water column by the dispersant Corexit 9500
- 1000 ppm weathered SLC over the water column without applying any dispersants
- A treatment with neither oil nor dispersant applied to the sods served as the control.

We simulated nearshore dispersed oil moving in and out of salt marshes by generating a tide with the appropriate concentrations of the oil or dispersed oil in the water so that 90% of the plant height was covered for a 30 minute period. Then, we caused the water to recede to 10 cm above the soil surface for the rest of a 12 hour high tide period. The standing water moved out of the sods from a hole in the buckets 10 cm above the soil surface. For the 12 hour low tide, the water table was lowered to the 10 cm below the soil surface. The water column 10 cm above the soil surface drained out of the sods through a hole in the buckets 10 cm below the soil surface. The water level was brought back to 10 cm above the sediment during the next high tide and 10 cm below the sediment during the next low tide for the following days until all oil was adsorbed into the sediment, and no oil floated back to the tidal water during the high tide. Thereafter, we maintained the water table fluctuation between 0 and 10 cm below the soil surface throughout the experiment. The experimental design was completely randomized with a 3 x 2 factorial treatment arrangement [three dispersant levels (JD-2000, Corexit 9500, and no dispersants) and two oil types (SLC and diesel)], plus an overall control. Each treatment-level combination was replicated five times. The experiment lasted a full growth cycle. The effects and toxicities of the oils and dispersed oils were analyzed by measuring the live stem density, plant mortality rate, and plant aboveground biomass.

2.3. Methods

Plant stem density. Plant live stem density was analyzed by directly counting the numbers of live stems in each experimental unit.
Plant mortality rate. The mortality rate was estimated visually for each experimental unit.
Aboveground biomass. Aboveground biomass was harvested at the soil surface, separated by live and dead stems, and dried at 65 °C to a constant weight.

2.4. Statistical Analysis

A statistical analysis was conducted with the Statistical Analysis System (SAS, version 8.02). Plant parameters were analyzed with general linear models (GLM). Duncan's Test was used to evaluate statistical differences. Significant differences were reported at the 0.05 probability level unless otherwise stated.

3.0. Results

3.1. Task 1 of Phase 1. Dose-Response Relationship between Dispersants Applied to the Soil and the Growth of the Salt Marsh Plant, *Spartina alterniflora*

Plant responses to dispersants are generally slower than responses of marine organisms as indicated by Lin and Mendelssohn (2003). Adverse effects of high concentrations of Corexit 9500 on *Spartina alterniflora* were observed 48 hours after the dispersant treatment (Fig. 1), with some plant leaves rolled up and brown in color at high concentrations of Corexit 9500. The impacts became more severe seven days after the treatment (Fig. 2). Four months after the treatment, the effects of high concentrations of Corexit 9500 were still very obvious (Fig. 3). However, application of JD-2000 did not have obviously visual effects *on Spartina alterniflora* even seven days after the dispersant treatment (Figs, 1, 2). No obvious effects of JD-2000 on *Spartina alterniflora* were observed four months after the treatments (Fig. 3).

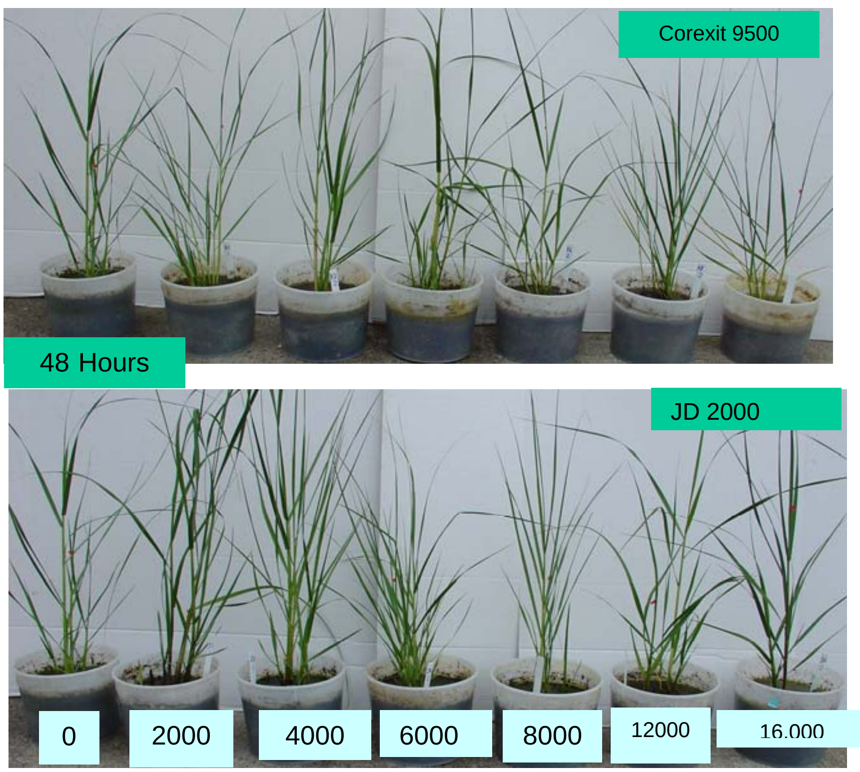

Fig. 1. Growth status of *Spartina alterniflora* in different concentration of dispersants applied to the soil substrate 48 hours after the treatment.

Fig. 2. Growth status of *Spartina alterniflora* in different concentration of dispersants applied to the soil substrate seven days after the treatment.

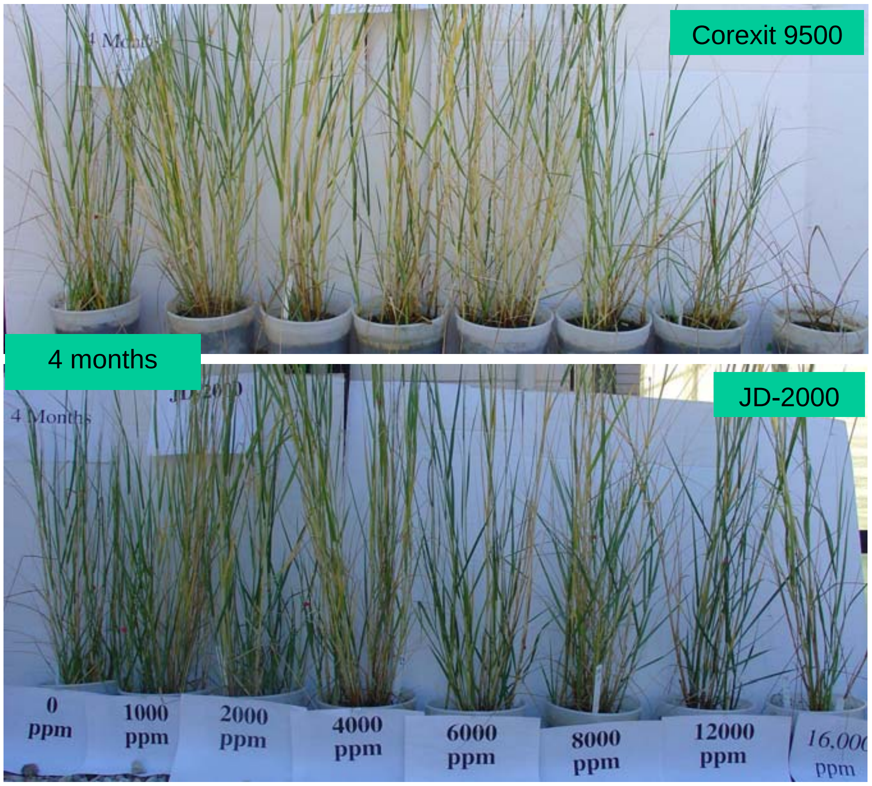

Fig. 3. Growth status of *Spartina alterniflora* in different concentrations of dispersants applied to the soil substrate four months after the treatment.

3.1.1 Plant Stem Density

The effect of dispersants on plant stem density differed with dispersant type and concentration. Live stem density of *Spartina alterniflora* decreased with increasing dispersant concentrations, especially for Corexit 9500. One month after application of dispersants, live stem density was significantly lower in the treatment with concentrations of Corexit 9500 > 12000 ppm (Fig. 4). Live stem densities tended to be lower in the treatments with high concentrations of JD-2000, although live stem densities were not significantly different among the treatments due to large variation (Fig 4). Two and half months after the treatment, live stem densities tended to be lower in the treatments with high concentrations of JD-2000 or Corexit 9500, although there were no significant differences among the treatments due to large variation (Fig. 5).

3.1.2 Mortality Rates of Salt Marsh Plants

Dispersant application increased plant mortality rates. We observed that plant leaf mortality occurred first for the oldest leaves of *Spartina alterniflora*. The mortality rate increased with increasing dispersant concentrations one month after the treatment (Fig. 6). One month after the treatments, the mortality rates were significantly higher in the treatment with the Corexit concentrations ≥ 6000 ppm and the JD-2000 ≥ 8000 ppm. In addition, mortality rates were higher in the treatment with Corexit 9500 than in treatments with JD-2000. Two and half months after the treatments, the mortality rates were significantly higher in the treatment with Corexit 9500 concentrations of ≥ 12000 ppm (Fig 7).

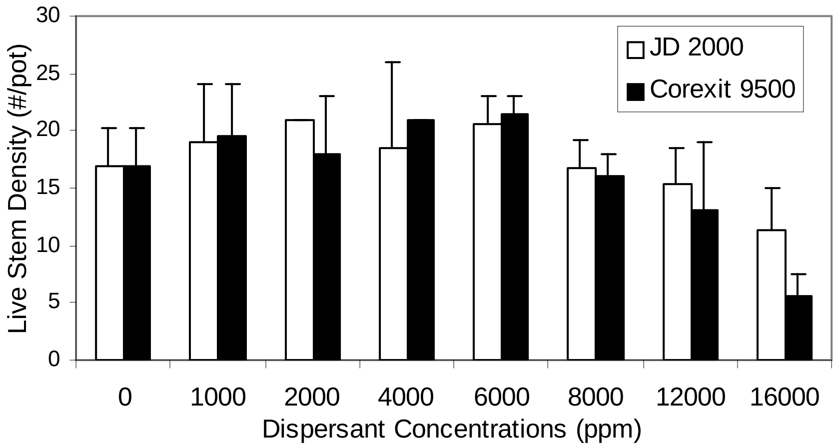

Fig. 4. Live stem density of *Spartina alterniflora* one month after different concentrations of the dispersant JD-2000 or Corexit 9500 were applied to the soil substrate.

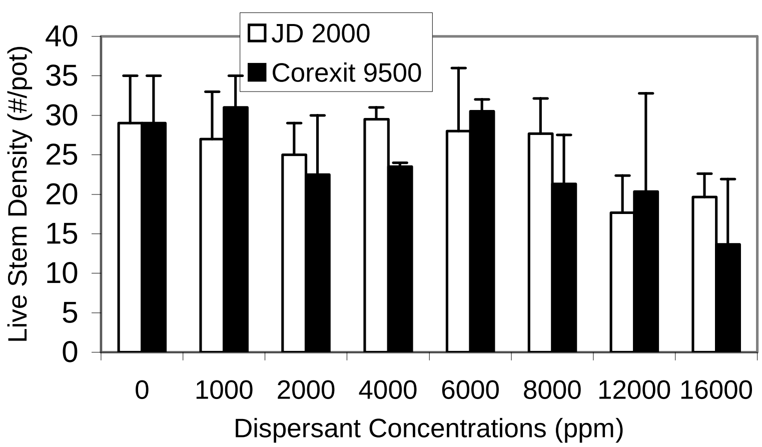

Fig. 5. Live stem density of *Spartina alterniflora* 2.5 months after different concentrations of the dispersant JD-2000 or Corexit 9500 were applied to the soil substrate.

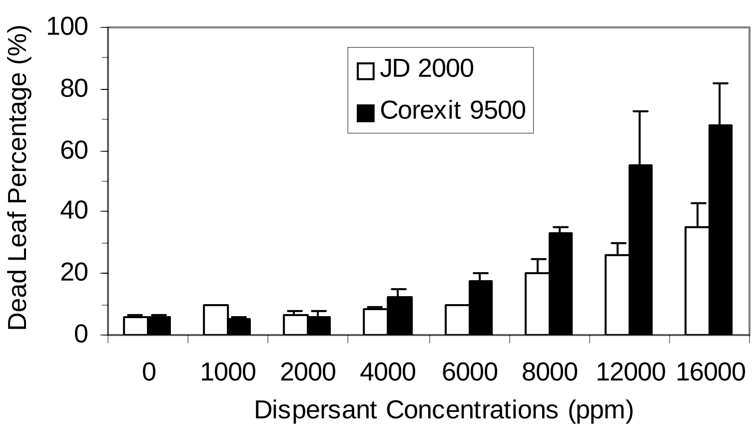

Fig. 6. Mortality rates of *Spartina alterniflora* one month after different concentrations of the dispersants JD-2000 or Corexit 9500 were applied to the soil substrate.

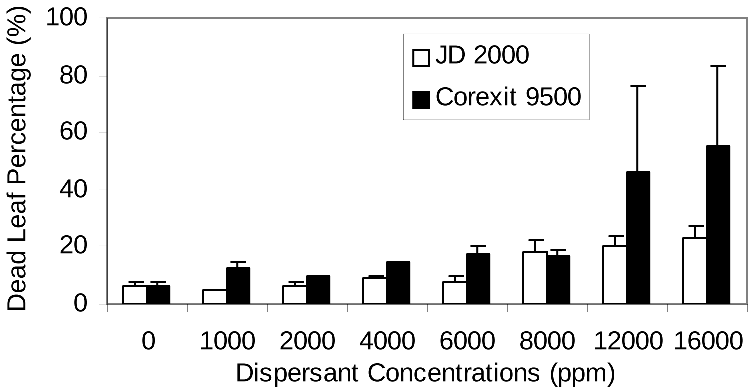

Fig. 7. Mortality rates of *Spartina alterniflora* 2.5 months after different concentrations of the dispersants JD-2000 or Corexit 9500 were applied to the soil substrate.

3.1.2.1 Biomass

Plant aboveground biomass was harvested four months after the treatments to determine the comprehensive effect of dispersants on the plants. Soil application of Corexit 9500 at high concentrations affected the plants' aboveground biomass. Aboveground biomass of *Spartina alterniflora* was significantly lower at the dispersant concentrations ≥ 12000 ppm of Corexit 9500 (Fig. 8). However, application of JD-2000 did not affect aboveground biomass of *Spartina alterniflora*, with no significant difference among all concentrations of JD-2000.

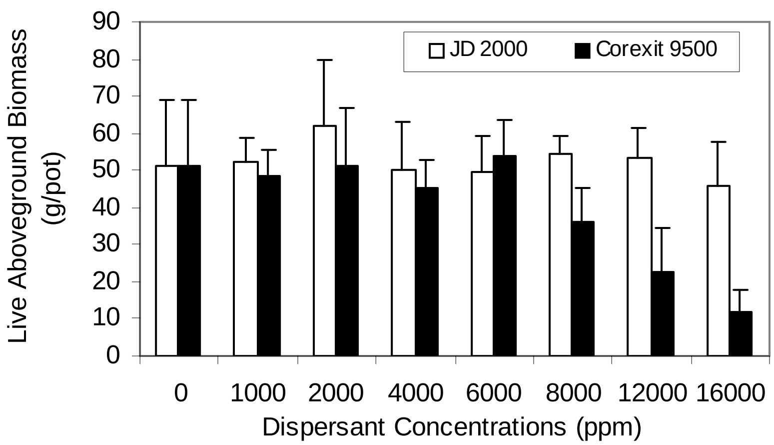

Fig. 8. Live aboveground biomass of *Spartina alterniflora* four months after different concentrations of the dispersants JD-2000 or Corexit 9500 were applied to the soil substrate.

3.2. Task 2 of Phase 1. Dose-Response Relationship between Dispersed Diesel Applied to the Soil and Growth of the Salt Marsh Plant, *Spartina alterniflora*

The effects of dispersed diesel on salt marsh plants increased with diesel concentrations. The visible impact symptoms on the salt marsh plant *Spartina alterniflora* showed 96 hours after the treatments, with leaves rolled and brown in color (Fig. 9). *Spartina alterniflora* was severely impacted by high concentrations of both Corexit 9500 and JD-2000 dispersed diesel (Fig. 10). The impacts of dispersed diesel in the soil at high concentrations lasted up to four months after the treatment (Fig 11.).

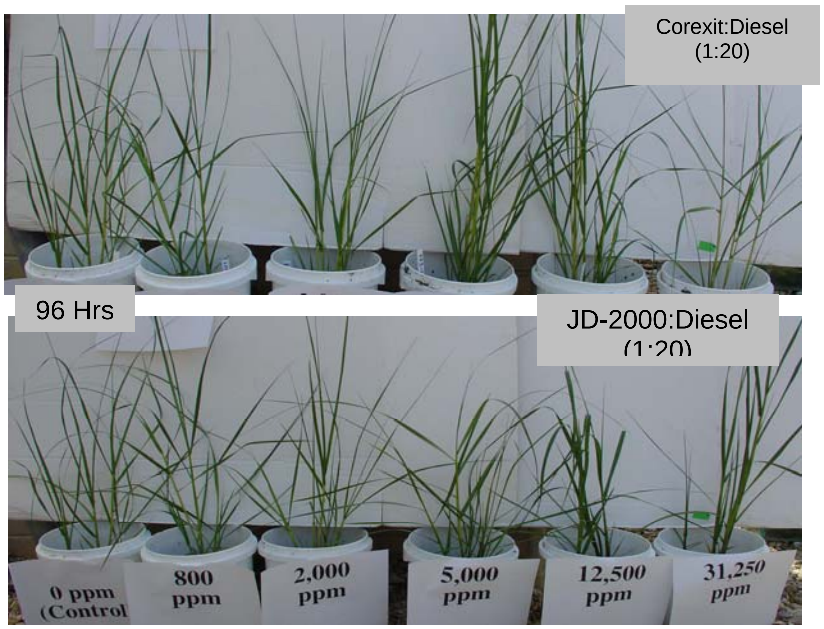

Fig. 9. Growth status of *Spartina alterniflora* 96 hours after different concentrations of Corexit 9500 or JD-2000 dispersed diesel were applied to the soil substrate.

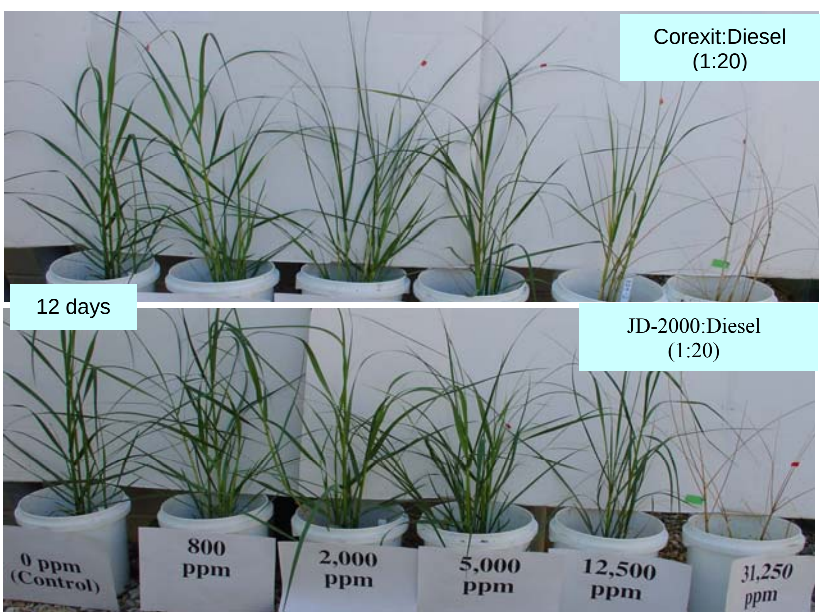

Fig. 10. Growth status of *Spartina alterniflora* 12 days after different concentrations of Corexit 9500 or JD-2000 dispersed diesel were applied to the soil substrate.

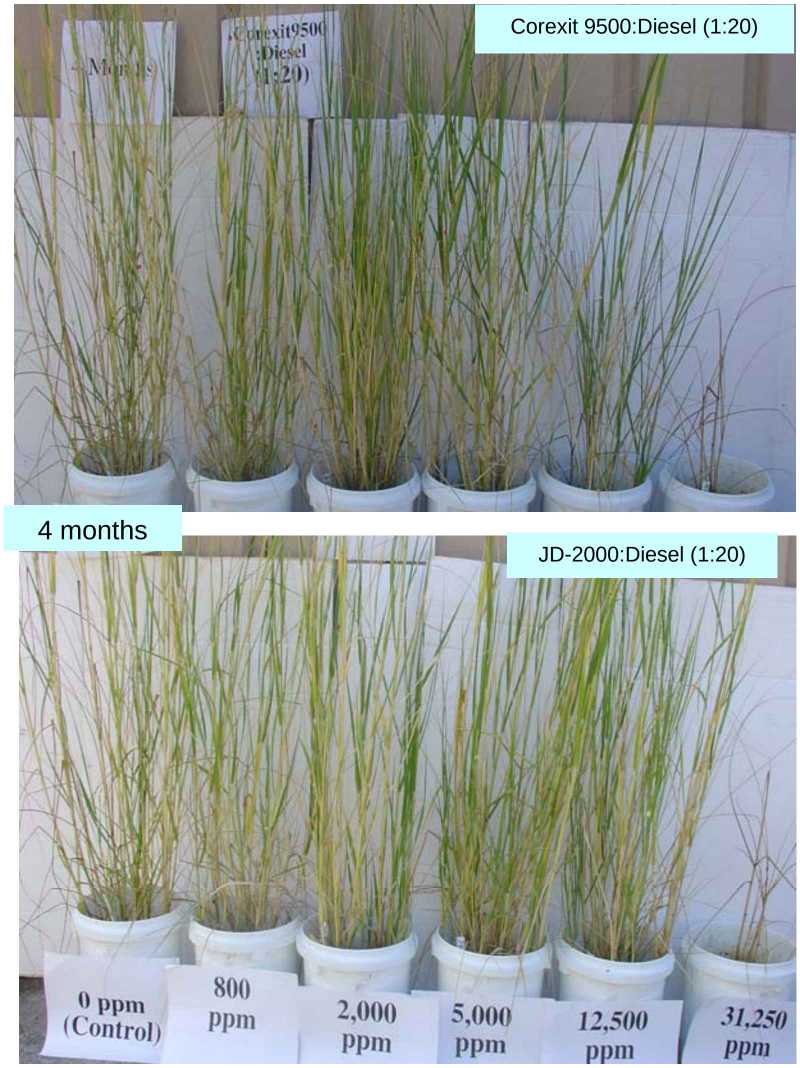

Fig.11. Growth status of *Spartina alterniflora* four months after different concentrations of Corexit 9500 or JD 2000 dispersed diesel were applied to the soil substrate.

3.2.1 Plant Stem Density

The effects of dispersed diesel on plant stem density differed with diesel concentrations. Live stem density decreased with increasing dispersed diesel concentrations. One month after treatments, live stem density of *Spartina alterniflora* was significantly lower in the treatments with dispersed diesel concentrations of 31,250 ppm (Fig. 12). Two and half months after the treatments, live stem density of *Spartina alterniflora* was significantly lower in the treatments with the dispersed diesel concentrations of 12,500 and 31,250 ppm (Fig. 13).

3.2.2 Mortality

The application of dispersed diesel increased plant mortality rates. One month after the treatments, the mortality rates were significantly higher in the treatments with the dispersed diesel concentrations of 12,500 and 31,250 ppm for both JD-2000 and Corexit 9500 (Fig. 14). Two and a half months after the treatments, the mortality rates of *Spartina alterniflora* were still significantly higher in the treatments with dispersed diesel concentrations of 12,500 and 31,250 ppm (Fig. 15).

3.2.3 Biomass

Plant aboveground biomass was harvested four months after the treatments to determine the comprehensive effects of dispersed diesel on the plants. Application of dispersed diesel at high concentrations affected the plant aboveground biomass. Live aboveground biomass of *Spartina alterniflora* was significantly lower when the concentrations of the Corexit 9500 dispersed diesel ≥ 12,500 ppm (Fig.16). Interestingly, the effect of the JD-2000 dispersed diesel on the live aboveground biomass of *Spartina alterniflora* was the same as the effect of the Corexit 9500 dispersed diesel, although JD-2000 alone was less toxic to *S. alterniflora* than Corexit 9500.

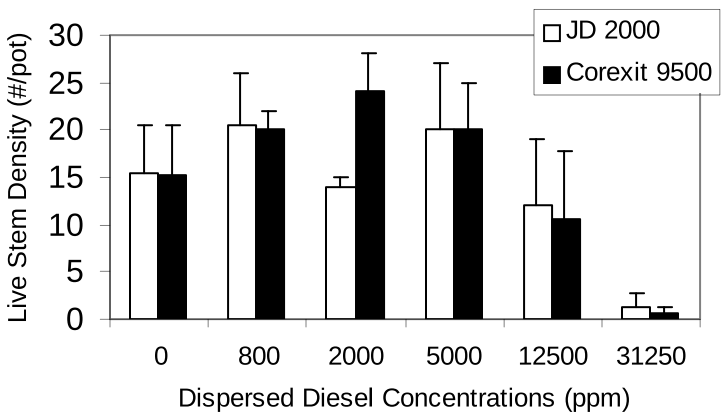

Fig. 12. Live stem density of *Spartina alterniflora* one month after different concentrations of the JD-2000 or Corexit 9500 dispersed diesel were applied to the soil substrate. The ratio of dispersant applied to oils was 1:20.

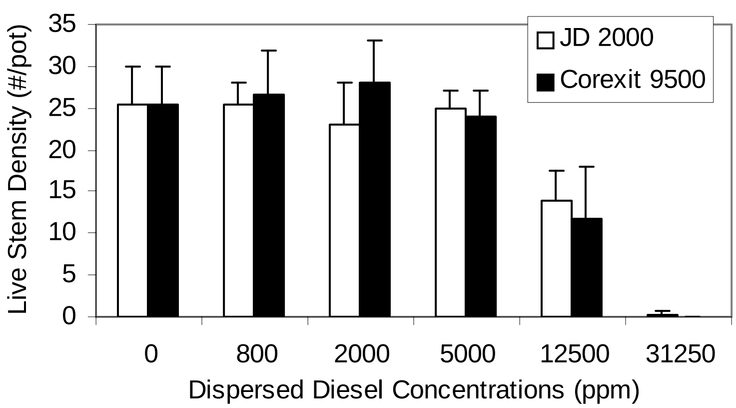

Fig. 13. Live stem density of *Spartina alterniflora* 2.5 months after different concentrations of the JD-2000 or Corexit 9500 dispersed diesel were applied to the soil substrate. The ratio of dispersant applied to oils was 1:20.

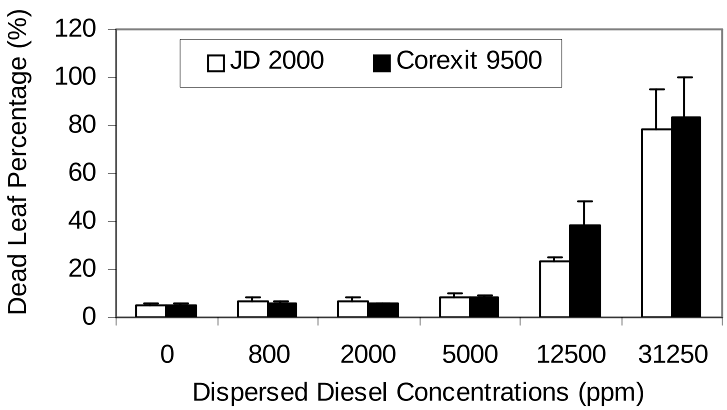

Fig. 14. Mortality rates of *Spartina alterniflora* one month after different concentrations of the JD-2000 or Corexit 9500 dispersed diesel were applied to the soil substrate. The ratio of dispersant applied to oils was 1:20.

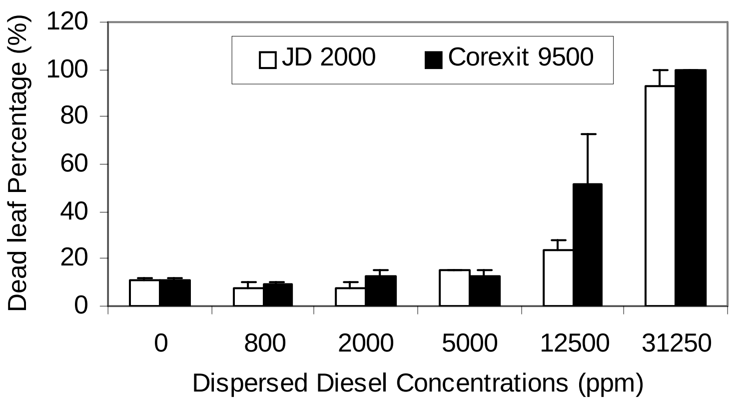

Fig. 15. Mortality rates of *Spartina alterniflora* 2.5 months after different concentrations of the JD-2000 or Corexit 9500 dispersed diesel were applied to the soil substrate. The ratio of dispersant applied to oils was 1:20.

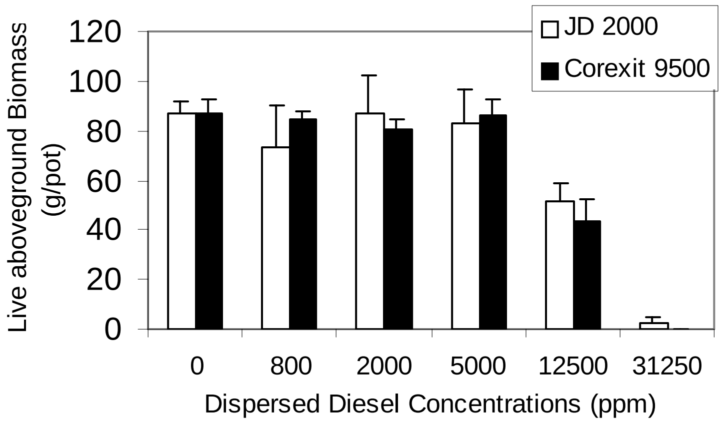

Fig. 16. Live aboveground biomass of *Spartina alterniflora* four months after different concentrations of the JD-2000 or Corexit 9500 dispersed diesel were applied to the soil substrate. The ratio of dispersant applied to oils was 1:20.

3.3. Phase 2. Effect and Effectiveness of Dispersant Application on the Impacts of Different Oils on Salt Marsh Plants and Oil Remediation

The simulated dispersant application in the nearshore environment greatly reduced the detrimental effects of oils on salt marsh plants. Diesel and South Louisiana crude (SLC) oil with and without dispersants came in contact with the aboveground stems and leaves during the simulated high tide. Without dispersants, oils, especially diesel oil, substantially impacted the salt marsh plants *Spartina alterniflora* three days (Fig. 17) and six weeks (Fig. 18) after the treatments. The plants showed rolled and brown leaves under these conditions.

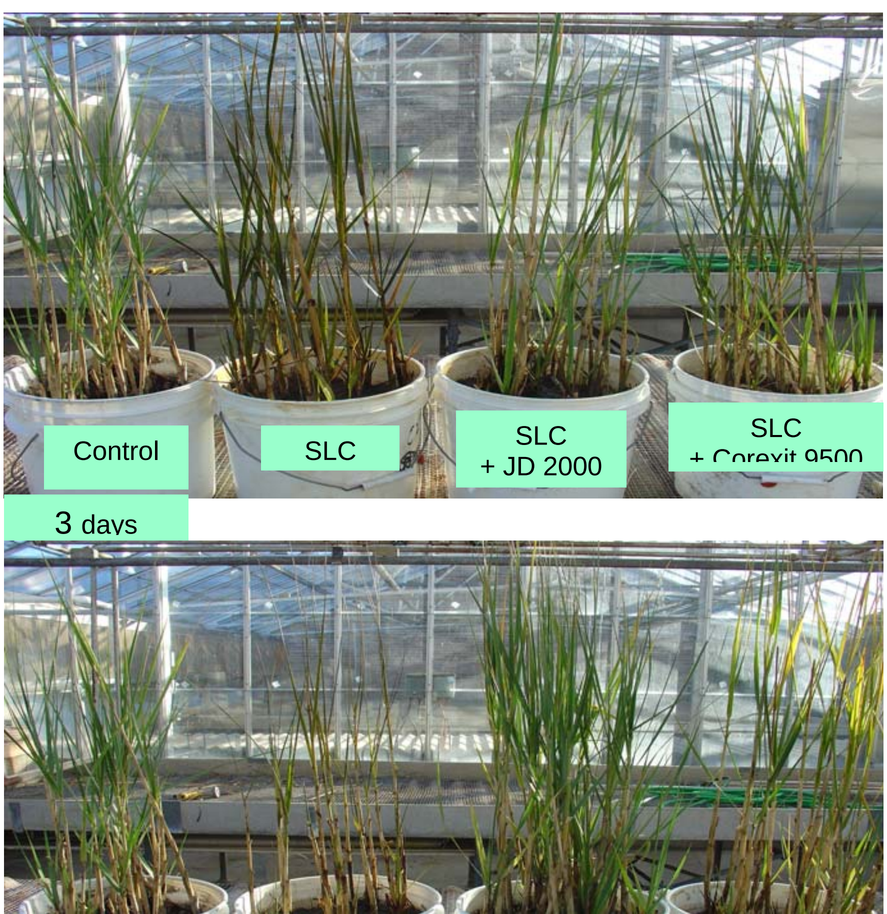

Fig.17. Growth status of *Spartina alterniflora* three days after the simulated application of Corexit 9500 or JD 2000 to diesel or crude oil at the oil concentration of 1000 ppm. The ratio of dispersant to oil was 1:20.

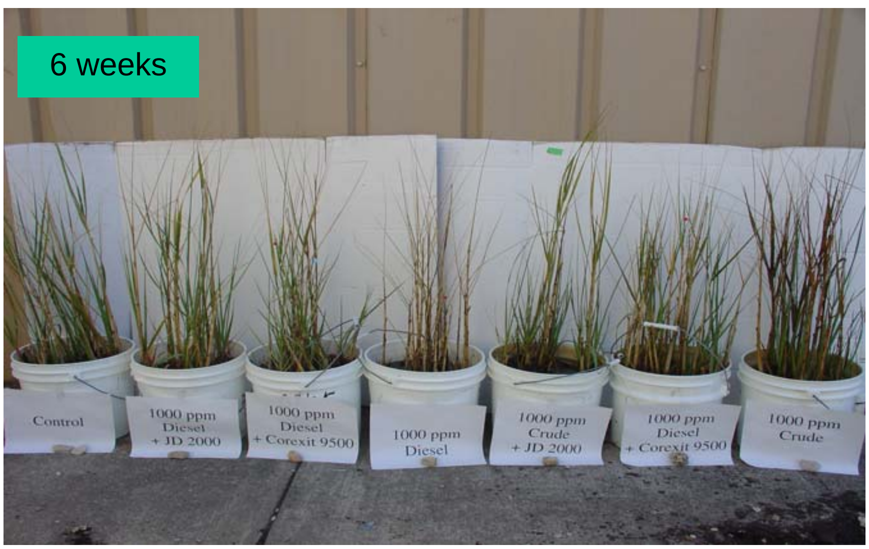

Fig.18. Growth status of *Spartina alterniflora* six weeks after the simulated application of Corexit 9500 or JD-2000 to diesel or crude oil at the oil concentration of 1000 ppm. Ratio of dispersant to oil was 1:20.

3.3.1 Plant Stem Density

Live stem densities of *S. alterniflora* were significantly lower in the treatment receiving oil without dispersants than in the control. Without dispersants, 1000 ppm of diesel had a greater adverse effect on live stem density of *S. alterniflora* than 1000 ppm of crude oil six weeks after the treatment, although 1000 ppm of crude oil significantly affected the live stem density compared to the control (Fig. 19). However, dispersant application greatly relieved the adverse effects of oils on the live stem density. The live stem density of *S. alterniflora* in the treatments receiving oils and dispersants (either JD-2000 or Corexit 9500), regardless of oil type, were not significantly different from the control.

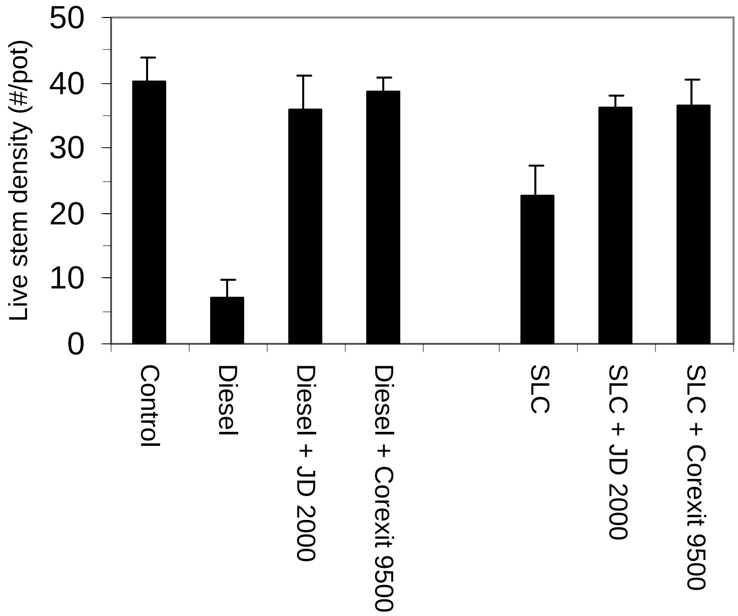

Fig. 19. Dispersants' effect on oil impact—live stem density of *Spartina alterniflora* six weeks after the treatments. The ratio of dispersant applied to oils was 1:20.

3.3.2 Plant Mortality Rate

Mortality rates of *S. alterniflora* were significantly higher in the treatment receiving oils without the dispersants than in the control. Without dispersants, 1000 ppm of diesel had a significantly greater adverse effect on the mortality rate of *S. alterniflora* than 1000 ppm of crude oil six weeks after the treatment (Fig. 20). The mortality rate of *S. alterniflora* in the treatment of 1000 ppm of crude oil was significantly higher compared to the control (Fig. 20). However, dispersant application greatly relieved the adverse effect of oils on mortality rate. The mortality rates of *S. alterniflora* in the treatments receiving oils and dispersants (either JD-2000 or Corexit 9500), regardless of oil type, were not significantly different from the control.

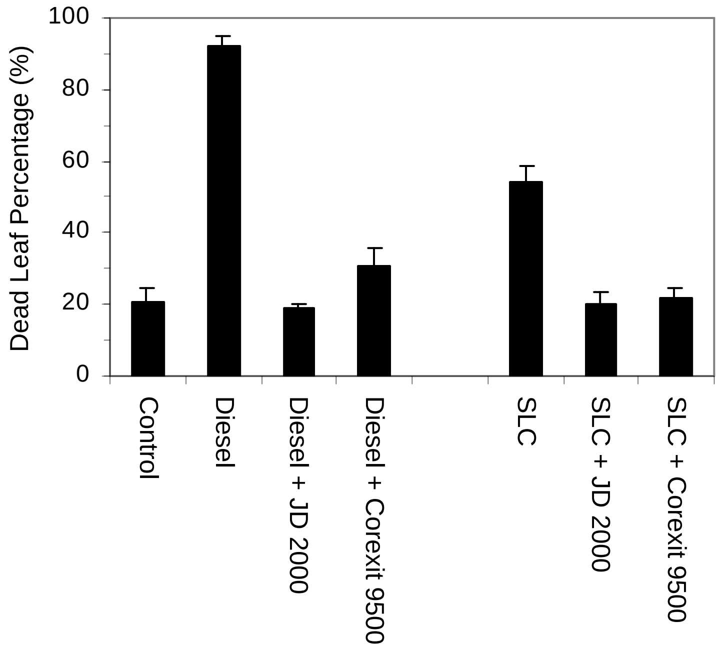

Fig. 20. Dispersants' effect on oil-induced mortality rates of *Spartina alterniflora* six weeks after the treatments. The ratio of dispersant applied to oils was 1:20.

3.3.3 Plant Biomass

Plant aboveground biomass was harvested six weeks after the treatments to determine the comprehensive short-term impacts of oil and dispersed oils on the plants. Live aboveground biomass of *S. alterniflora* in the treatment of 1000 ppm of diesel alone was significantly lower than all other treatments. Live aboveground biomass of *S. alterniflora* in the treatment of 1000 ppm of crude oil was significantly lower than in the control (Fig. 21). However, dispersant application greatly relieved the adverse effect of oils on live aboveground biomass. Live aboveground biomass of *S. alterniflora* in the treatments receiving oils and dispersants (either JD-2000 or Corexit 9500), regardless of oil type, was not significantly different from the control.

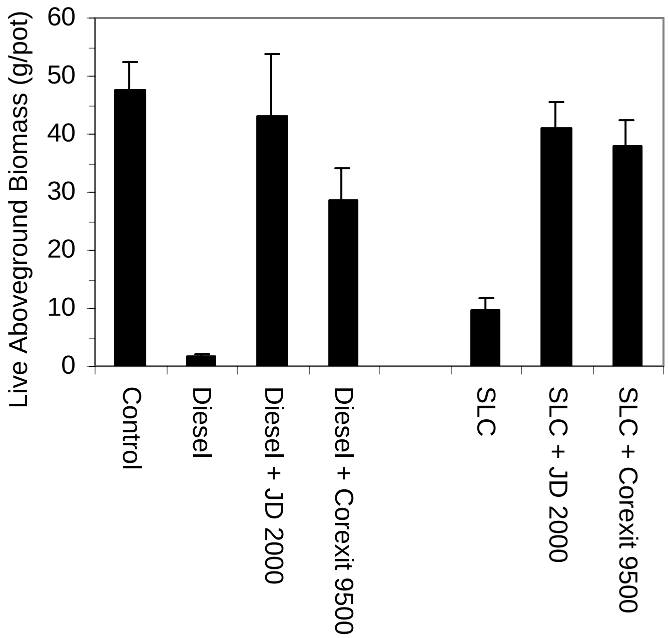

Fig. 21. Dispersants' effect on oil impact—live aboveground biomass of *Spartina alterniflora* six weeks after the treatments. The ratio of dispersant applied to oils was 1:20.

The results of plant live stem densities, mortality rates, and live aboveground biomass clearly indicated that application of dispersants, both JD-2000 and Corexit 9500, greatly relieved the short-term impacts of diesel and crude oil on the salt marsh plant *Spartina alterniflora*. After harvesting the aboveground biomass six weeks after the treatments, we analyzed the various plant parameters of the re-growing plants from the rhizomes in the soil to determine the long-term effects of the treatments for the following six months.

3.3.4 Long-term Effects of Oils and Dispersed Oil on *Spartina alterniflora*

New shoots of *S. alterniflora* quickly grew from the belowground rhizomes after the original aboveground biomass was harvested. One and a half months after the harvest, numerous shoots of *Spartina alterniflora* grew from the rhizomes, except in the treatment of 1000 ppm of diesel oil (Fig 22).

Fig.22. Re-growth status of *Spartina alterniflora* 1.5 months after harvest in the simulated application of Corexit 9500 or JD 2000 to diesel or crude oil at the oil concentration of 1000 ppm. The ratio of dispersant to oil was 1:20.

3.3.4.1 Plant Stem Density and Biomass

New shoots of *S. alterniflora* grew constantly with time. All stems were re-grown, live shoots because the original old shoots were harvested for determining the short-term effects of treatments. Three and six weeks after the harvest, stem densities of the treatment of 1000 ppm of diesel were still significantly lower than those of the other treatments (Fig. 23). However, stem densities of the treatment of 1000 ppm of crude oil alone were not significantly different from the control. Stem densities of the treatment of dispersed oils were not significantly different from the control. However, we noticed that the stem density in the treatment of 1000 ppm of diesel alone gradually caught up with others. Six months after the harvest, stem densities of *S. alterniflora* were not significantly different among all treatments.

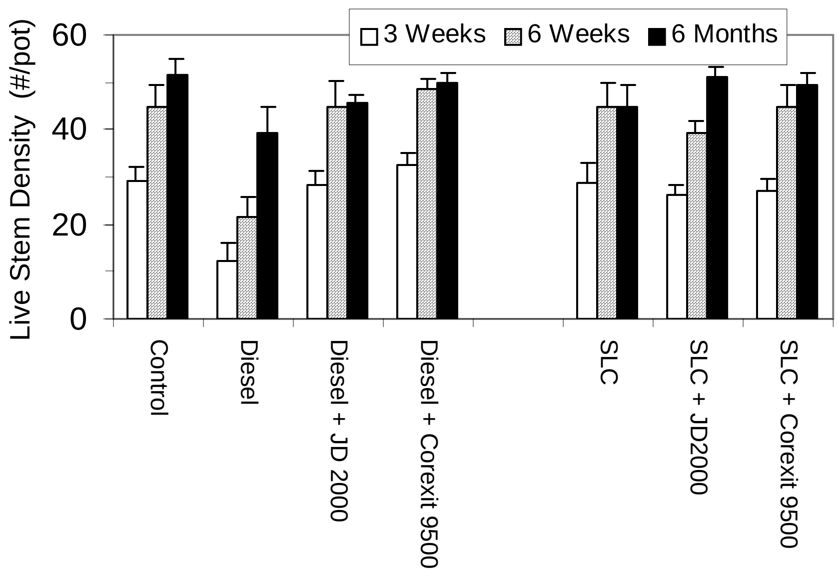

Fig. 23. Dispersants effect on oil impact—live stem density of *Spartina alterniflora* six weeks after the treatments. The ratio of dispersant applied to oils was 1:20.

Plant aboveground biomass was harvested six months after the harvest of the original biomass to determine the comprehensive long-term impacts of oil and dispersed oils on plants. Aboveground biomass of *S. alterniflora* in all treatments did not significantly differ among all treatments, indicating that the impacts of oils, even in the treatment of 1000 ppm of diesel oil, disappeared with time (Fig. 24).

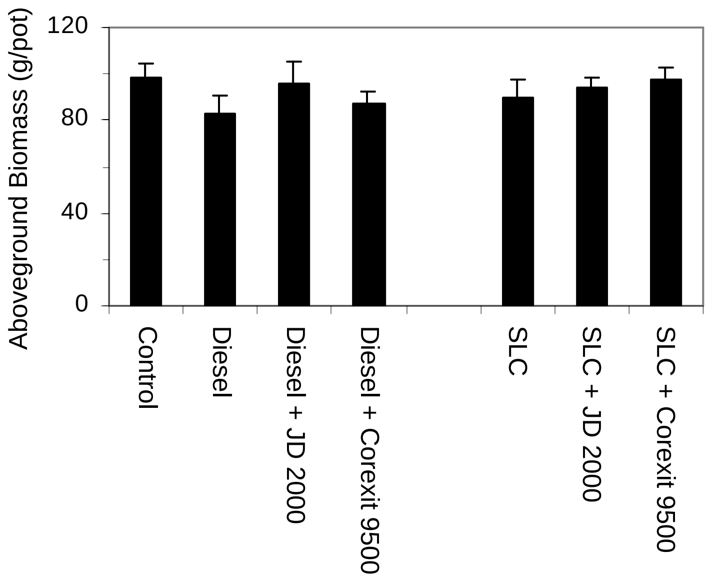

Fig. 24. Dispersants' effect on oil impact—re-growth of aboveground biomass for *Spartina alterniflora* six months after the harvest. The ratio of dispersant applied to oils was 1:20.

4.0. Discussion

The current study indicated that plant tolerance to the dispersant JD-2000 and Corexit 9500 was relatively high. The salt marsh plant *Spartina alterniflora* was not impacted by the dispersant JD-2000 at dosages ≤ 12,000 ppm, based on plant stem density and plant biomass. *Spartina alterniflora* was able to recover at JD-2000 dosages as high as 16,000 ppm, although the mortality rate was higher in the early stage of the treatment. Corexit 9500 showed a higher toxicity to *S. alterniflora* than did JD-2000; obvious impacts on the plant occurred between 4000 to 6000 ppm in the early treatment stage, and the plant in the treatment with the high concentrations of Corexit 9500 did not recover to the control level even four months after the treatment. As in our previous study (Lin and Mendelssohn 2003), the current study demonstrated that the tolerance of marsh plants to the dispersant JD-2000 and Corexit 9500 was much greater than tolerances for the EPA standard bioassay organisms. The National Contingency Plan (EPA 2001) states that the $LC_{50\ (96\text{-hr})}$ for *Menidia beryllina* is 407 ppm and $LC_{50\ (48\text{-hr})}$ for *Mysidopsis bahia* is 90.5 ppm for the dispersant JD-2000, as well as 25.2 ppm and 32.2 ppm, respectively, for Corexit 9500. However, the present study indicated that LC_{50} for the salt marsh plant, *Spartina alterniflora*, was greater than 16,000 ppm for JD-2000 and between 8000 to 12000 ppm for Corexit 9500. This is more than 40 to 200 times higher, respectively, than the test marine organism's LC_{50}.

Similar to the response of plants to dispersants alone, plant tolerance to the chemically dispersed oil was relatively high. The marsh plant *Spartina alterniflora* was not impacted by the JD-2000 or Corexit 9500 dispersed diesel at dosages ≤ 5,000 ppm based on plant stem density and plant mortality rate, as well as aboveground biomass. The LC_{50} was about 12,500 ppm for both JD-2000 and Corexit 9500 dispersed diesel in the present study. This tolerance for dispersed diesel was much greater than tolerances observed for marine organisms reported in other studies. The National

Contingency Plan (EPA 2001) states that the $LC_{50\ (96\text{-hr})}$ for *Menidia beryllina* is 3.59 ppm and $LC_{50\ (48\text{-hr})}$ for *Mysidopsis bahia* is 2.19 ppm for the JD-2000 dispersed No. 2 fuel, and 2.6 ppm and 3.4 ppm, respectively, for the Corexit 9500 dispersed No. 2 fuel oil. The toxicity of No. 2 fuel oil is similar to that of diesel fuel. Thus, the plants' tolerance appears to be more than 1000 times higher than the EPA test organisms, in some cases. We therefore conclude that marine organisms seem to be more sensitive to dispersed oil than marsh plants.

The current study also provided information about the toxicity of the chemically dispersed oil, such as the dispersed diesel used in this study. Our study found that the toxicity to marsh plants primarily resulted from the oil itself because: (1) the JD-2000 dispersed diesel and Corexit 9500 dispersed diesel had similar toxicities to the salt marsh plant, although JD-2000 alone was less toxic to the salt marsh plants than Corexit 9500 alone in the present study; (2) only very small portions of dispersant were applied to the oils (ratio of 1:20); and (3) the salt marsh plants' high tolerances for dispersants was shown in the present study. In a real world spill situation, dispersant concentrations in the water may never be as high as 4000 to 6000 ppm, the concentration at which plants will be affected.

In the present experiment that simulated dispersants applied in nearshore and estuarine environments, the dispersants JD-2000 and Corexit 9500 greatly relieved oil impacts on the aboveground components of salt marsh plants. Without the dispersant application, both diesel and crude oil severely impacted *Spartina alterniflora*. Dispersant application significantly reduced the oil impacts on the plants, with high live stem density, live aboveground biomass, and low mortality rate all found in the treatments of dispersed diesel and crude oil. Duke et al. (2000) reported that an experimental application of Corexit-9527 to weathered crude oil reduced mangrove tree mortality in a field trial. The strategy of the present study is to apply dispersants in the nearshore before oil moves into coastal salt marshes. The present study and our previous study (Lin and Mendelssohn 2003) differ from a handful of previous studies (Bake et al. 1984; Lane et al. 1987; Little and Scales 1987), in which oil came in contact with marsh plants before dispersant application. Baker et al. (1984) reported that the dispersant BP1100WD was ineffective in cleaning an oiled salt marsh, reduced *Spartina anglica* density in one to two years, and resulted in short-term loss of *Salicornia* spp. Similarly, salt marshes exposed to weathered crude oil and the dispersant Corexit 9527 showed that dispersant and dispersed oil had a greater impact on *S. alterniflora* than the oil alone (Lane et al. 1987). Application of the dispersant BP Enersperse 1037 to coastal salt marshes contaminated with weathered Nigerian crude, fuel oil, and mousse showed that dispersed oil was more destructive to *Spartina* and *Aster* than untreated oil (Little and Scales 1987). In contrast, other studies (Smith et al. 1984) demonstrated that dispersants applied to Louisiana crude oil-contaminated *Spartina alterniflora* provided short-term benefits to plant photosynthesis. In addition, in a 24-inch pipeline rupture in Nigeria, which released 40,000 bbl of light crude oil into the marine environment, dispersants played an important role in preventing shoreline and estuarine mangrove habitats from oiling (Olagbende et al. 1999). Therefore, the strategy of applying dispersants in nearshore environments before oil comes in contact with coastal marshes appears to have great potential for protecting sensitive coastal habitats, such as most vulnerable coastal salt marshes. Dispersed oil may move into the marsh with tides or currents, but most dispersed oil appears to move out with the ebbing tide because dispersed oil is not adhesive to the surface of sediment particles or plant aboveground components.

5.0. Conclusion

The current study elucidates the potential and effectiveness of dispersants as oil spill countermeasures in nearshore environments for protecting sensitive coastal habitats. The dose-response relationship of the salt marsh plant *Spartina alterniflora* to the dispersant JD-2000 and Corexit 9500 indicated that that the tolerance of salt marsh plants to dispersants was relatively high, and 40 to 200 times higher than the EPA bioassay marine organism's response. In addition, the plant tolerance to the dispersed oil was relatively high; diesel dispersed with both JD-2000 and Corexit 9500 applied to the soil substrate had similar toxicities to the marsh plants and affected *Spartina alterniflora* at the concentration ≥12,500 ppm. It appeared that the toxicity of dispersed oil to the salt marsh plants primarily resulted from the oil itself. Furthermore, dispersants can greatly reduce oil's impact on vegetation if the oil is dispersed in nearshore environments before it comes in contact with coastal salt marshes. The dispersants JD-2000 and Corexit 9500 greatly relieved the adverse effects of both diesel and crude oil on the aboveground components of *S. alterniflora*. Without the dispersant application, both diesel and crude oil significantly affected the salt marsh plants. The current study indicates the potential of using dispersants as alternative countermeasures to oil spills in nearshore environments for protecting the most vulnerable coastal salt marshes.

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