COASTAL MARSH RECOVERY AND OIL REMEDIATION AFTER *IN-SITU* BURNING: EFFECTS OF WATER DEPTH, OIL AND MARSH TYPE

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Coastal Marsh Recovery and Oil Remediation After In Situ Burning: Effects of Water Depth, Oil and Marsh Type

Abstract

In situ burning of oiled wetlands potentially provides a cleanup technique that is compatible with the wetland environment and consistent with wetland management procedures. As such, *in situ* burning could be a highly valued cleanup method. However, effects of wetland burning can vary with different scenarios, producing beneficial as well as detrimental impacts. Factors such as water depth over the soil surface, marsh types with different plant species, and oil types may influence the response of wetlands to the burn. These factors have not been adequately addressed scientifically. Our previous research demonstrated that 10 cm of water overlying the soil surface was sufficient to protect the marsh soil from burn impacts to the salt marsh grass, *Spartina alterniflora*. In contrast, a water table 10 cm below the soil surface resulted in high soil temperatures and almost completely inhibited the survival of the grass. However, the effect on plant recovery of water level between 2 cm and 0 cm relative to the soil surface was equivocal. Therefore, a mesocosm scale investigation was conducted to study the effects of water depth, different types of oil burning, and oil application on the relationship between recovery of marsh vegetation, soil temperature, and oil remediation for different marsh types.

Marsh sods were collected from a *Spartina alterniflora* dominated salt marsh, a *Spartina patens* and *Distichlis spicata* co-dominated brackish marsh, and a *Sagittaria lancifolia* dominated fresh marsh in southeast Louisiana. The sods were placed in five gallon metal buckets, instrumented with thermocouples, and assigned to the following treatments: (a) oil exposure: diesel (0.5 liters m^{-2}), crude oil (0.5 liters m^{-2}), and no oil application; (b) burn types: 700 second crude oil burn and 700 second diesel fuel burn; and (c) water depth: 10, 2 and –2 cm over the marsh surface during *in situ* burning. Soil temperature, as a function of soil depth, sod elevation, and marsh type was continuously recorded during the 700 second burn and for 4700 seconds post-burn. After the burns, the mesocosms were returned to the greenhouse, where plant recovery was evaluated. Oil residue floating on the water surface after burning was analyzed to determine the efficiency of burning compared to the initial oil (diesel or crude). Soil samples for total petroleum hydrocarbon and GC/MS analyses were collected 24 hours post-burn to evaluate the *in situ* burning remediation of oil in the soil.

The water depth over the soil surface during *in situ* burning was a key factor controlling marsh plant recovery. Ten and 2 cm of water overlying the soil surface were sufficient to protect marsh vegetation of all three types from burning impacts. Soil surface temperatures did not exceed 40 degrees C and 50 degrees C when 10 and 2 cm of water overlaid the soil surface, respectively. Plant survival rate was 100%, and growth responses after the burn with 10 and 2 cm of water over the soil surface were not significantly different from the unburned control. In contrast, a water table 2 cm below the soil surface (2 cm of soil exposure to the fire) during the burn resulted in high soil temperatures, with 80-100 degrees C at 0 to 0.5 cm below the soil surface. The effect of thermal stress on plant survival differed with species at 2 cm of water below the soil surface. Two cm of soil exposure during *in situ* burning impeded the post-burn recovery of the salt marsh grass, *S. alterniflora*, and the fresh marsh species, *S. lancifolia*. However, 2 cm of soil exposure during *in situ* burning did not detrimentally affect the post-burn recovery of the brackish marsh grasses, *S. patens* and *D. spicata*. The *in situ* burn effectively removed floating oil from the water surface, with about 99% destruction efficiencies in TTAH and TTNH in terms of mass balance. This prevented the oil from potentially contaminating adjacent habitats and penetrating the soil when the water receded. In addition, *in situ* burning remediated diesel oil that had touched the soil, although burning did not remove the oil that came in contact with the soil as effectively as it did the floating oil.

1.0 Introduction

Wetland ecosystems are considered among the most valuable, as well as the most fragile, of all natural systems (Costanza *et al*. 1998). Oil pollution from pipeline ruptures, tanker accidents, exploration, and production blowouts poses a serious risk to the health of wetland systems. The cleanup of oil spills in the wetland environment is problematic and can do more damage than the oil itself (McCauley and Harrel 1981; DeLaune *et al*. 1984; Kiesling *et al*. 1988). Despite these risks, it is often essential to remove spilled oil before it spreads to other habitats and adjacent waterbodies. For this reason, it is important to develop less intrusive oil spill cleanup procedures that exert little or no long-term impact on the wetland system. A cleanup technique that is compatible with the wetland environment and is consistent with present wetland management procedures would be highly valued.

In situ burning of oiled wetlands potentially provides such a procedure. Wetlands, both coastal and inland, are burned periodically to provide better wildlife habitat (Chabreck 1975; Kirby *et al*. 1988; Schmalzer *et al*.1991). Although burning has become an accepted practice in wetland management, examples in the scientific literature show that burning wetlands can have beneficial, detrimental, or no impacts. For example, prescribed burns in salt marshes in Georgia (Turner 1987) and Florida (Schmalzer *et al.* 1991) reduced regrowth of the vegetation compared to controls, while management burns in a fresh marsh in the Netherlands had little to no impact (van der Toor and Mook 1982). Factors such as the water level during the burn, burn type, season of the burn, and the wetland type likely control post-burn recovery (Mallik and Wein 1986; Hess 1975; van der Toor and Mook 1982; Timmins 1992, Hyde *et al*. 1999; Pahl and Mendelssohn 1999; Lin *et al.* 2002).

Although the factors mentioned above are often cited as controlling recovery success after prescribed burning, little is known about the primary variables that determine the successful recovery of wetlands subjected to *in situ* burning after an oil spill. Not only is the literature on *in situ* burning limited, but it is often contradictory. For example, Holt *et al*. (1978) found that burning an oiled *Spartina alterniflora* marsh in Texas resulted in better recovery than an unburned marsh, supporting earlier findings by Baker (1970). Lindau *et al*. (1999) and Pahl and Mendelssohn (1999) observed rapid recovery of salt marsh vegetation in Louisiana after *in situ* burning. Mendelssohn *et al.* (1995) reviewed *in situ* burning and concluded that burning is suitable for oil spill cleanup. In contrast, burning an oiled *S. patens* marsh in Texas had a more negative impact than no action at all (McCauley and Harrel 1981). Burning may also facilitate the penetration of the oil into the marsh substrate (Kiesling *et al*. 1988).

Our most recent study (Lin *et al*. 2002) showed that water depth over the soil surface during *in situ* burning was a key factor in controlling the recovery of the salt marsh grass, *Spartina alterniflora*. Ten cm of water overlying the soil surface were sufficient to protect the marsh soil from burn impacts (soil temperature was < 37 degrees C during the *in situ* burns and plant survival and regrowth was high). In contrast, a water table 10 cm below the soil surface (10 cm of soil exposure) resulted in high soil temperature (120 degrees C at 2 cm soil depth). Thermal stress completely inhibited the post-burn recovery of *S. alterniflora* at this water level. Burn duration (five minutes vs. 20 minutes) did not have a significantly different effect on the recovery of *S. alterniflora*. However, Lin *et al*. (2002) suggested that poor recovery of *S. alterniflora* at water levels of 2 and 0 cm relative to the soil surface was most likely due to chemical stress. This stress occurred when diesel oil that was used to create the fire entered the sod containers during the burn. The high concentration of diesel in the soil at these water levels probably caused greater stress to the plants than the thermal effect. Thus, the present research was designed to separate the oil stress from the thermal stress at water levels less than 10 cm. This information will allow the development of scientifically based guidelines that will better predict the environmental conditions under which *in situ* burning should be attempted.

The overall goal of this research was to elucidate the factors that maximize the recovery of oil contaminated wetlands after *in situ* burning. Specifically, we determined the effects of water level and oil type (crude oil and diesel fuel) on soil temperature, oil remediation, and vegetation recovery of coastal salt, brackish and fresh marshes. This research provides quantitative data on the interaction among burn dynamics, oil chemistry, and recovery of various coastal marshes.

2.0. Materials and Methods

2.1. Experimental design

Intact marsh sections, 30 cm in diameter and 30 deep, were collected from a *Spartina alterniflora* dominated salt marsh, a *Spartina patens* and *Distichlis spicata* co-dominated brackish marsh, and a *Sagittaria lancifolia* dominated fresh marsh in southeast Louisiana. The marsh sections were placed in five gallon metal buckets. After collection, marsh sods were instrumented with thermocouples, allowed to acclimate under greenhouse conditions for a period of ca. five weeks, and randomly assigned to the following treatments: (a) oil exposure: unweathered diesel fuel (0.5 liters m^{-2}), unweathered Louisiana crude oil (0.5 liters m^{-2}), and no oil application; (b) burn type: 700 seconds crude oil burn and 700 seconds diesel fuel burn; and (c) water depth: 10, 2 and –2 cm (2 cm below the marsh surface) of water over the marsh surface during *in situ* burning. For the salt and brackish marshes, the experimental design was a completely randomized block with a 3 x 2 x 2 factorial arrangement of treatments (three water depths, two oil levels, and two burn types, respectively). For the fresh marsh, only the crude oil burn was conducted. Thus, the experimental design for the fresh marsh was a completely randomized block with a 3 x 2 factorial arrangement of treatments (three water depths and two oil levels). Each treatment-level combination was replicated four times. Each block [3 (water level) x 2 (oil level) x 2 (marsh types for diesel burn) or 3 (marsh types for crude burn)] was burned separately. In addition, four unburned-oiled sods for each oil type (diesel and crude) and four unburned-unoiled sods served as controls. Aboveground vegetation of the unburned treatments was cut at about 5 cm above the soil surface to simulate fire consumption of the aboveground vegetation; thus, biomass at the initiation of the recovery period was similar for all treatments. A total of 184 experimental units were used in the experiment. The soil characteristics of the three types of marshes were documented (Table 1).

Table 1. Soil characteristics of the three types of marshes used in the *in-situ* burns.

Marsh Types	% Clay	% Silt	% Sand	Class	% Organic Matter
Salt Marsh	28.5	70.6	0.8	Silty Clay Loam	15.7
Brackish Marsh	28.8	68.0	3.2	Silty Clay Loam	11.8
Fresh Marsh	23.7	69.1	7.2	Silty Loam	33.6

Fifty-seven of the 184 marsh sods among three types of marshes were instrumented with thermocouples inserted into the soil to monitor soil temperature during the *in situ* burn. Thermocouples were inserted at 0, 0.5, 1, 2, 3, 5, 7, and 10 cm below the soil.

Water and air temperature as well as total heat flux at the water surface were also recorded. For each of the 12 burns, a total of 8 to 15 marsh sods, both instrumented and uninstrumented, were positioned at 10 cm, 2 cm, and -2 cm below the water surface level (Figs. 1, 2, and 3). *In situ* burns were conducted in a 6 m diameter test tank at Louisiana State University's Fire and Emergency Training Institute. Either diesel fuel or South Louisiana Crude oil was added to the water surface, ignited, and allowed to burn for periods of 700 seconds (Figs. 4 and 5). The total volume of oil added to the water surface for the 700 second burn duration was about 1350 liters per burn (>40 mm thick layer of fuel floating on the water surface). The soil temperature, as a function of soil depth and sod elevation, was continuously recorded during the burn and for a period of one to two hours post-burn (for details on thermocouple installation and measurements see Bryner *et al*. 2001).

Figure 1. *The 6 m burn tank, containing salt and brackish marsh sods with soil surface at different elevations, was filled with water before the burn.*

Figure 2. *Fine adjustment of the soil surface of the sods to 10, 2, and -2 cm below the water surface in the 6 m burn tank was conducted before the burn.*

Figure 3. *Diesel fuel was added to the 6 m burn tank before the burn.*

Figure 4. *The fire intensity in the burn tank was similar to that of an in situ burn in the field.*

Figure 5. *Most diesel fuel was consumed by the fire after a 700 second burn.*

Figure 6. *Burned marsh sods were held in the greenhouse to evaluate the treatment effects on vegetation recovery. Most aboveground biomass of the marsh plants was consumed by the fire during the in situ burns.*

Figure 7. *Vegetation recovery was apparent 40 days after in situ burning.*

After the burns, the mesocosms were returned to the greenhouse (Fig. 6) where plant recovery (Fig. 7) was evaluated as described below. Soil samples for the analyses of total petroleum hydrocarbons (TPH) and total targeted aromatic hydrocarbons were collected 24 hours after oil addition and 24 hours after the burn. Additionally, the initial concentration and chemical composition of the oil and the oil concentration in the soil before burning were evaluated in representative mesocosms. Recovery of the salt marsh plants was evaluated by determining plant survival rate, stem density after the burn, and aboveground biomass.

2.2 Methods

Plant Growth and Survival. Plant regrowth was assessed by measuring plant survival rate, stem density of plants regenerated during the experiment after the burn, and aboveground biomass at the termination of the experiment. Stem density was determined by counting the number of stems of each species in each experimental unit. The plant material harvested at the end of the experiment (one year after burning) was separated by species and dried at 65 degrees C to a constant weight. Also, percent sod survival was determined as the number of the experimental units having regenerated dominant plant species divided by the total number of experimental units per treatment level (4) times 100%.

TPH Analysis (GC/FID). TPH (total petroleum hydrocarbons) analysis was based on EPA Method 1664. Samples were extracted with dichloromethane and analyzed by conventional gas chromatography with flame ionization detection (GC-FID). Silica gel treatment was not used. Results were corrected for background extractable material by comparison with oil free soil blanks. GC separations used a 30 meter, 0.25 mm i.d. column with a 5% phenyl-95% dimethylpolysiloxane (DB-5) stationary phase. The initial GC temperature was 50 degrees C for two minutes followed by temperature programming to 280 degrees C at 15 degrees C /minute. The temperature was held at 280 degrees C for an additional 12 minutes.

Detailed Chemical Analysis of Aromatic and Alkanes with GC/MS. All samples were analyzed by GC-MS (gas chromatography / mass spectrometry) to confirm and expand the GC-FID results. A GC-MS profile of the initial oil material was obtained for comparison with the residue. The GC/MS instrumentation used was a Hewlett Packard 5890 GC configured with a DB-5 high resolution capillary column (0.25 mm ID, 30 meter, 0.25 micron film, J&W Scientific) directly interfaced to a Hewlett Packard 5971 MS detector system. The GC flow rates and temperature were optimized to provide the required degree of separation (i.e. phytane and n-C18 should be baseline resolved, and pristane and n-C17 should be near baseline resolved). The GC was operated in the temperature program mode with an initial column temperature of 55 degrees C for three minutes, then increased to 290 degrees C at a rate of 5 degrees C /minute and held at the upper temperature for 15 minutes. The injection temperature was set to 250 degrees C and only high-temperature, low thermal bleed septa were used. The interface to the MS was maintained at 290 degrees C. All gases used were of the highest purity available. The MS was operated in the Selected Ion Detection mode (SIM) to maximize the detection of several trace target constituents in crude oil. The instrument was operated such that the selected ions for each acquisition window were scanned at a rate greater than 1.4 scans/sec. The targeted constituents and the quantitative ions monitored for each are provided in Table 2. An internal standard mix composed of nitrobenzene-d5, 2-flurobiphenyl, and terphenyl-d14 was coinjected with each analysis to monitor instrument performance during each run.

2.3 Statistical Analysis

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

Table 2. Target compounds assessed by GC/MS. The sum of these compounds,

excluding those identified with a *, constitutes the TTAH value. Ion mass 85 was used for alkanes* (nC-10 thru nC-31). * Those compounds noted with a * are used primarily for source-fingerprinting and generally not quantified.

Compound	***ion* mass**
alkanes* (nc-10 thru nC-31)	85
decalin*	138
C-1 decalin*	152
C-2 decalin*	166
C-3 decalin*	180
naphthalenes	128
C-1 naphthalenes	142
C-2 naphthalenes	156
C-3 naphthalenes	170
C-4 naphthalenes	184
fluorene	166
C-1 fluorenes	180
C-2 fluorenes	194
C-3 fluorenes	208
dibenzothiophene	184
C-1 dibenzothiophene	198
C-2 dibenzothiophene	212
C-3 dibenzothiophene	226
phenanthrene	178
C-1 phenanthrenes	192
C-2 phenanthrenes	206
C-3 phenanthrenes	220
naphthobenzothiophene	234
C-1 naphthobenzothiophene	248
C-2 naphthobenzothiophene	262
C-3 naphthobenzothiophene	276
fluoranthrene/pyrene	202
C-1 pyrenes	216
C-2 pyrenes	230
chrysene	228
C-1 chrysene	242

C-2 chrysene	256
benzo(b)fluoranthene	252
benzo(k)fluoranthene	252
benzo(e)pyrene	252
benzo(a)pyrene	252
perylene	252
indeno(1,2,3-cd)pyrene	276
dibenzo(a,h)anthracene	276
hopanes (191 family)*	191
sterenes (217 family)*	217

3.0 Results

3.1. Recovery of Marsh Plants after *In Situ* Burning

Percent Survival. Recovery of marsh plants from *in situ* burning mainly depended upon the plant species as well as the depth of water over the soil surface during the burn. Generally, 10 and 2 cm of water overlying the soil surface were sufficient to protect the plants from burn impacts for all marsh types. Percent survival of the experimental units (marsh sods) after *in situ* burning was 100%, with 10 and 2 cm of water over the soil surface (Fig. 8). Sod survival decreased at –2 cm of water for *Spartinaalterniflora* and *Sagittaria lancifolia*, but not for *Spartina patens* and *Distichlis spicata*. We noted a 30% decrease in survival for *S. alterniflora* and a 50% decrease for *S. lancifolia*.

Stem Density. The effect of *in situ* burning on stem densities regenerated after the burn varied with marsh plant species and water depth over the soil surface during burning. For *S. alterniflora*, water depth over the soil surface during burning significantly ($p<0.0001$) affected growth of new stems after the burn (Fig. 9). Stem density of *S. alterniflora* was significantly lower in the treatment with –2 cm water than in the control, while stem densities of the treatments with 10 and 2 cm of water overlying the soil surface were not significantly different from the control. Oil addition before the burn and burning type (crude vs. diesel) did not significantly affect the stem density of *S. alterniflora*. For the brackish marsh co-dominated by *S. patens* and *D. spicata*, the effect of water depth over the soil surface during the burn depended upon the plant species (Fig.10). Stem density of *S. patens* was significantly lower in the treatment with –2 cm of water than in the control, while the stem densities of the treatments with 10 and 2 cm of water overlying the soil surface were not significantly different from the control. However, water depth over the soil surface during burning did not significantly affect the stem density of *D. spicata* (Fig. 10). Oil addition before the burn and burning type (crude vs. diesel) did not significantly affect the stem densities of *S. patens* and *D. spicata*. Although the fresh marsh was dominated by *Sagittaria lancifolia*, it also contained several other species. The effect of water depth over the soil surface during the burn also depended upon the plant species. Stem density of *S. lancifolia* was significantly lower in the treatment with –2 cm of water than in the control, while the stem densities of the treatments with 10 and 2 cm of water overlying the soil surface were not significantly different from the control (Fig. 11A). However, *in situ* burning did not significantly affect the stem density of *Eleocharis* (Fig. 11B). For the other species, effects of burning generally were not significant, except for *Pannicum dichotomiflorum*. In this case, stem density was significantly higher in the unburned treatment than in other treatments (Table 3).

Table 3. Effect of water table level during the burns on stem density of fresh marsh species one year after the crude oil burn. Values (number/pot) are means with standard errors in parentheses (n=4). Notation of 10 cm, 2cm, and –2cm indicate the water surface relative to the soil surface during the burn.

Water Level	***Ipomoea sagittata***	***Alternanthera philoxeroides***	***Aster subulatus***	***Echinochloa crus-galli***	***Pannicum dichotomiflrum***
unburned	0.5 (0.3)	3.1 (1.8)	1.5 (0.7)	0	15.3 (7.9)
10 cm	0.2 (0.1)	3.5 (1.8)	0.4 (0.2)	1.4 (0.7)	0
2 cm	0.4 (0.4)	2.1 (1.1)	2.8 (1.3)	1.9 (1.2)	0
–2 cm	0	1 (0.6)	0	0	2.7 (1.9)

Table 4. Effect of water level during the burn on aboveground biomass with standard errors in parentheses of fresh marsh species one year after the crude oil burn. Values (g/pot) are means with standard errors in parentheses (n=4). Notation of 10 cm, 2 cm, and –2 cm indicate the water surface relative to the soil surface during the burn.

Water Level	***Ipomoea sagittata***	***Alternanthera philoxeroides***	***Astersubulatus***	***Echinochloa crus-galli***	***Pannicum dichotomiflorum***
Unburned	0.5 (0.4)	1.1 (0.7)	1.2 (0.8)	0	11.1 (5.5)
10 cm	0.2 (0.2)	1.5 (0.7)	1.1 (0.9)	1.1 (0.7)	0
2 cm	0.6 (0.6)	0.8 (0.5)	5 (2.5)	1.0 (0.6)	0
-2 cm	0	0.3 (0.2)	0	0	2.6 (1.8)

Figure 8. *Effects of water table level on sod survival one year after the burns. Values are averaged over oil application and burn type. Notation of 10 cm, 2 cm, and –2 cm indicate the water surface relative to the soil surface during the burn.*

Figure 9. *Effects of water table level and oil application on stem density of Spartina alterniflora one year after the crude oil (A) and diesel (B) burns. Notations of 10 cm, 2 cm, and –2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).*

Figure 10. *Effects of water table level and oil application on stem density of Spartina patens and Distichlis spicata one year after the crude oil (A) and diesel (B) burns. Notations of 10 cm, 2 cm, and –2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).*

Figure 11. *Effects of water table level and oil application on stem density of Sagittaria lancifolia (A) and Eleocharis spp. (B) one year after the crude oil burns. Notations of 10 cm, 2 cm, and –2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).*

3.1.1 Plant Aboveground Biomass

Aboveground biomass and stem density exhibited similar responses to the experimental treatments. Generally, water depth over the soil surface during the burn had a significant effect on plant aboveground biomass. For *S. alterniflora*, water depth over the soil surface during the burn significantly ($p<0.0001$) affected new biomass regenerated after the burn (Fig. 12). Aboveground biomass of *S. alterniflora* was significantly lower in the treatment with –2 cm water (29.9 g/pot ± 5.5) than in the control (48.1 g/pot ± 2.7,) while the biomass of the treatments with 10 and 2 cm of water overlying the soil surface was not significantly different from the control. Oil addition before the burn and burning type (crude vs. diesel) did not significantly affect the biomass of *S. alterniflora*. For the brackish marsh co-dominated by *S. patens* and *D. spicata*, water depth over the soil surface during the burn, oil addition before the burn, and burning type (crude vs. diesel) did not significantly affect the biomass of *S. patens*, *D. spicata*, or the combined biomass of the two species (Fig. 13). For the fresh marsh, the effect of treatments was plant species-specific. Water depth over the soil surface during the burn affected aboveground biomass of *S. lancifolia* regenerated after the burn (Fig. 14). The aboveground biomass of *S. lancifolia* was significantly lower ($p<0.005$) in the treatment with –2 cm water than in the control, while the aboveground biomass of the treatments with 10 and 2 cm of water overlying the soil surface was not significantly different from the control. In addition, the biomass of *Aster subulatus* was significantly lower in the treatment with –2 cm water than in the control, while the biomass of the treatments with 10 and 2 cm of water overlying the soil surface were not significantly different from the control (Table 4). The aboveground biomass of all fresh marsh species combined was significantly impacted in the –2 cm water level treatment compared to the control, while burning with 10 and 2 cm of water over the soil surface did not significantly impacted total biomass (Fig. 14).

3.2. Soil Temperature

Peak soil temperature at 0, 0.5, 2, and 5 cm below the soil surface was documented during the *in situ* burns (Figs. 15, 16, and 17). Water levels over the soil surface significantly ($p<0.0001$) affected soil temperature. The peak temperature also decreased rapidly with soil depth. For the treatments with 2 cm of soil exposure during the burn, at 0 and 0.5 cm soil depths, average peak soil temperatures were well above 60 degrees C, ranging between 70 to 100 degrees C (Figs. 15 to 17). At 2 cm soil depths, average peak soil temperatures generally were between 45 and 60 degrees C (Figs. 15 to 17). At 5 cm soil depths, average peak soil temperatures were below 40 degrees C (Figs. 15 to 17). For the treatments with 2 cm of water over the soil surface during the burn, average peak soil temperatures were below 50 degrees C at 0 cm soil depth, and decreased with soil depth (Figs.15 to 17). For the treatments with 10 cm of water over the soil surface during the burn, average peak soil temperatures were ca. 35 degrees C for all soil depths.

Burning type (diesel vs. crude), oil application to the soil prior to the burn, and marsh type generally did not significantly affect average peak soil temperature (see Bryner *et al*. 2001 for detailed soil temperature data).

Figure 12. *Effects of water table level and oil application on aboveground biomass of Spartina alterniflora one year after the crude oil (A) and diesel (B) burns. Notations of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the*

burn. Error bars are standard errors (n=4).

Figure 13. *Effects of water table level and oil application on aboveground biomass of Spartina patens and Distichlis spicata one year after the crude oil (A) and diesel (B) burns. Notations of 10 cm, 2 cm, and –2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).*

Figure 14. *Effects of water table level and oil application on aboveground biomass of fresh marsh species one year after the crude oil (A) and diesel (B) burns. Notations of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).*

Figure 15. *Average peak soil temperature as a function water level over the soil surface and burn type during the crude oil (A) and diesel fuel (B) salt marsh burns. Notations of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).*

Figure 16. *Average peak soil temperature as a function of water level over the soil surface and burn type during the crude oil (A) and diesel fuel (B) brackish marsh burns. Notations of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).*

Figure 17. *Average peak soil temperature as a function of water level over the soil surface during the crude oil fresh marsh burns. Notations of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn.*

3.3. Petroleum Hydrocarbon Concentrations

The experimental treatments affected the total petroleum hydrocarbons (TPH) in the soil. For diesel fuel, TPH concentrations in the soil receiving the diesel burn at the various water levels were significantly ($p<0.0001$) lower than the control (without burn) for the *S. alterniflora* dominated salt marsh (Fig. 18B) and the *S. patens* dominated brackish marsh (Fig 18B), especially at the –2 cm water level. Generally, TPH concentrations salt marsh soil dominated by *S. alterniflora* were not significantly different from those of brackish marsh dominated by *S. patens*. For crude oil, TPH concentrations in the soil receiving a crude oil burn at the various water levels were not significantly different from the control (without the burn) for the salt marsh dominated by *S. alterniflora*, the brackish marsh dominated by *S. patens*, and the fresh marsh dominated by *S. lancifolia* (Fig. 18A). However, TPH concentrations in the salt marsh soil (493 ug/g ± 24, n=16) were significantly ($p<0.0001$) lower than the brackish (2258 ug/g ± 114, n=16) and fresh (2357 ug/g ± 104, n=16) marshsoils.

The total targeted aromatic hydrocarbons (TTAH) in the soil after *in situ* burning showed a similar trend to the soil TPH. For the crude oil burn, the concentration of total targeted aromatic hydrocarbons (TTAH) (Fig. 19A) and total targeted normal hydrocarbons (TTNH) (Fig. 20 A) in the soil were not substantially different between burning treatments and the unburned control. For the diesel burn, TTAH (Fig 19B) and TTNH (Fig. 20B) concentrations in the burn treatments appeared to be lower compared to the control, especially for the *S. alterniflora* dominated marsh.

The TTAH concentrations in the residual oil floating on the water surface after the burn decreased substantially compared to concentrations in original diesel fuel before the burn (Table 5). There was a 75% reduction in concentration for the diesel burn and a 56% reduction in concentration for the crude oil burn. In addition, the TTNH concentrations in the residual oil floating on the water surface after the burn decreased compared to concentrations in the original crude oil before the burn (Table 6). We recorded a 77.5% reduction in concentration for the diesel burn and an 88.2% reduction in concentration for the crude oil burn. Interestingly, changes in concentrations varied with individual compounds of the petroleum. The removal of petroleum compounds during *in situ* burning generally decreased with increasing carbon number of compounds. For example, the reduction in concentration of alkanes remaining in the residual oil after the burn was greatly decreased, e.g. 99% for nC-11 undecane. At the same time, concentrations remaining in the residue after burning were higher for compounds with carbon numbers > nC-22 and nC-26 for the diesel and crude burns, respectively (Table 6). For aromatic hydrocarbons, a reduction in concentrations in the residual oil after burning was more than 90% for napthalene, while concentrations remaining in the residue after burning were higher for compounds with carbon numbers > fluoranthene (four rings) (Table 5). *In situ* burning also greatly reduced the thickness or amount of the oil remaining on the water surface, with only a thin film (< 1 mm or < 2.5% of the original amount) of residual oil remaining compared to the amount of oil originally added to the water surface (> 40 mm of oil). However, accurate estimations of oil thickness are extremely difficult. Total amounts of both aromatic compounds and alkanes remaining in the residue were greatly reduced for both the diesel and crude burns; with more than 99% removal (Tables 7 and 8) in term of mass balance. Even for large molecular compounds (> nC-22 for alkanes and > fluoranthen for aromatic compounds, respectively), more than 90% of the compounds were removed during the burn in terms of mass balance, although their concentrations in the residue were higher compared to the original oils (Tables 7 and 8).

Figure 18. *Effect of water table level and burning type on total petroleum hydrocarbons in the soil 0 to 4 cm below the soil surface one day after the crude oil (A) and diesel fuel (B) burns. Notations of 10 cm, 2 cm, and –2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4). Oil was applied to all treatments prior to the burn.*

Figure 19. *Effect of water table level and burning type on the total targeted aromatic hydrocarbons (TTAH) in the soil 0 to 4 cm below the soil surface one day after the crude oil (A) and diesel fuel (B) burns. Values are derived from an analysis of four replicates composited. Notations of 10 cm, 2 cm, and –2 cm indicate the water surface relative to the soil surface during the burn. Oil was applied to all treatments prior to the burn.*

Figure 20. *Effect of water table level and burning type on the total target normal hydrocarbons (TTAH) in the soil 0 to 4 cm below the soil surface one day after the crude oil (A) and diesel fuel (B) burns. Values are derived from an analysis of four replicates composited. Notations of 10 cm, 2 cm, and –2 cm indicate the water surface relative to the soil surface during the burn. Oil was applied to all treatments prior to the burn.*

Table 5. Effect of *in situu* burning on aromatic hydrocarbon concentrations in the residual oil after burning compared to concentrations before burning

Compound	Diesel	Crude Oil

	Diesel Before Burning (ug/g)	Diesel after Burning (ug/mg)	% reduction in concentration for diesel after burn	Crude Before Burning (ug/g)	Crude after Burning (ug/mg)	% reduction in concentration for crude after burning
Napthalene	223	19	91.7%	112	4	96.7%
C-1 Napthalene	1,889	143	92.4%	267	14	94.9%
C-2 Napthalene	3,727	463	87.6%	521	51	90.2%
C-3 Napthalene	3,111	573	81.6%	487	73	84.9%
C-4 Napthalene	838	239	71.5%	155	30	80.6%
Fluorene	177	41	76.6%	9	3	68.3%
C-1 Fluorene	644	187	71.0%	37	12	67.1%
C-2 Fluorene	603	250	58.6%	57	18	68.3%
C-3 Flourene	372	206	44.5%	72	37	48.8%
Dibenzothiophene	7	10	-47.6%	103	40	61.5%
C-1 Dibenzothiophene	61	26	57.7%	110	49	54.8%
C-2 Dibenzothiophene	158	90	43.4%	342	197	42.3%
C-3 Dibenzothiophene	106	76	28.8%	259	190	26.5%
Phenanthrene	252	103	59.1%	26	15	41.9%
C-1 Phenanthrene	667	340	49.0%	76	38	49.9%
C-2 Phenanthrene	492	331	32.7%	85	55	35.8%
C-3 Phenanthrene	175	145	17.1%	52	43	18.0%
C-4 Phenanthrene	31	30	1.1%	16	20	-22.1%
Fluoranthene	6	8	-17.5%	0	3	-1428.1%
Pyrene	5	28	-434.8%	1	6	-642.0%
C-1 Pyrene	64	60	6.9%	6	10	-59.0%
C-2 Pyrene	31	35	-12.9%	12	19	-57.2%
C-3 Pyrene	9	13	-38.2%	16	26	-63.2%
C-4 Pyrene	3	4	-18.6%	12	23	-96.6%
Napthobenzothiophene	0	0	0	5	10	-87.0%
C-1 Napthobenzothiophene	0	0	0	24	49	-101.7%
C-2 Napthobenzothiophene	0	0	0	38	76	-100.5%
C-3 Napthobenzothiophene	0	0	0	36	83	-131.8%
Benzo(a) Anthracene	0	1	n/a	0	2	-304.3%
Chrysene	0	3	n/a	4	10	-130.0%
C-1 Chrysene	2	4	-92.0%	10	20	-92.7%
C-2 Chrysene	1	3	-95.2%	14	33	-129.7%
C-3 Chrysene	0	1	n/a	13	31	-131.9%
C-4 Chrysene	0	0	0	9	27	-194.4%
Benzo(b) Fluoranthene	0	1	-997.1%	1	3	-152.4%
Benzo(k) Fluoranthene	0	0	-3.7%	1	2	-208.1%
Benzo(e) Pyrene	0	0	-227.6%	1	5	-235.9%
Benzo(a) Pyrene	0	1	-522.3%	1	3	-293.3%
Perylene	1	1	-72.2%	1	1	23.5%
Benzo(g,h,i) Perylene	0	0	0	0	3	n/a
Total TTAH	**13659**	**3433**	**74.9%**	**2994**	**1334**	**65.4%**

Table 6. Effect of *in situ* burning on the TTNH concentrations in the residual oil after the burn compared to concentrations before the burn

Compound	**Diesel**			**Crude Oil**		
	Concentration Before Burning (ug/g)	Concentration after Burning (ug/mg)	% reduction in Concentration after burn	Concentration Before Burning (ug/g)	Concentration after Burning (ug/mg)	% reduction in concentration after burning
nC-10 Decane						
nC-11 Undecane	15	3	82.6%	5,644	18	99.7%
nC-12 Dodecane	2,410	29	98.8%	5,207	22	99.6%
nC-13 Tridecane	3,600	137	96.2%	4,093	24	99.4%
nC-14 Tetradecane	4,517	336	92.6%	3,173	39	98.8%
nC-15 Pentadecane	5,550	587	89.4%	2,539	69	97.3%
nC-16 Hexadecane	5,828	890	84.7%	2,058	101	95.1%
nC-17 Heptadecane	5,863	1,211	79.3%	1,730	134	92.3%
Pristane	4,963	1,275	74.3%	1,358	151	88.9%
nC-18 Octadecane	3,290	852	74.1%	257	28	89.2%
Phytane	3,521	1,177	66.6%	1,076	165	84.7%
nC-19 Nonadecane	1,725	520	69.8%	413	64	84.5%
nC-20 Eicosane	2,463	1,078	56.2%	904	188	79.2%
nC-21 Heneicosane	1,442	828	42.6%	792	209	73.6%
nC-22 Docosane	799	621	22.4%	622	219	64.8%
nC-23 Tricosane	383	416	-8.5%	472	208	56.1%
nC-24 Tetracosane	191	246	-28.9%	372	200	46.3%
nC-25 Pentacosane	103	149	-43.9%	317	220	30.6%
nC-26 Hexacosane	46	90	-94.0%	237	195	17.7%
nC-27 Heptacosane	18	40	-125.0%	200	207	-3.8%
nC-28 Octacosane	6	16	-173.0%	163	168	-3.0%
nC-29 Nonacosane	2	5	-253.6%	137	170	-23.6%
nC-30 Triacontane	0	2	-415.1%	111	152	-37.5%
nC-31	0	1	n/a	111	154	-38.2%
Hentriacontane	0	0	0	109	158	-45.5%
nC-32	0	0	0	95	147	-55.0%
Dotriacontane	0	0	0	69	120	-75.3%
nC-33	0	0	0	56	107	-90.5%
Tritriacontane	0	0	0	51	127	-146.4%
nC-34	0	0	0	36	66	-86.8%
Tetratriacontane						

nC-35 Pentatriacontane nC-30 17a, 21b-Hopane						
TTNH	**46,736**	**10,508**	**77.5%**	**32,400**	**3,829**	**88.2%**

Table 7. Effect of *in situ* burning on total mass of aromatic hydrocarbons in the residual oil after the burn compared to the mass before the burn

Compound	**Diesel**			**Crude-Oil**		
	Total Mass Before Burning (mg)	Total Mass after Burning (mg)	%reduction in Total Mass after Burning	Total Mass Before Burning (mg)	Total Mass after Burning (mg)	%reduction in Total Mass Burning

Napthalene	217,913	452	99.8%	109,370	91	99.9%
C-1 Napthalene	1,842,600	3,495	99.8%	260,821	332	99.9%
C-2 Napthalene	3,634,647	11,295	99.7%	508,059	1,251	99.8%
C-3 Napthalene	3,034,330	13,965	99.5%	474,617	1,791	99.6%
C-4 Napthalene	817,659	5,820	99.3%	151,342	734	99.5%
Fluorene	172,202	1,007	99.4%	9,141	72	99.2%
C-1 Fluorene	628,124	4,556	99.3%	35,955	296	99.2%
C-2 Fluorene	588,203	6,091	99.0%	55,822	442	99.2%
C-3 Flourene	363,151	5,034	98.6%	70,130	898	98.7%
Dibenzothiophene	6,468	239	96.3%	100,177	965	99.0%
C-1 Dibenzothiophene	59,546	630	98.9%	106,806	1,206	98.9%
C-2 Dibenzothiophene	154,264	2,183	98.6%	333,351	4,807	98.6%
C-3 Dibenzothiophene	103,822	1,848	98.2%	252,789	4,644	98.2%
Phenanthrene	245,416	2,510	99.0%	24,959	363	98.5%
C-1 Phenanthrene	650,613	8,295	98.7%	74,511	934	98.7%
C-2 Phenanthrene	480,111	8,073	98.3%	82,900	1,331	98.4%
C-3 Phenanthrene	170,857	3,542	97.9%	51,037	1,047	97.9%
C-4 Phenanthrene	29,770	736	97.5%	15,957	487	96.9%
Fluoranthene	6,278	184	97.1%	221	85	61.8%
Pyrene	5,088	680	86.6%	841	156	81.5%
C-1 Pyrene	62,825	1,462	97.7%	5,921	235	96.0%
C-2 Pyrene	30,291	855	97.2%	11,835	465	96.1%
C-3 Pyrene	9,053	313	96.5%	15,826	646	95.9%
C-4 Pyrene	3,254	97	97.0%	11,516	566	95.1%
Napthobenzothiophene	0	0	n/a	5,252	245	95.3%
C-1 Napthobenzothiophene	0	0	n/a	23,588	1,189	95.0%
C-2 Napthobenzothiophene	0	0	n/a	36,987	1,854	95.0%
C-3 Napthobenzothiophene	0	0	n/a	34,783	2,016	94.2%
Benzo(a) Anthracene	0	14	n/a	363	37	89.9%
Chrysene	0	67	n/a	4,345	250	94.3%
C-1 Chrysene	1,780	85	95.2%	10,137	488	95.2%
C-2 Chrysene	1,344	66	95.1%	13,980	803	94.3%
C-3 Chrysene	0	33	n/a	12,995	753	94.2%
C-4 Chrysene	0	0	n/a	8,834	650	92.6%
Benzo(b) Fluoranthene	78	21	72.6%	1,003	63	93.7%
Benzo(k) Fluoranthene	100	3	97.4%	573	44	92.3%
Benzo(e) Pyrene	101	8	91.8%	1,354	114	91.6%
Benzo(a) Pyrene	86	13	84.34%	684	67	90.2%
Perylene	544	23	95.7%	1,083	21	98.1%
Benzo(g,h,i) Perylene						
Total TTAH	**13,320,637**	**83,704**	**99.4%**	**2,919,864**	**35,524**	**98.9%**

Table 8. Effect of *in situ* burning on the total mass of alkane (normal) hydrocarbons in the residual oil after the burn compared to the mass before the burn

Compound	**Diesel**			**Crude Oil**		
	Total Mass Before Burning (mg)	Total Mass after Burning (mg)	% reduction in Total Mass after burn	Total Mass Before Burning (mg)	Total Mass after Burning (mg)	% reduction in Total Mass after Burning
nC-10 Decane	14,281	62	99.6%	5,503,808	439	99.99
nC-11 Undecane	2,350,381	700	99.97%	5,078,255	545	99.99%
nC-12 Dodecane	3,511,306	3,342	99.9%	3,991,215	591	99.99%
nC-13 Tridecane	4,404,713	8,182	99.8%	3,094,378	945	99.97%
nC-14 Tetradecane	5,412,334	14,304	99.7%	2,476,046	1,684	99.9%
nC-15 Pentadecane	5,683,398	21,695	99.6%	2,006,644	2,461	99.9%
nC-16 Hexadecane	5,718,034	29,537	99.5%	1,686,891	3,265	99.8%
nC-17 Heptadecane	4,839,778	31,079	99.4%	1,324,150	3,688	99.7%
Pristane	3,209,023	20,769	99.4%	250,187	675	99.7%
nC-18 Octadecane	3,433,933	28,703	99.2%	1,049,835	4,012	99.6%
Phytane	1,682,253	12,681	99.2%	402,696	1,560	99.6%
nC-19 Nonadecane	2,402,047	26,294	98.9%	882,103	4,578	99.5%
nC-20 Eicosane	1,406,598	20,186	98.6%	772,573	5,095	99.3%
nC-21 Heneicosane	779,657	15,132	98.1%	606,279	5,337	99.1%
nC-22 Docosane	373,938	10,148	97.3%	460,641	5,061	98.9%
nC-23 Tricosane	186,182	6,001	96.8%	362,776	4,873	98.7%
nC-24 Tetracosane	100,758	3,624	96.4%	308,831	5,357	98.3%
nC-25 Pentacosane	45,121	2,189	95.1%	231,176	4,758	97.9%
nC-26 Hexacosane	17,534	986	94.4%	194,870	5,059	97.4%
nC-27 Heptacosane	5,714	390	93.2%	159,278	4,103	97.4%
nC-28 Octacosane	1,515	134	91.2%	133,855	4,136	96.9%
nC-29 Nonacosane	340	44	87.1%	108,030	3,713	96.6%
nC-30 Triacontane	0	16	n/a	108,360	3,745	96.5%
nC-31 Hentriacontane	0	4	n/a	105,951	3,854	96.4%
nC-32 Dotriacontane	0	0	n/a	92,276	3,576	96.1%
nC-33 Tritriacontane	0	0	n/a	68,816	2,928	95.6%
nC-34 Tetratriacontane	0	0	n/a	54,918	2,616	95.2%
nC-35 Pentatriacontane	0	0	n/a	50,162	3,090	93.8%
nC-30 17a, 21b-Hopane	0	0	n/a	34,690	1,620	95.3%
Total TTNH	**45,578,838**	**256,202**	**99.4%**	**31,597,690**	**93,362**	**99.7%**

4.0. Discussion

The recovery of coastal marsh plants from *in situ* burning mainly depended upon the depth of water over the soil surface during the burn as well as the specific marsh plant species. Standing water over the marsh surface during *in situ* burning protected the marsh vegetation. Increased water depth over the marsh surface provided increased protection to the marsh vegetation during the *in situ* burn, resulting in lower soil temperatures and higher survival rates. However, the impact of *in situ* burning on marsh plants was species specific.

Ten cm of water over the soil surface were sufficient to protect all three types of marsh vegetation from burning impacts. Soil surface temperature 10 cm below the water did not exceed 40 degrees C. Thermal stress on plants was absent. The plant survival and growth responses to the water level treatments support the temperature data. Two cm of water over the soil surface also protected the marsh sods from burn impacts. Soil temperatures for different marsh and burn types were below 50 degrees C, even at the soil surface for most marsh sods. Plant survival and growth responses were not significantly different from the unburned control.

Two cm of soil exposure during *in situ* burning impeded the post-burn recovery of the salt marsh grass, *S. alterniflora,* and fresh marsh species, *S. lancifolia*. Burning with the water table 2 cm below the soil surface resulted in average peak soil temperatures of about 100 degrees C at the soil surface and 50 to 60 degrees C at a depth of 2 cm below the soil surface. Thermal stress on the plants was the main factor inhibiting post-burn plant recovery compared to the control.

Research on prescribed burning has also demonstrated that the water level during a burn can affect post-burn recovery (Mallik and Wein 1986; Hess 1975; Timmins 1992; Lin *et al*. 2002). A prescribed burn during higher water levels produced greater stem post-burn density and height of *Scirpus olneyi* (Hess 1975). A burn in the drained portion of an impoundment resulted in lower plant coverage than the control, while a burn in the flooded portion of an impoundment stimulated plant coverage above the controls (Mallik and Wein 1986). In a New Zealand bog, burning also resulted in a more favorable response in wet compared to drier sites (Timmins 1992). A very recent study (Lin *et al*. 2002) demonstrated that burning marsh sods 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 a significant recovery of *S. alterniflora*, similar to the present results. The present study demonstrated that 2 cm of water over the soil surface were enough to allow for plant recovery. This result further demonstrates that standing water over the marsh surface during *in situ* burning is the primary factor in controlling post-burn recovery.

Soil temperatures during the in situ burns generally depended upon the water depth over the soil surface. In addition, soil temperatures generated during the burns differed with soil depth. Lower temperatures were found with greater depth in the soil. However, a question that must be addressed regarding *in situ* burning is: what soil temperature will result in plant mortality? In the present study, all plants survived with 10 and 2 cm of water over the soil surface and with soil temperature < 40 and 50 degrees C at the soil surface, respectively. Therefore, a 50 degree C surface soil temperature during the burn with 2 cm of standing water over the soil surface was safe for most plants. Lethal temperatures for most vascular plants have been cited in the range of 60 degrees C to 65 degrees C (Byram 1948; Ahlgren 1974; and Levitt 1980).

However, 2 cm of soil exposure during *in situ* burning resulted in a wide range of soil temperatures (100 degrees C at 0 cm of soil depth to <40degrees C at 5 cm of soil depth) and differentially affected the survival of marsh plant species to *in situ* burning. The effect of burning on plant species was greatest for *S. lancifolia*, with a 50% decrease in survival rate and a significantly lower stem density and aboveground biomass. The effect of burning on *S. alterniflora* was also significant, with a 30%decrease in survival rate and a significantly lower stem density and aboveground biomass. However, 2 cm of soil exposure during *in situ* burning did not detrimentally affect the post-burn recovery of the brackish marsh grasses, *S. patens* and *D.spicata*. Therefore, it is apparent that the thermal effect during *in situ* burning is plant species specific.

The causes for the species specific effect of *in situ* burning appear to be due to the location of reproductive organs in the soil profile. All of these species are perennial and reproduce new plants mainly from belowground rhizomes. Rhizomes of *S. lancifolia* are large and shallowly located. Parts of the *S. lancifolia's* rhizome are often located at the soil surface or even extrude above the soil surface. Thus, 80 to 100 degree Ctemperatures at 0 to 0.5 cm of soil depth could greatly affect the survival of the rhizomes of *S. lancifolia*. For *S. alterniflora,* as indicated by Lin *et al*. (2002), surface soil temperatures (0 and 0.5 cm below the soil surface) may not be appropriate to predict thermal effects on this plant species, since they were in the range of 80 to 100 degrees C. At the 2 cm soil depth, a mean temperature of 55 degrees C with a large standard error means that temperatures of some experimental units were > 60 degrees C. These temperatures may affect the survival of reproductive organs of *S.alterniflora*.

However, 2 cm of soil exposure during *in situ* burning did not detrimentally affect the post-burn recovery of the brackish marsh grasses, *S. patens* and *D. spicata*. These two species have very dense stems, and some rhizomes may be located at deeper soil depths. In addition, they generally reproduce rapidly from rhizomes. Thus, the biomass of new plants grown from surviving rhizomes could rapidly reach the level of the unburned control. Pahl *et al*. (1997 and 1999) indicated that the response to burning differed with marsh plant species after an *in situ* burn at the Rockefeller Wildlife Refuge on Louisiana's southwest coast. Initial revegetation within the oiled and burned marsh was dominated by *Schoenoplectus robutus*. However,the frequency of *S. robutus* within the burned marsh decreased during the growing season, while the frequency of the graminoid species, such as *D.spicata* and *S. patens*, increased. After three years (Pahl and Mendelssohn1999), *D. spicata* and *S. patens* co-dominated the site, and *S. robutus* was only a minor constituent.

Application of oil (diesel or crude) prior to the burn did not affect plant survival. Diesel is more toxic to plants than crude oil. In general, petroleum hydrocarbon toxicity increases from alkanes to aromatics, and within each series of hydrocarbons, the small molecular weight hydrocarbons are more toxic than the large (Baker 1970). Alexander and Webb (1985)demonstrated that 1.5 l/m^2 of *No.* 2 fuel oil significantly reduced live aboveground biomass of *S. alterniflora*, while 2 l/m^2 of crude oil did not. The composition and toxicity of No. 2 fuel oil and diesel oil are similar. Furthermore, Lin and Mendelssohn (1996) reported that even 4 l/m^2 of Louisiana Crude oil did not significantly reduce live aboveground biomass of *S. alterniflora* four and nine months after oiling. This result supports the contention that No. 2 fuel oil and diesel are more toxic to plants than crude oil. In the present study, application of oil (diesel or crude) at a rate of 0.5 L/m^2 prior to the burn was not high enough to reduce plant survival.

The effectiveness of *in situ* burning for oil cleanup may differ if the oil is floating on the water surface or has contacted the soil. *In situ* burning can effectively reduce floating oil from the water surface, thus preventing it from either penetrating the soil when the water recedes, or from drifting and contaminating adjacent habitats. In an *in situ* diesel burn in Mobile Bay, AL, the average destruction efficiencies for total targeted diesel PAHs were estimated to be greater than 99% (Wang et al. 1994). However, the high molecular weight PAHs with five or more rings were found to be largely generated by combustion (Wang *et al*. 1999). Garrett *et al*. (2000) reported that the concentrations of several of the pyrogenic aromatic compounds were somewhat enriched in the residue, but these increases were outweighed by the mass of oil consumed in the burn. They 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. Benner et al. (1990) also found that while the total PAHs were reduced in the residue as compared to the crude oil, a number of four and five ringed compounds increased in mass in the smoke. In the present study, a more than 75% reduction in concentration of total targeted normal hydrocarbons (TTNH) occurred after the burns, although concentrations in residual oil after burning were higher for compounds with carbon numbers > nC-22 and nC-26 for the diesel and crude burns, respectively. In addition, concentrations of total targeted aromatic hydrocarbons (TTAH) were reduced by more than 50% after the burns, although concentrations remaining in the residual oil after the burn were higher for compounds with molecular weight > fluoranthene (fourrings). The total mass of diesel and crude oil was greatly reduced. We estimated that more than 97% of the floating diesel or crude oil used to create the burn was consumed by the fire. Therefore, destruction efficiencies for total targeted aromatic hydrocarbons (TTAH) and total targeted normal hydrocarbons (TTNH, or alkanes) of both diesel and crude oils were about 99% in terms of mass balance, further demonstrating the high efficiency of *in situ* burning for the cleanup of oil floating on the water surface.

However, removal efficiency of oil that had contacted the soil during *in-situ* burning differed with oil type. *In situ* burning did not appear to effectively remove crude oil that had contacted the soil. The TPH concentrations in the soil of treatments with crude oil added 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 the burn. However, *in situ* burning more effectively removed diesel fuel added prior to the burn compared to the crude oil. The TPH concentrations in the soil of treatments with diesel oil addition prior to the burn were lower with *in situ* burning than without burning in the present study.

5.0. Conclusions

Water depth over the soil surface during *in situ* burning is a key factor controlling recovery of coastal marsh plants. Ten cm of water overlying the soil surface were sufficient to protect all three types of marsh vegetation from burning impacts. Soil surface temperatures 10 cm below the water did not exceed 40 degrees C. The plant survival rate was 100%, and growth responses after the burn with 10 cm of water over the soil surface were not significantly different from the unburned control. Two cm of water overlying the soil surface provided as much protection to all three types of marsh vegetation as 10 cm of water, with < 50 degrees C soil surface temperature 2 cm below the water, 100% plant survival rate, and similar plant growth responses as those observed in the unburned control. In contrast, a water table 2 cm below the soil surface (2 cm of soil exposure to the fire) resulted in high soil temperatures, with 80 to 100 degrees Cat 0 to 0.5 cm below the soil surface. Thermal stress generated with a water table 2 cm below the soil surface differed with plant species. Two cm of soil exposure during *in situ* burning impeded the post-burn recovery of the salt marsh grass, *S. alterniflora*, and fresh marsh species, *S. lancifolia*. However, 2 cm of soil exposure during *in situ* burning did not detrimentally affect the post-burn recovery of the brackish marsh grasses, *S. patens* and *D. spicata*. *In situ* burning effectively removed floating oil from the water surface, with about 99% destruction efficiencies in TTAH and TTNH in terms of mass balance. This high destruction efficiency could prevent the hydrocarbons from contaminating adjacent habitats and penetrating the soil when the water recedes. In addition, *in situ* burning remediated diesel oil that had contacted the soil, although not as effectively as it did the floating oil. In summary, our results show that some standing water over the marsh surface is important during *in situ* burning for post-burn recovery of marsh vegetation. For most marshes, 10 cm of overlying water is sufficient. Lower water levels, such as 2 cm of overlying water also appear to be adequate. However, a water table below the soil surface that could create conditions such as the 2 cm soil exposure during *in situ* burning in this experiment, should be avoided for most marshes.

6.0. References

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