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Salt Marsh Recovery and Oil Spill Remediation after In-Situ Burning: Effects of Water Depth and Burn Duration

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Effects of water depth, burn duration, and diesel fuel concentration on the relationship between recovery of marsh vegetation, soil temperature, and oil remediation during in-situ burning of oiled mesocosms were investigated. The water depth over the soil surface during in-situ burning was a major factor controlling recovery of the salt marsh grass, *Spartina alterniflora*. Ten centimeters of water overlying the soil surface was sufficient to protect the marsh soil from burn impacts with soil temperatures <37 °C and high plant survival rate. In contrast, a water table 10 cm below the soil surface resulted in mean soil temperatures >100 °C at the 2-cm soil depth, which completely inhibited the post-burn recovery of *S. alterniflora*. Although poor plant recovery was also apparent in the treatments with 0 and 2 cm of water over the soil surface, this result was likely due to the chemical stress of the diesel fuel used to create the fire rather than the heat, per se, which never reached the estimated lethal temperature of 60 °C. In-situ burning effectively removed more than 95% of floating oil from the water surface. Thus, in-situ burning prevented the oil from potentially contaminating adjacent habitats. However, in-situ burning did not effectively remediate the oil that had penetrated the soil.

Introduction

Wetland ecosystems are considered among the most valuable as well as the most fragile of natural systems (*1*). Oil pollution from pipeline ruptures, tanker accidents, exploration, and production blowouts poses a serious risk to the health of wetland systems. However, the cleanup of oil spills in wetland environments is problematic and can do more damage than the oil itself (*2, 3*). Regardless, it is often essential to remove spilled oil before it spreads to other habitats and to adjacent water bodies.

The in-situ burning of oiled wetlands to clean up spilled oil is potentially compatible and consistent with present wetland management procedures. In fact, wetlands are often burned on an annual cycle in order to provide better wildlife habitat (*4*). Although prescribed burning is an accepted practice in wetland management along the northern Gulf of Mexico and throughout much of the world, examples in the scientific literature demonstrate that burning of wetlands can have varying effects, ranging from beneficial to detrimental (*4–6*). Factors such as water level during the burn, duration and intensity of the burn, season of the burn, and wetland type likely controlled post-burn recovery (*7–9*).

Although the factors mentioned above are often cited as controlling successful wetland recovery after prescribed burns, the primary variables determining the successful recovery of wetlands subject to in-situ burning for oil spill remediation have received little attention. The impact of the two types of burns are likely to be different due to the much greater fuel load in most petroleum burns. Not only is the literature on in-situ burning of oil contaminated wetlands limited, but it is often contradictory. The burning of an oiled *Spartina alterniflora* marsh in Texas resulted in better recovery than an unburned marsh (*10*), supporting earlier findings by Baker (*11*). In contrast, the burning of an oiled *Spartina patens* marsh in Texas had a more negative impact than no action at all (*2*). However, for an in-situ burn in a high salt marsh along Chiltipin Creek near Bayside, San Patricio County, TX, most of the burned area was revegetated within the first two growing seasons, although a significant difference in vegetation composition from the control continued to exist 5 years after the burn (*12*). In some cases, burning may facilitate the penetration of the oil into the marsh substrate (*3*) and may be the reason for slow recovery. A recent study (*13*) observed rapid recovery of salt marsh vegetation in Louisiana after in-situ burning. The factors responsible for these differential responses of oiled wetlands to in-situ burning have not been adequately addressed. More information is needed to better predict under what environmental conditions in-situ burning should be attempted and would likely result in satisfactory wetland recovery, so that sound, scientifically based guidelines for its use can be formulated.

The objectives of this study were to determine the effects of burn duration (fuel load) and wetland characteristics (water level) on soil temperature, oil remediation, and vegetation recovery of salt marshes dominated by *S. alterniflora*. This research provides the first quantitative data on the interaction of burn dynamics, oil chemistry, and marsh recovery and helps to elucidate the factors that maximize the recovery of oil-contaminated wetlands after in-situ burning.

Materials and Methods

Experimental Design. Intact salt marsh sections, 30 cm in diameter and 30 cm tall, were collected from a *S. alterniflora* dominated intertidal salt marsh in southeast Louisiana and placed in 19-L metal buckets. *S. alterniflora*, commonly called smooth cordgrass, dominates intertidal salt marshes along the Atlantic and Gulf Coasts of the United States; therefore, results from this study are applicable to marshes outside of the northern Gulf of Mexico. After collection, half of the marsh sods were instrumented with vertical arrays of thermocouples, allowed to acclimate under greenhouse conditions for a period of 5 weeks, and randomly assigned to the following treatments: (a) oil exposure, unweathered diesel fuel (1.5 L/m^2) vs no diesel fuel application; (b) burn duration, 400 s vs 1400 s; and (c) water depth, 10, 2, and 0 cm over the soil surface and 10 cm below the soil surface. The burn durations selected are within the range of a typical marsh

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burn, and they are sufficiently different from each other to potentially elicit a difference in soil temperature. The four water depths were chosen because they commonly occur in coastal salt marshes. The experimental design was a completely randomized block with a 4 × 2 × 2 factorial arrangement of treatments (4 water depths, 2 oil levels, and 2 burn durations, respectively). Each treatment–level combination was replicated five times for a total of 80 experimental units (marsh sods). Each block [4 (water level) × 2 (diesel level)] was burned separately. In addition, five unburned–oiled and unburned–unoiled sods served as controls. Thus, 90 experimental units were used in the experiment. Twenty-four hours before the burn, 1.5 L/m^2 unweathered diesel was added to the water surface of oiled buckets and allowed to distribute evenly on the water surface. The diesel was allowed to penetrate the soil to a depth of 10 cm by draining interstitial water from the bottom of the sod containers.

Experimental Procedures. Forty of the marsh sods were instrumented with thermocouples inserted into the soil to monitor soil temperature during in-situ burning. Thermocouples were inserted at 0, 0.5, 2, and 5 cm below the soil surface. Water and air temperature as well as total heat flux at the water surface were also recorded. For each of the 10 burns, a total of eight marsh sods, four instrumented and four uninstrumented, were positioned at 10, 2, 0, and −10 cm water depth over the soil surface. Diesel fuel burns were conducted in a 6 m diameter test tank at Louisiana State University's Fire and Emergency Training Institute (FETI). Diesel fuel was added to the water surface, ignited, and allowed to burn for periods of either 400 or 1400 s. For the 400-s burn duration, sufficient diesel fuel (568 L) for the entire 400-s burn exposure was added to the water surface before ignition. For the longer 1400-s burn exposure, sufficient diesel fuel was added to allow for 400 s of burn, and as the diesel fuel burned, additional fuel oil was added via inlets below the water surface. The soil temperature, as a function of soil depth and sod elevation (i.e., water depth), was continuously recorded during the burn, 400 or 1400 s, and monitored for a total of 5400 s (for details on thermocouple installation and measurements, see Bryner et al.; *14*).

After the burns, the mesocosms were returned to the greenhouse where plant recovery was assessed as described below. The water table in the mesocosms was maintained at 5 cm below the soil surface to provide the plants with sufficient water for growth, while not stressing the plants with excessive water depths during recovery. Soil samples for the analyses of total petroleum hydrocarbons (TPH) and total targeted aromatic hydrocarbons (TTAH) were collected from 0 to 4 cm below the soil surface 24 h after oil addition (but right before the burn) and 24 h after the burn. The oil concentrations of soil samples from 5 to 8 cm below the soil surface were ca. 30% of that from 0 to 4 cm and were not reported in this study. Recovery of the salt marsh grass, *S. alterniflora*, was assessed by determining plant live aboveground biomass.

Methods. *Plant Growth and Survival.* Plant regrowth was assessed by measuring plant live aboveground biomass at the termination of the experiment. The plant material harvested at the end of the experiment (7 months after burn exposure) was separated into live and dead biomass and dried at 65 °C to a constant weight.

Total Petroleum Hydrocarbons (TPH) Analysis by GC/FID. Soil samples collected from a depth interval of 0–4 cm were extracted with dichloromethane and analyzed by capillary gas chromatography with flame ionization detection (GC/FID). Results were corrected for background-extractable material by comparison with oil-free soil blanks. Gas chromatographic separations used a 30 m, 0.25 mm i.d. column with a 5% phenyl–95% dimethylpolysiloxane (DB-5) stationary phase. The initial GC temperature was 50 °C for 2 min followed by temperature programming to 280 °C at 15 °C/min. The temperature was held at 280 °C for an additional 12 min.

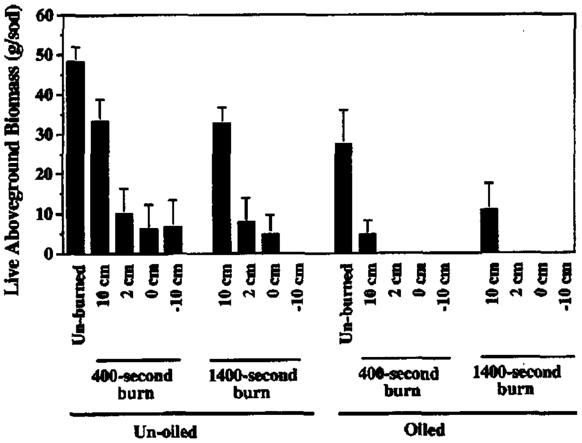

FIGURE 1. Effects of burn exposure duration, water table level, and diesel fuel application on live aboveground biomass of *S. alterniflora* 7 months after the burn. Notation of 10, 2, 0, and −10 cm represent 10, 2, 0, and −10 cm of water over the soil surface during the burn. Error bars are standard errors ($n = 5$).

Total Targeted Aromatic Hydrocarbons (TTAH) by GC/MS. The soil samples collected from a depth interval of 0–4 cm were analyzed by gas chromatography/mass spectrometry (GC/MS) to confirm and expand on the GC/FID results. The GC/MS instrumentation used was a Hewlett-Packard 5890 GC configured with a DB-5 high-resolution capillary column (0.25 mm i.d., 30 m, 0.25 μm film, J&W Scientific) directly interfaced to a Hewlett-Packard 5971 MS detector system. The targeted constituents, quantitation ions, and chromatographic conditions can be found in Lin et al. (*15*).

Statistical Analysis. Statistical analysis was conducted with the Statistical Analysis System (*16*). Plant parameters, total petroleum hydrocarbons, and soil temperature were analyzed with a general linear model (GLM). Duncan's test was used to evaluate statistical differences of the main factors when no interaction occurred. The least-squares means (LSD) test was used when interaction between main factors occurred. Significant differences were reported at the 0.05 probability level, unless otherwise stated.

Results

Recovery of Marsh Plants after In-Situ Burning. Effects of diesel fuel added to the soil prior to the burn ($p < 0.0001$), the water depth over the soil surface during the burn ($p < 0.0001$), and the interaction between the diesel fuel addition and water level ($p < 0.005$) on live aboveground biomass were significant. Recovery of the salt marsh grass, *S. alterniflora*, after exposure to in-situ burning mainly depended upon the depth of water over the soil surface. Ten centimeters of water overlying the soil surface was sufficient to protect the plants from thermal stress. In the absence of diesel fuel additions to the soil, live aboveground biomass of the marsh sods was significantly higher with 10 cm of water over the soil surface as compared to the other water levels regardless of burn duration (400 vs 1400 s) (Figure 1), although live aboveground biomass was still significantly lower than the control (without burn exposure). Furthermore, in the presence of diesel fuel added to the soil, live aboveground biomass was not significantly different among water depths, although it tended to be higher with 10 cm of water over the soil surface (Figure 1). No regrowth of live aboveground biomass after burn exposure in the lower water level treatments (2, 0, and

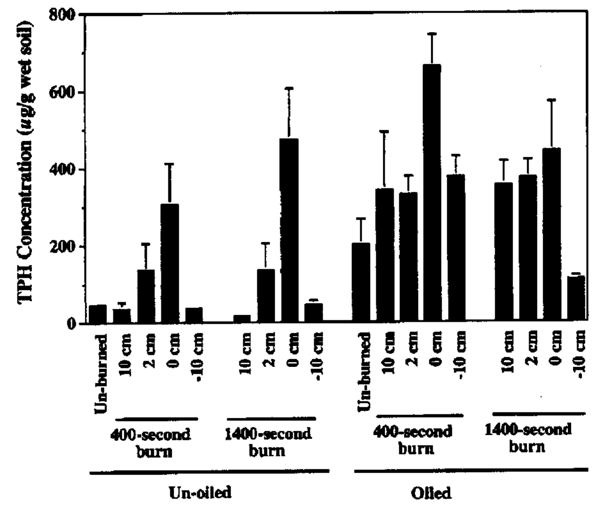

FIGURE 2. Effects of burn exposure duration, water table level, and oil application on total petroleum hydrocarbons in the soil 0−4 cm below the soil surface 1 day after the burn. Notation of 10, 2, 0, and −10 cm represent 10, 2, 0, and −10 cm of water over the soil surface during the burn. Error bars are standard errors ($n = 5$).

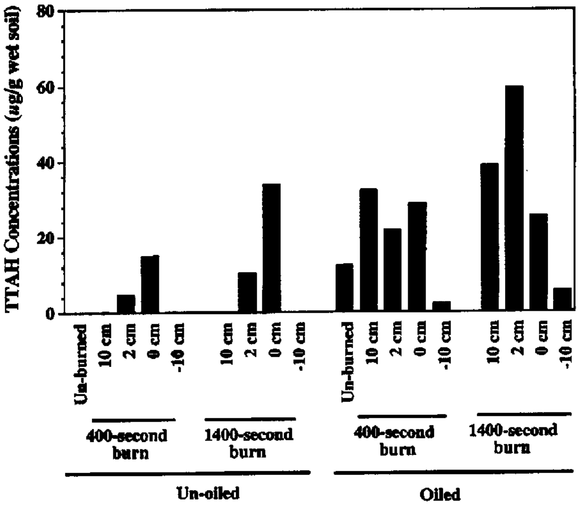

FIGURE 3. Effects of burn exposure duration, water table level, and oil application on the total targeted aromatic hydrocarbons (TTAH) in the soil 0−4 cm below the soil surface 1 day after the burn. Values are derived from an analysis of five replicates composited. Notation of 10, 2, 0, and −10 cm represent 10, 2, 0, and −10 cm of water over the soil surface during the burn.

−10 cm) occurred. Live aboveground biomass was not significantly different between burn duration (400 vs 1400 s).

Petroleum Hydrocarbon Concentrations. The experimental treatments affected total petroleum hydrocarbons (TPH) in the soil. It was not surprising that the TPH in the soil was significantly ($p < 0.0001$) higher in the treatments with diesel fuel added to the soil than without (Figure 2). In addition, water level over the soil surface during the burn significantly ($p < 0.0001$) affected TPH in the soil. In the absence of diesel fuel added to the soil, TPH concentrations in the soil with 10 cm of overlying water and with the water table 10 cm below the soil surface were lowest regardless of burn duration (400 vs 1400 s) (Figure 2) and were not significantly different from the overall control (unburned and unoiled). However, TPH concentrations in the soil with 2 and 0 cm of water overlying the soil surface were significantly higher than that in the treatments with 10 cm of water over the soil surface and 10 cm below the soil surface regardless of burn duration (Figure 2). When the diesel fuel was added to the soil, the water level effect on soil TPH was similar to that in the absence of diesel additions, but TPH concentrations were generally higher than the comparable treatments without diesel addition. There was no significant difference in TPH in the soil between burn duration (400 vs 1400 s). In-situ burning did not appear to remove significant amounts of diesel fuel that had penetrated into the soil. With diesel addition to the soil, TPH concentrations in all burning treatments were equal to or higher than in the unburned treatment. In addition, average TPH concentrations prior to the burn in the sods with diesel addition were 226 mg/g wet soil ($n = 15$, ± 34 standard error) in the 0−4 cm soil depth, which were similar to that in the treatment with diesel addition but unburned (Figure 2).

The total targeted aromatic hydrocarbons (TTAH) in the soil 1 day after in-situ burning showed a similar trend to the soil TPH at this time. In the absence of diesel addition to the soil, TTAH in the soil with 10 cm of overlying water and with the water table 10 cm below the soil surface was negligible regardless of burn duration (400 vs 1400 s) (Figure 3) and was not different from the overall control (unburned and unoiled). However, TTAH in the soil with 0−2 cm of water overlying the soil surface was higher than that in the treatments with 10 cm of water over the soil surface and 10 cm below the soil surface regardless of burn exposure duration. When diesel fuel was added to the soil, the TTAH concentrations in the treatments with burn exposure were higher than without burn exposure except in the treatment with a 10-cm water table below the soil surface.

In-situ burning greatly reduced the thickness and amount of the diesel oil on the water surface. Only a thin layer of residual oil covered a small portion of the water surface. Although determining the thickness of residual oil is extremely difficult, it is estimated that the oil layer was less than 1 mm. In-situ burning was estimated to have removed more than 95% of the diesel fuel regardless of the original amount of diesel fuel added to the water surface (≥20 mm initially).

Soil Temperature and Plant Recovery. Water levels over the soil surface significantly ($p < 0.0001$) affected soil temperature (Figure 4). At 0, 0.5, and 2 cm soil depths, average peak soil temperature in the treatment with 10 cm of soil exposure during the burn was above 100 °C, ranging from 160 to 700 °C during the 1400-s burn (Figure 4B) and from 75 to 370 °C during the 400-s burn (Figure 4A). Average peak soil temperature in the treatment with 0 cm of overlying water during the burn was below 80 °C even at the soil surface, ranging from 40 to 80 °C at the 0−5 cm soil depth, respectively (Figure 4A,B). Average peak soil temperature at all soil depths, including the soil surface, was below 60 °C for the treatment with 2 cm of overlying water. Temperatures at all soil depths were below 40 °C for the treatment with 10 cm of overlying water (see ref *14* for detailed soil temperature profiles). In addition, burn duration significantly affected soil temperature. Average peak soil temperature during the 1400-s burn was significantly ($p < 0.0001$) higher than that of the 400-s burn at 0, 0.5, 2, and 5 cm soil depths (Figure 4A,B).

The relationship between live aboveground biomass of *S. alterniflora* and soil temperature at 0, 0.5, 2, and 5 cm below the soil surface was analyzed to determine the thermal effect on the plant recovery after in-situ burning. The soil temperature varied greatly at the 0 and 0.5 cm soil depths, but was relatively constant (<40 °C) at the 10 cm soil depth (data not shown). The soil temperatures at the 2 cm soil depth in most marsh sods were below 60 °C except in the treatment with 10 cm of soil exposure. Most *S. alterniflora* exhibited survival and recovery when soil temperatures were less than 60 °C at the 2 cm soil depth (Figure 5). No plants survived at temperatures >60 °C at the 2 cm soil depth (Figure 5).

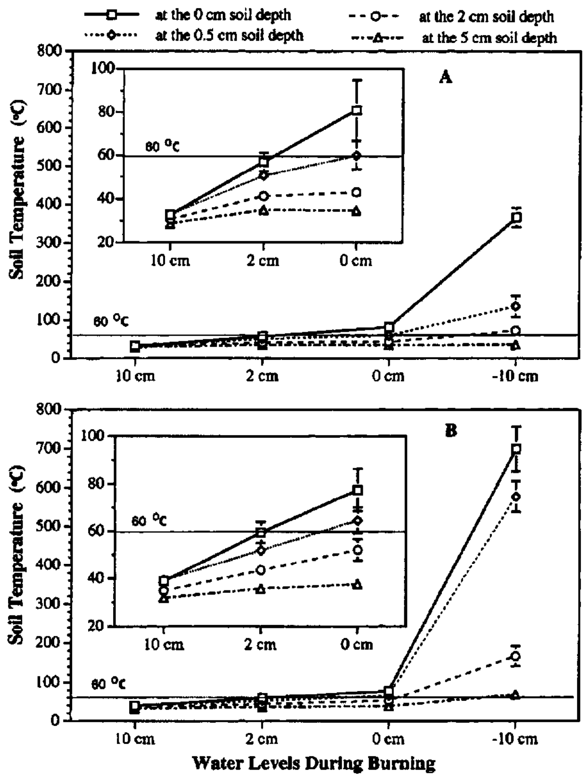

FIGURE 4. Average peak soil temperature as a function water level over the soil surface during 400- (A) and 1400-s (B) burn durations. Notation of 10, 2, 0, and −10 cm represent 10, 2, 0, and −10 cm of water over the soil surface during the burn. Error bars are standard errors ($n = 5$).

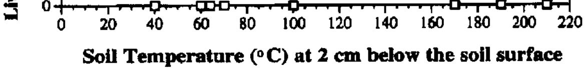

FIGURE 5. Relationship between live aboveground biomass produced 7 months after the burn exposure and soil temperature at 2 cm below the soil surface.

Discussion

Recovery of the salt marsh grass, *S. alterniflora*, to in-situ burning of diesel mainly depended upon the depth of water over the soil surface during the in-situ burn and the residual oil content in the soil. Increased water depth over the marsh surface provided increased protection to the marsh vegetation during the in-situ burn, resulting in lower soil temperature and higher survival rates. In addition, less diesel fuel was able to penetrate the soil, and more plant recovery occurred.

Effect of Water Depth. Ten centimeters of water over the soil surface was sufficient to protect the marsh sods from burn impacts. Soil surface temperatures 10 cm below the water did not exceed 40 °C for either 400 or 1400 s burn durations. Thermal stress on plant belowground organs was negligible. The plant growth responses to the water level treatments support the temperature data. However, plant survival was greatly reduced when diesel was added to the soil before the burn. The poor recovery in the treatment with 10 cm of overlying water and diesel fuel added to the soil was obviously due to the stress of the added petroleum hydrocarbons prior to the burn because recovery was good at this water level in the absence of diesel. In addition, the degree of diesel penetration into the soil may have been enhanced by the fire as evidenced by higher TPH and TTAH in the treatments with 10 cm of overlying water during the burn than those for unburned treatments receiving diesel.

Marsh sods with surfaces located at 2 and 0 cm below the water level exhibited poor recovery most likely due to hydrocarbon stress. Average peak soil temperatures in the 0 and 2 cm water level treatments at a 2 cm soil depth were 42 and 48 °C, respectively, which was probably not high enough to severely stress the plants. However, significantly higher TPH and TTAH concentrations were documented in the 0 and 2 cm water level treatments, and these oil levels likely stressed the plants.

Ten centimeters of soil exposure during in-situ burning almost completely impeded the post-burn recovery of the marsh grass, *S. alterniflora*. When the water table was 10 cm below the soil surface, the burn resulted in average peak soil temperatures of about 400–700 °C at the soil surface and 70 and 160 °C at a depth of 2 cm below the soil surface for 400 and 1400 s of burn exposure, respectively. However, TPH and TTAH concentrations were low at this water level, causing little chemical stress to the marsh plants. Thus, thermal stress on the plants appeared to be the main factor responsible for the poor recovery of *S. alterniflora* even in the absence of added diesel fuel.

The contamination of the marsh sods with the diesel used to create the burn exposure, referred to as "rogue diesel fuel", was likely the primary reason for the high mortality and poor regrowth in the treatments with soil surfaces located at 2 and 0 cm below the water level. For these two water level treatments, four access holes, each 1 cm in diameter, were drilled at the water line to allow the water in the marsh sod to equilibrate with the water level in the tank. However, the holes also allowed the rogue diesel fuel to enter the sod containers. This is evidenced by the significantly higher TPH and TTAH concentrations in the 0 and 2 cm water level treatments as compared to the control even in the absence of diesel addition to the soils prior to the burn (Figures 2 and 3). Thus, chemical stress induced by the entry of the rogue diesel fuel into containers at the 0 and 2 cm water levels and contamination of these sods likely caused the main stress to the vegetation and played the key role in preventing post-burn recovery of these marsh sods. However, the marsh sods with soil surfaces 10 cm above the water, which were too high above the waterline to be contaminated by the rogue diesel fuel, showed poor vegetative recovery due to the thermal stress alone. The chemical stress played no role in the poor recovery of sods with soil surfaces 10 cm above the water line. For the marsh sods with soil surfaces 10 cm below the water line, the 10 cm water layer separated the floating rogue diesel fuel from the soil surface thus, minimizing contamination by the rogue diesel.

Research on prescribed burning has also demonstrated that water level during the burn can affect post-burn recovery. In a *Typha glauca* dominated marsh in Canada (*7*), a burn in the drained portion of an impoundment resulted in lower plant recovery than the control. However, a burn in the flooded portion of the impoundment stimulated plant coverage above the controls. Similarly, a prescribed burn during higher water levels produced greater stem density and height of *Scirpus olneyi* (*8*). In a New Zealand bog, a burn also resulted in a more favorable response in wet as compared to drier sites (*9*). In the present study, marsh sods burned with a 10 cm soil exposure almost completely inhibited recovery of *S. alterniflora*. In contrast, burn exposure with 10 cm of water overlying the soil surface resulted in near complete recovery of *S. alterniflora*, further demonstrating that standing water over the marsh surface during in-situ burning is important for post-burn recovery.

Effect of Burn Duration and Soil Temperature. Duration of burn exposure affected soil temperatures at depths ≥2 cm below the soil surface. Although a 1400-s burn resulted in significantly higher soil temperatures at 2 and 5 cm below the soil surface than a 400-s burn, both burn exposures had similar effects on plant survival and post-burn recovery of marsh vegetation. The soil temperature during a 400-s burn exposure was high enough to kill *S. alterniflora* when water level was 10 cm below the soil surface. However, soil temperature during a 1400-s exposure was not high enough to affect *S. alterniflora* when water level was 10 cm over the soil surface; thus, it is not surprising that 400-s exposure did not cause mortality at this water depth. In the 0 and 2 cm water level treatments, the concentration of diesel fuel in the soil played a more important role in plant recovery than thermal effects (or burn duration) because of contamination by the rogue diesel fuel at these two water levels. Diesel is much more toxic to plants than crude oil. In an experimental spill in a salt marsh (*17*), 1.5 L/m^2 no. 2 fuel oil significantly reduced live aboveground biomass of *S. alterniflora*, while 2 L/m^2 crude oil did not. The composition and toxicity of no. 2 fuel oil and diesel oil are similar. Furthermore, a mesocosm study (*18*) indicated that even 4 L/m^2 Louisiana crude oil did not significantly reduce live aboveground biomass of *S. alterniflora* 4 and 9 months after oiling, supporting the contention that no. 2 fuel oil and diesel have a greater toxicity on plants than crude oil.

Soil temperatures differed with soil depth during the in-situ burns. Lower temperatures were found with greater depth in the soil. Two important questions regarding in-situ burning are as follows: (i) What soil temperature will result in plant mortality? (ii) At what soil depth is the temperature appropriate to predict lethal effects on plants? In the present study, some *Spartina alterniflora* recovered in sods with the soil temperatures as high as 110 and 80 °C at 0 and 0.5 cm below the soil surface, respectively. Therefore, surface soil temperature (0 and 0.5 cm below the soil surface) may not be appropriate to predict thermal effects on plants. Plant reproductive organs, such as rhizomes, are located below the soil surface. In contrast, soil temperatures 5 cm below the soil surface of sods that exhibited regrowth after burning were <37 °C, which was not high enough to kill the belowground rhizomes. Furthermore, no *S. alterniflora* recovered at temperatures >60 °C at the 2 cm depth, and almost all *S. alterniflora* recovered at temperatures <60 °C at this soil depth. It appears that the critical temperature for survival of *S. alterniflora* is 60 °C at a 2 cm soil depth. Since lethal temperatures for most vascular plants have been cited in the range of 60–65 °C (*19–21*), we suggest that plant recovery may be predicted based on the temperatures recorded at 2 cm below the soil surface. The effect of soil temperature on plant survival during in-situ burning of wetlands may vary with plant species and soil characteristics, and these factors are currently being investigated.

Oil Spill Remediation. The effectiveness of in-situ burning on oil cleanup may differ if the oil is floating on the water surface or has penetrated the soil. In-situ burning can effectively reduce floating diesel from the water surface, thus preventing it from penetrating the soil when the water recedes or drifting and contaminating adjacent habitats. In an in-situ diesel burn in Mobile Bay, AL, it was estimated that the average destruction efficiencies for total targeted diesel PAHs, including five alkylated PAH series and other EPA priority unsubstituted PAHs, were greater than 99% (*22*). In addition, in a simulated marine oil slick burn (*23*), the concentrations of several of the pyrogenic aromatic compounds were somewhat enriched in the residue, but the potential negative effect of these increases were outweighed by the positive effect of the mass of oil consumed in the burn. It was concluded that in-situ burning of a marine oil slick of Statfjord crude oil substantially reduced the total amount of polycyclic aromatic hydrocarbons left on the water surface after the spill. In the present study, more than 95% reduction in the total amount of diesel fuel due to the in-situ burning also greatly reduced the total amount of toxic compounds, such as PAHs, that could impact the marsh ecosystem.

In-situ burning, however, did not appear to effectively remove oil that had penetrated the soil. The TPH and TTAH concentrations in the soil of treatments with diesel fuel addition prior to the burn were not lower with in-situ burning than without burning, indicating that the oil in the soil was not combusted or evaporated during in-situ burning. The temperatures in the soil appeared not high enough to remove oil that had penetrated the soil under these conditions.

Our results indicate that some standing water over the marsh surface is important during in-situ burning for post-burn recovery of marsh vegetation. For a *S. alterniflora* marsh, 10 cm of overlying water is certainly sufficient. Lower water levels may also be adequate, but diesel stress at these lower water level treatments (0 and 2 cm of water over the soil surface) prevented a definitive conclusion regarding the causes for low plant recovery at these water levels, i.e., thermal stress or oil stress. Ongoing research will separate the thermal effect from the oil effect at these lower water levels.

Acknowledgments

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