Coastal Marsh Recovery and Oil Remediation after *In-situ* Burning: Effects of Water Depth, Oil and Marsh Type

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ABSTRACT

In-situ burning of oiled wetlands potentially provides a cleanup technique that is compatible with the wetland environment and is consistent with present wetland management procedures; thus, it would be highly valued. However, effects of burning of wetlands can vary with different scenarios, and burning of wetlands can have 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, yet they have not been adequately addressed scientifically. Our previous research demonstrated has that ten centimeters 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 temperature and almost completely inhibited the survival of the grass. However, the effect of water level between 10 cm and −10 cm relative to the soil surface on the vegetation was not unequivocally identified. 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, 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 and placed in 5 gallon metal buckets, were 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 s (seconds) crude oil burn and 700 s 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 s (second) burn and for a period of 4700 s 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 centimeters of water overlying the soil surface were sufficient to protect marsh vegetation of all 3 types of marshes from burning impacts. Soil surface temperatures did not exceed 40 °C and 50 °C for 10 and 2 centimeters of water overlying 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 was 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 °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 over 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 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, thus preventing the oil from potentially contaminating adjacent habitats and penetrating the soil when the water recedes. In addition, *in-situ* burning remediated diesel oil that had contacted with the soil, although it 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 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). None-the-less, it is often essential to remove spilled oil before it spreads to other habitats and to adjacent water bodies. Furthermore, it is important to develop less intrusive oil spill cleanup procedures that exert little to no long term impact to 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 in order 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 exist in the scientific literature showing that burning of wetlands can have beneficial, detrimental, or no impact. 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 are controlling 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 determining the successful recovery of wetlands subjected to *in-situ* burning after an oil spill. Not only is the literature on *in-situ* burning of oil contaminated wetlands 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). 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 facilitate the penetration of the oil into the marsh substrate (Kiesling et al. 1988). 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.

Our most recent study (Lin et al. 2002) showed that water depth over the soil surface during *in-situ* burning was a key 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 (soil temperature was < 37 °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 °C at 2 cm soil depth). Thermal stress completely inhibited the post-burn recovery of *S. alterniflora* at this water level. Burn duration (5 minutes vs. 20 minutes) did not have a significantly differential 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 of the diesel 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 the water levels less than 10 cm. This information will allow the development of scientifically based guidelines and to better predict under what environmental conditions *in-situ* burning should be attempted and would likely result in satisfactory wetland recovery.

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 types (crude oil and diesel fuel) on soil temperature, oil remediation, and vegetation recovery of coastal salt, brackish and fresh marshes. This research provides the 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 and placed in 5 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 s (seconds) crude oil burn and 700 s 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 (3 water depths, 2 oil levels and 2 burn types, respectively). For the fresh marsh, only 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 (3 water depths and 2 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 4 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 sod among 3 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 twelve 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 water surface, ignited, and allowed to burn for periods of 700 s (Figs. 4 and 5). The total volume of oil added to the water surface for 700 s burn duration was about 1350 liter 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 2 hours post-burn (for details on thermocouple installation and measurements see Bryner et al. 2001).

Fig. 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.

Fig. 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.

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

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

Fig. 5. Most diesel fuel was consumed by the fire after a 700 s burn.

Fig. 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.

Fig. 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 were evaluated by determining plant survival rate, stem density after the burn, aboveground biomass.

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 °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 °C for 2 minutes followed by temperature programming to 280 °C at 15 °C /minute. The temperature was held at 280 °C for an additional 12 minutes. Depth profiles of TPH (0-4 cm and 4-8 cm depth of soil) were determined shortly after the burn to assess any migration of the burned oil into the soil.

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 °C for 3 minutes then increased to 290 °C at a rate of 5 °C /minute and held at the upper temperature for 15 min. The injection temperature was set to 250 °C and only high-temperature, low thermal bleed septa were used. The interface to the MS was maintained at 290 °C. All gasses 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 is 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 *, costitute 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
naphthalene	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 dibenzothiophenes	198
C-2 dibenzothiophenes	212
C-3 dibenzothiophenes	226
phenanthrene	178
C-1 phenanthrenes	192
C-2 phenanthrenes	206
C-3 phenanthrenes	220
naphthobenzothiophene	234
C-1 naphthobenzothiophenes	248
C-2 naphthobenzothiophenes	262
C-3 naphthobenzothiophenes	276
fluoranthrene/pyrene	202
C-1 pyrenes	216
C-2 pyrenes	230
chrysene	228
C-1 chrysenes	242
C-2 chrysenes	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 to *in-situ* burning mainly depended upon the depth of water over the soil surface during the burn and the plant species. Generally, 10 and 2 centimeters 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 Spartina alterniflora* and *Sagittaria lancifolia*, but not for *Spartina patens* and *Distichlis spicata*. A 30 % decrease in survival resulted for *S. alterniflora* and 50% 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 at the treatment with –2 cm water than the control, while stem densities of the treatments with10 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 at the treatment with –2 cm of water than the control while the stem densities of the treatments with10 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 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 *D. spicata* (Fig. 11B). For the other species, effects of the burning generally were not significant, except for *Pannicum dichotomiflorum*, where stem density was significantly higher in the unburned treatment than the rest (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, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn.

Water level	Ipomoea sagittata	Alternanthera philoxeroides	Aster subulatus	Echinochloa crus-galli	Pannicum dichotomiflorum
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 table 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	Aster subulatus	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)
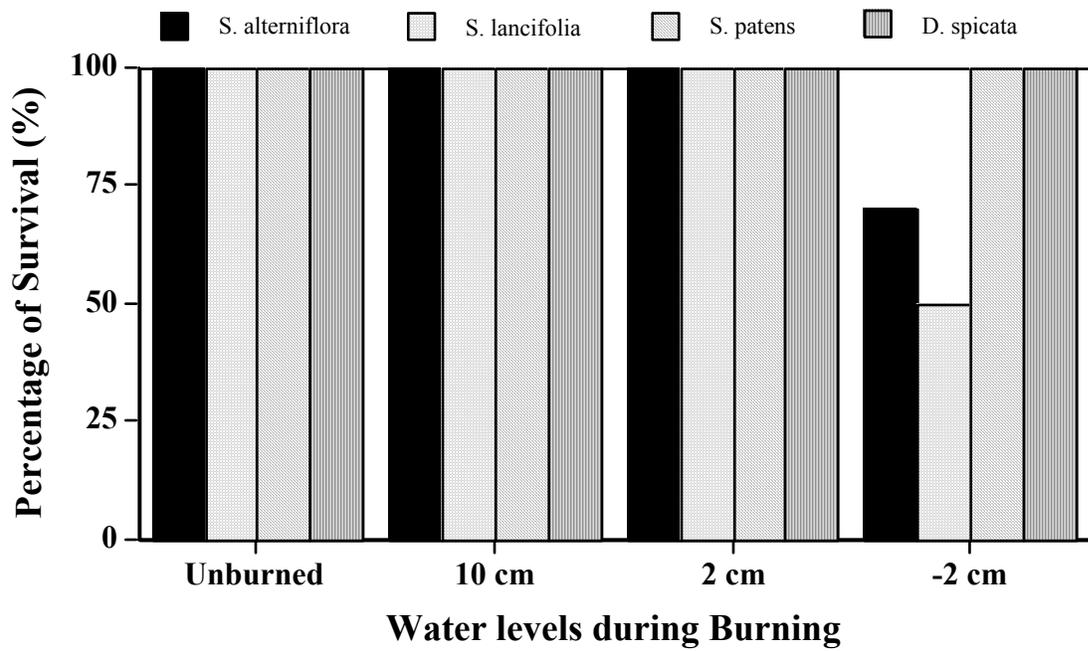
Fig. 8. Effects of water table level on sod survival one year after the burns. Values are averaged over oil application and burn type. Notation of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn.
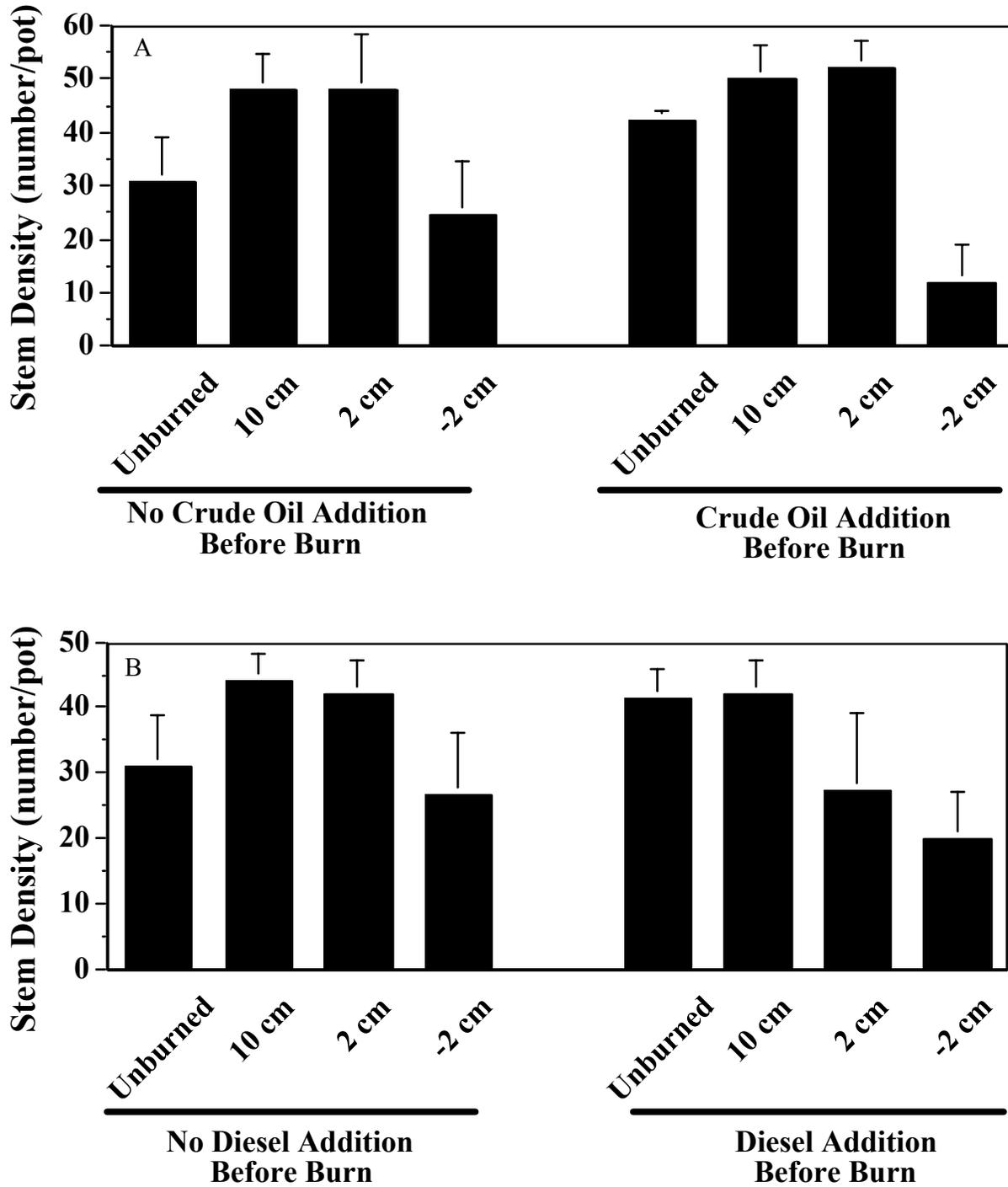
Fig. 9. Effects of water table level and oil application on stem density of *Spartina alterniflora* one year after the crude oil (A) and diesel (B) burn. Notation of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).
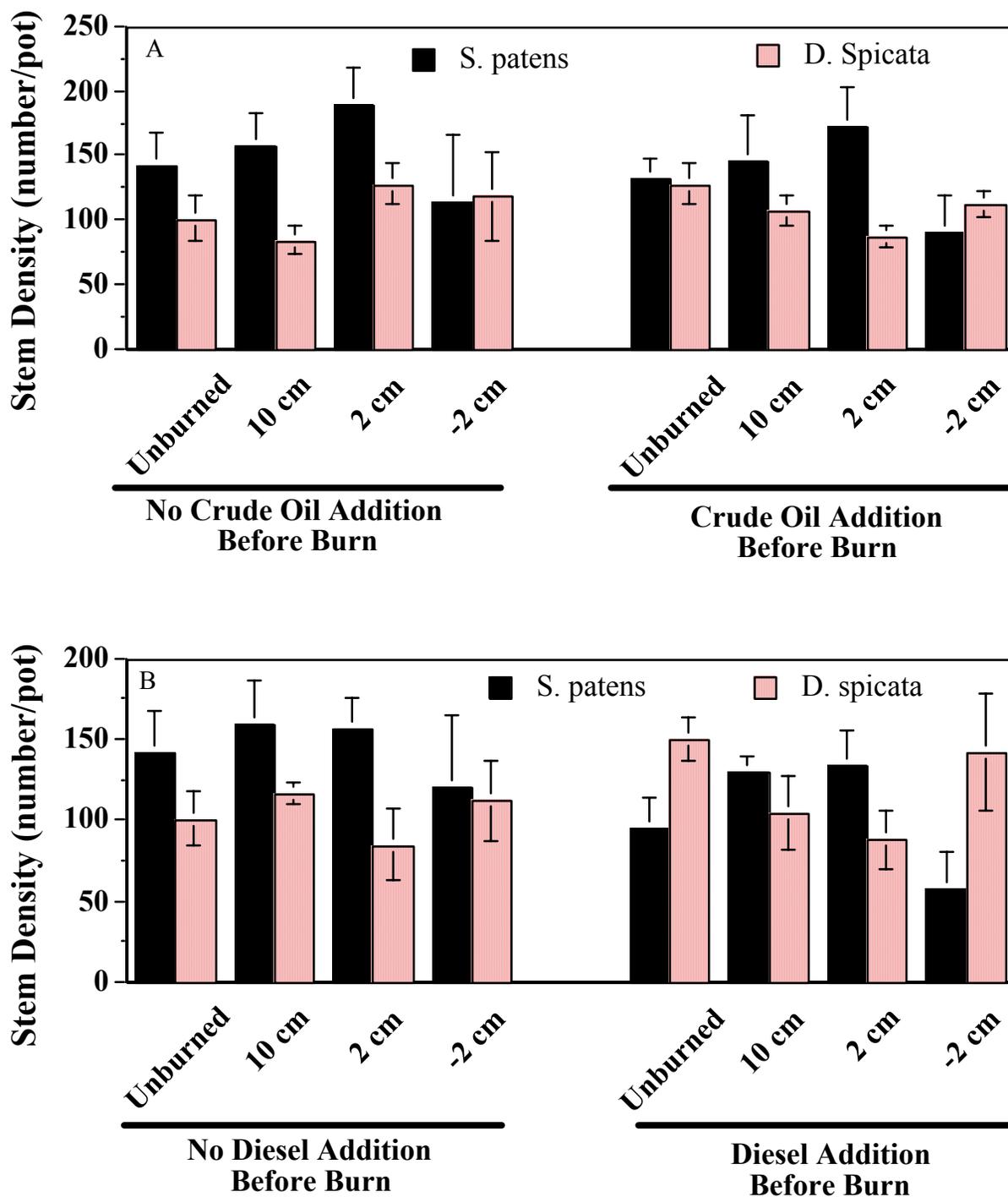
Fig. 10. Effects of water table level and oil application on stem density of *Spartina patens* and *Distichlis spicata* one year after the crude oil (A) and diesel (B) burns. Notation of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).
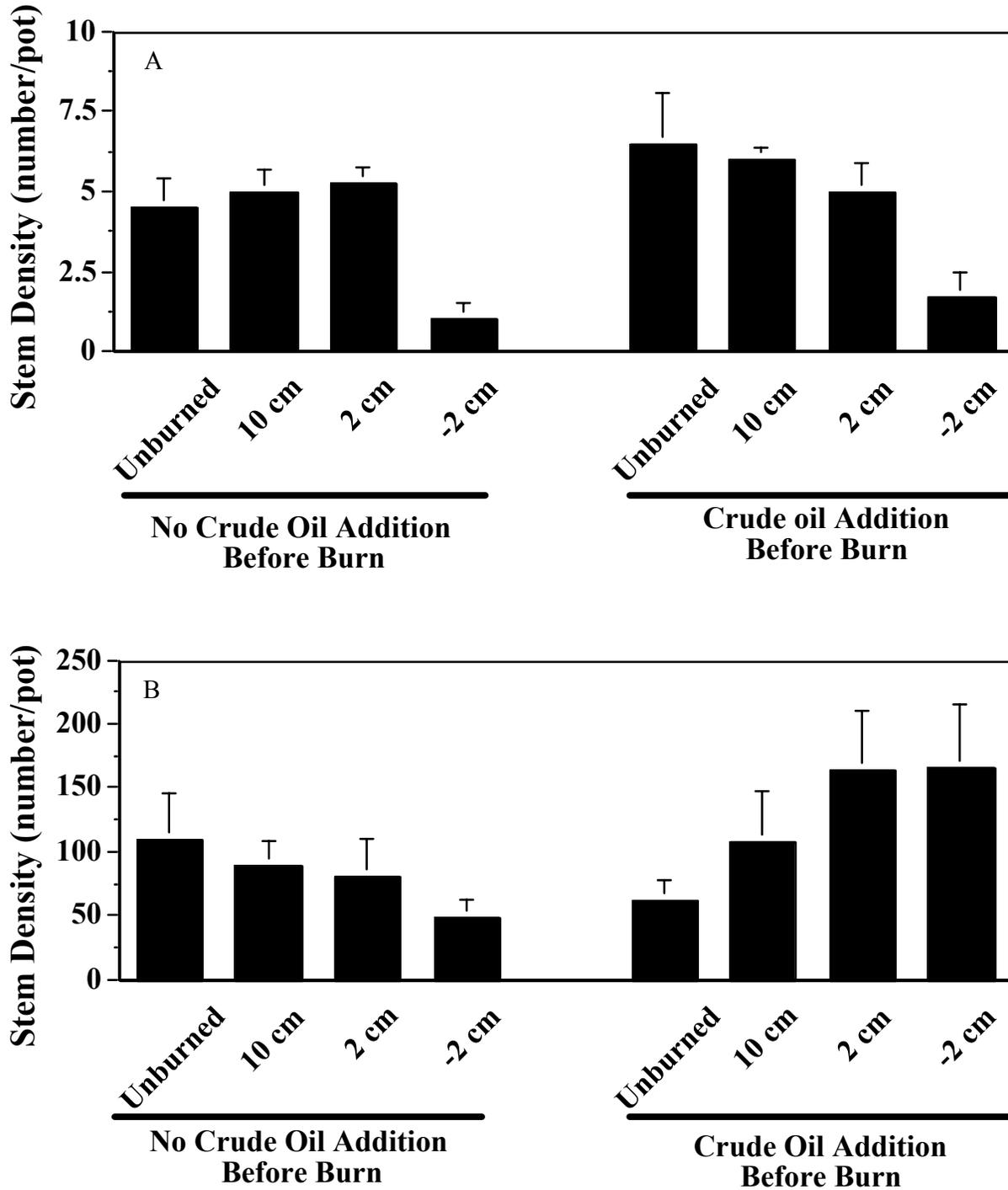
Fig. 11. Effects of water table level and oil application on stem density of *Sagittaria lancifolia* (A) and *Eleochlis spp.* (B) one year after the crude oil burns. Notation of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).

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 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 were 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 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 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 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 of was significantly impacted in the –2 cm of 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 *in-situ* burning (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 °C, ranging between 70 to 100 °C (Figs. 15 to 17). At 2 cm soil depths, average peak soil temperatures generally were between 45 and 60 °C (Figs. 15 to 17). At 5 cm soil depths, average peak soil temperatures were below 40 °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 °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 °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).

**No Crude Oil Addition Before Burn**   **Crude Oil Addition Before Burn**
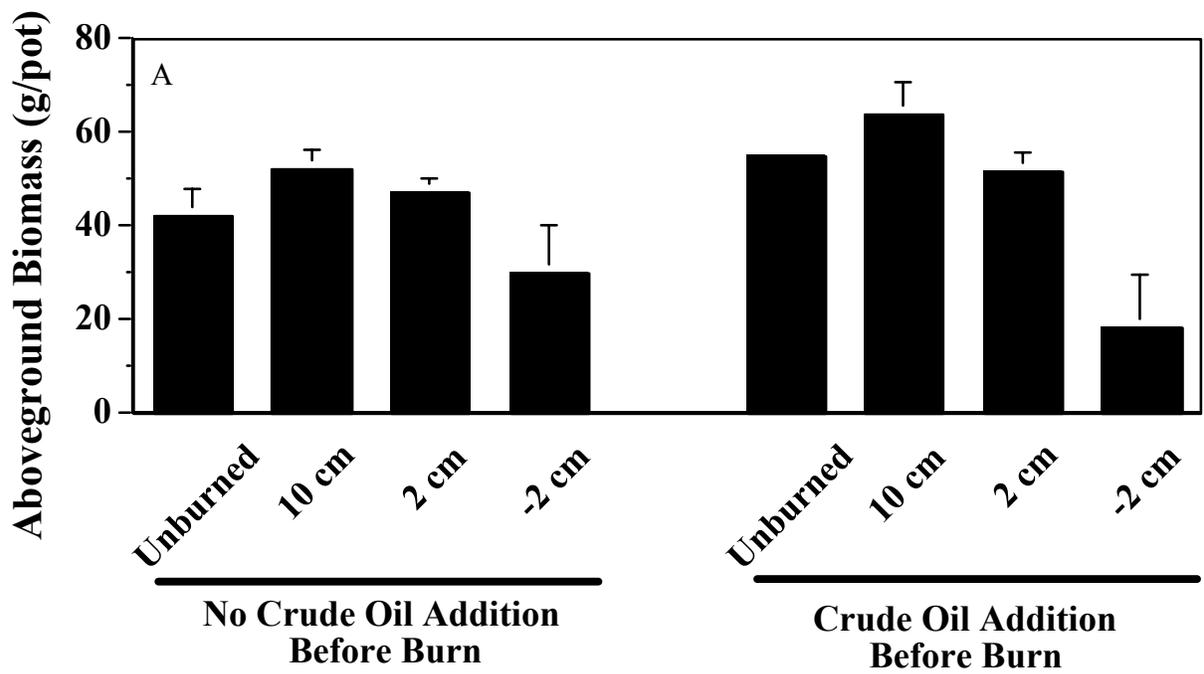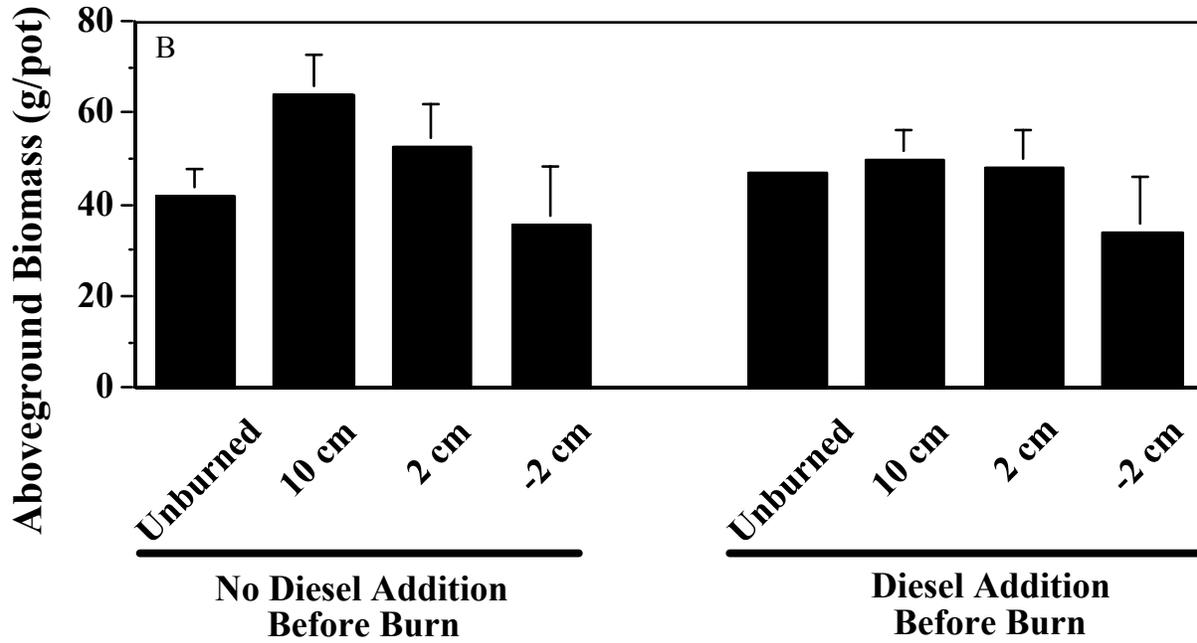
Fig. 12. Effects of water table level and oil application on aboveground biomass of *Spartina alterniflora* one year after the crude oil (A) and diesel (B) burns. Notation of 10 cm, 2 cm, and - 2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).
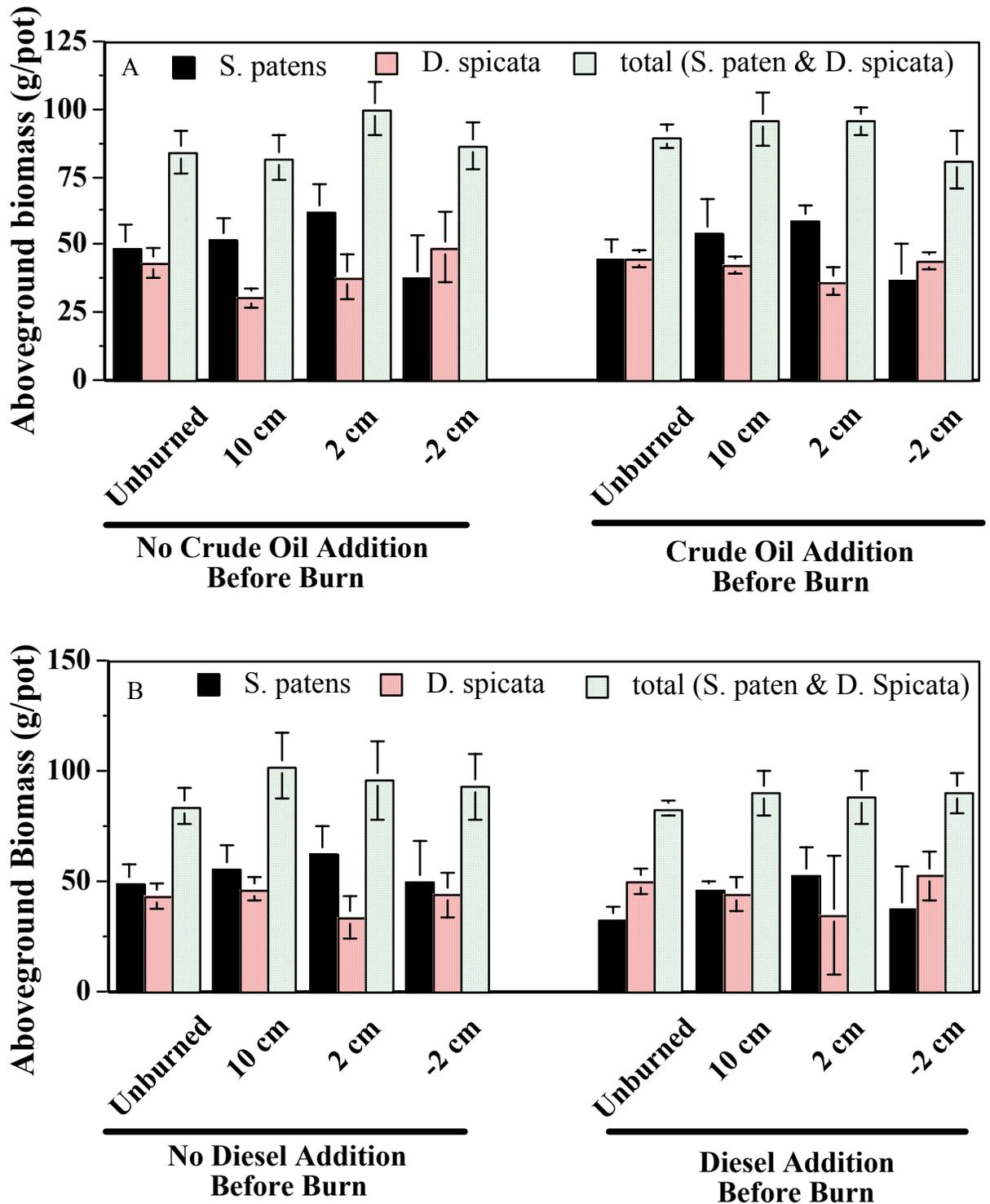
Fig. 13. Effects of water table level and oil application on aboveground biomass of *Spartina patens* and *Distichlis spicata* one year after the crude oil (A) and diesel (B) burns. Notation of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).
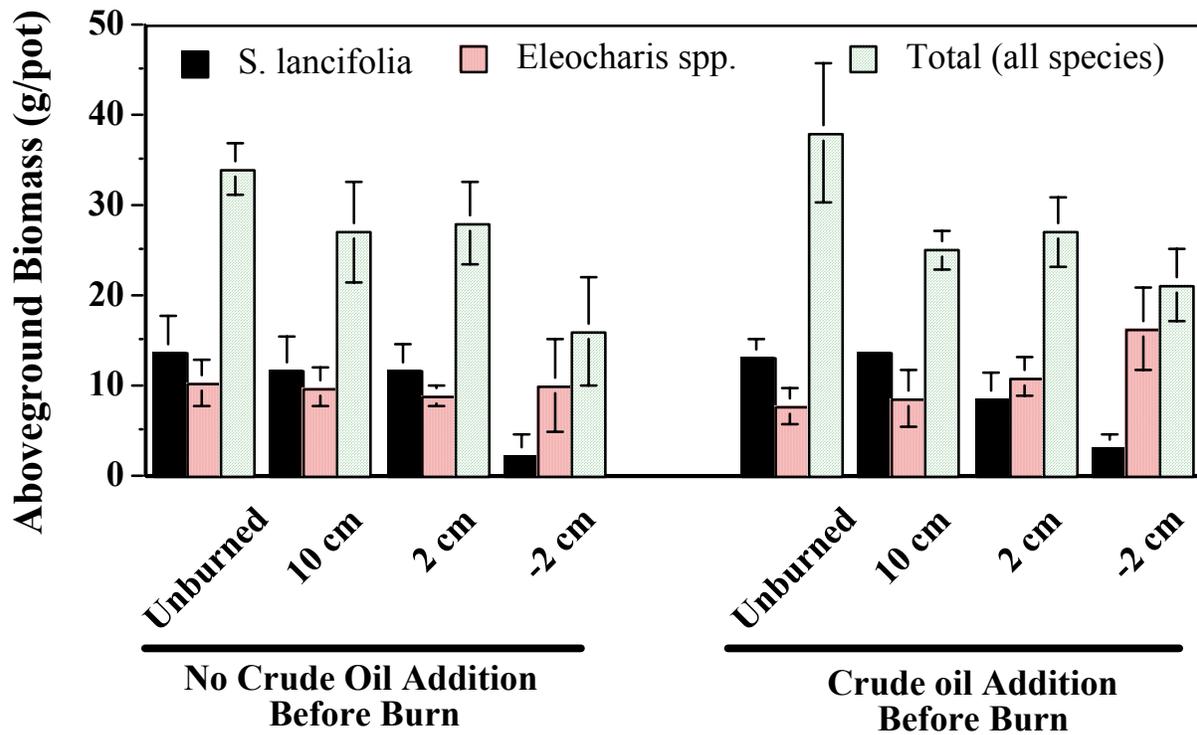
Fig. 14. Effects of water table level and oil application on aboveground biomass of fresh marsh species one year after the crude oil (A) and diesel (B) burns. Notation of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).
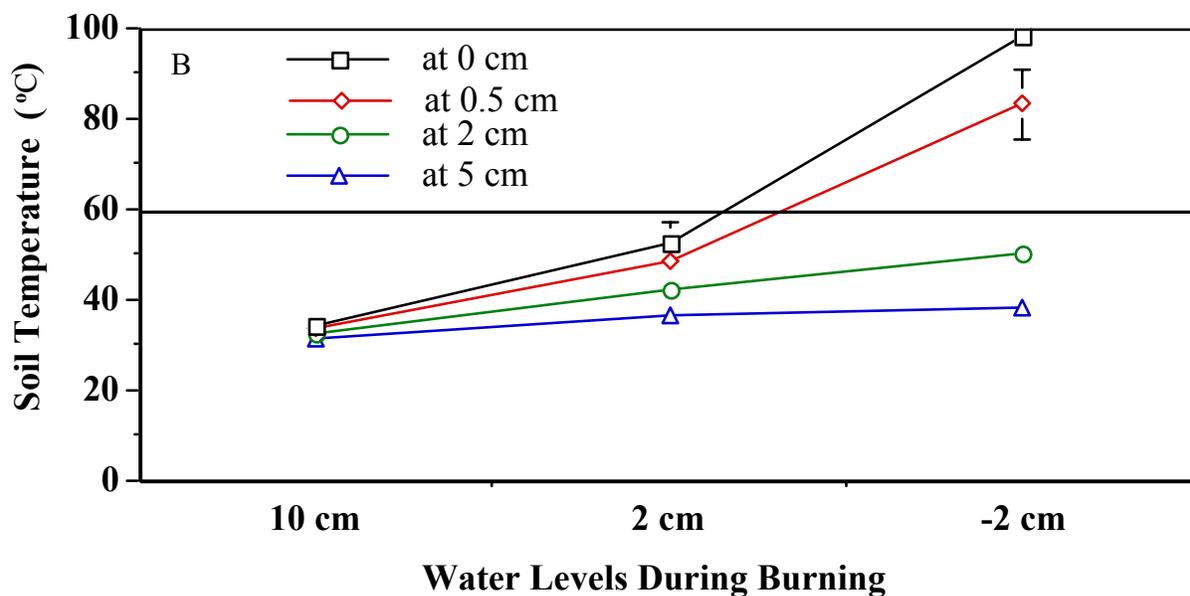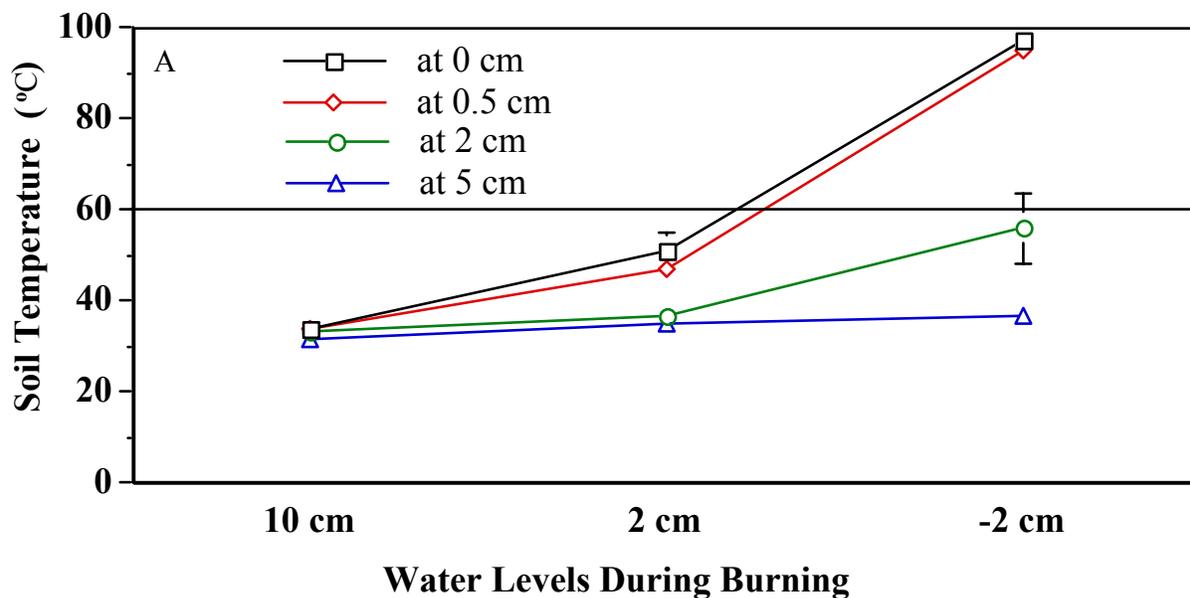
Fig. 15. Average peak soil temperature as a function water level over the soil surface and burn type during the crude oil (A) and diesel fuel (B) salt marsh burns. Notation of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).
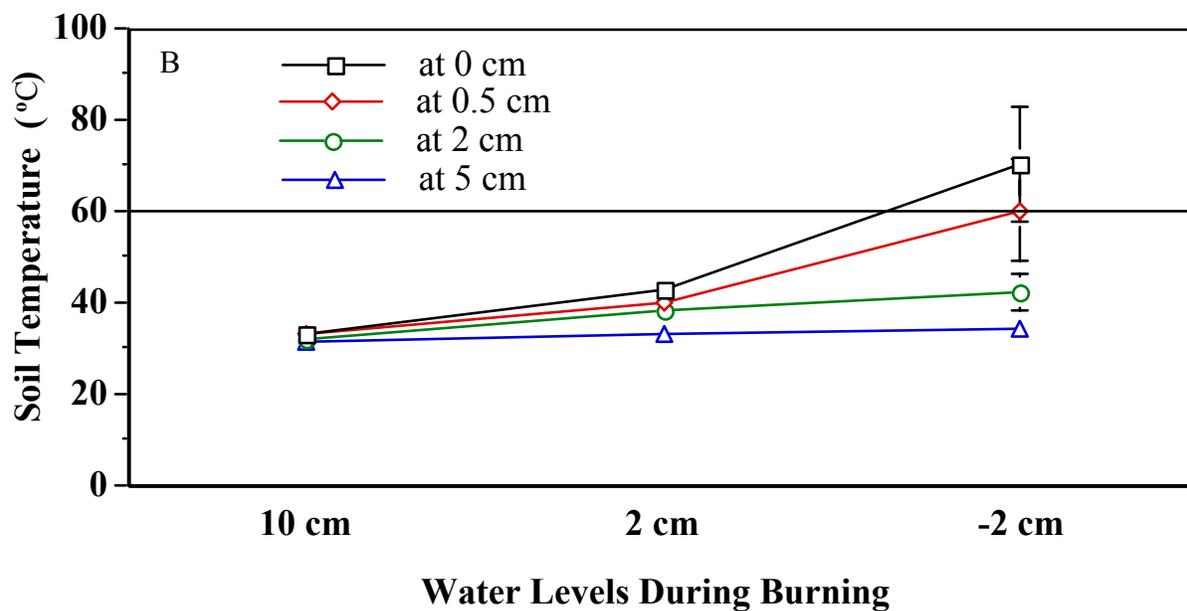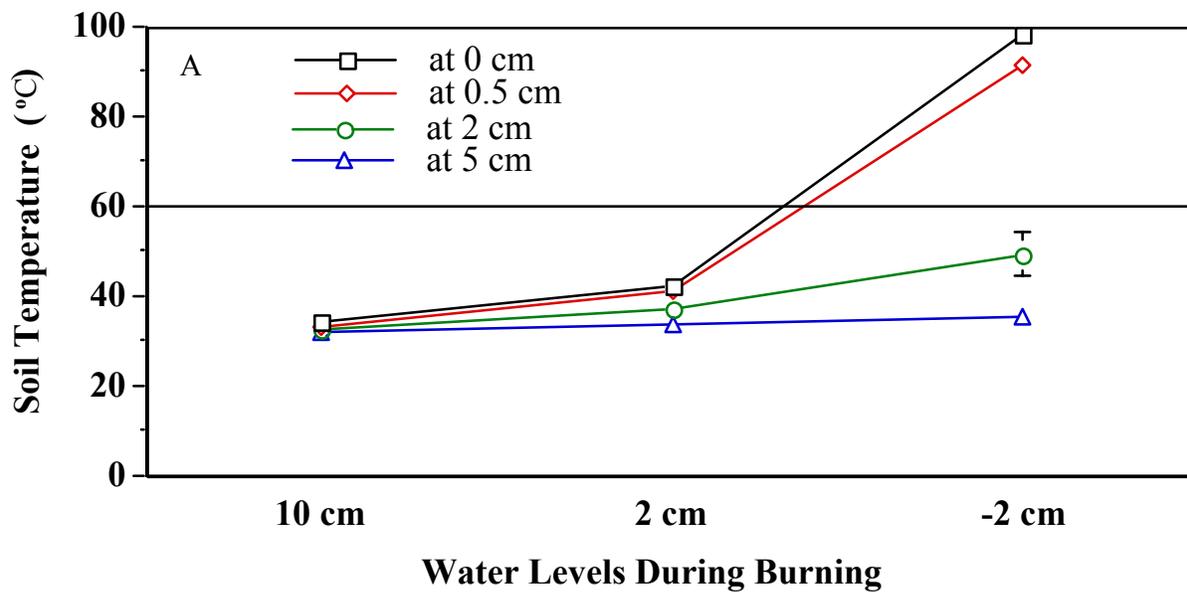
Fig. 16. Average peak soil temperature as a function water level over the soil surface and burn type during the crude oil (A) and diesel fuel (B) brackish marsh burns. Notation of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4).
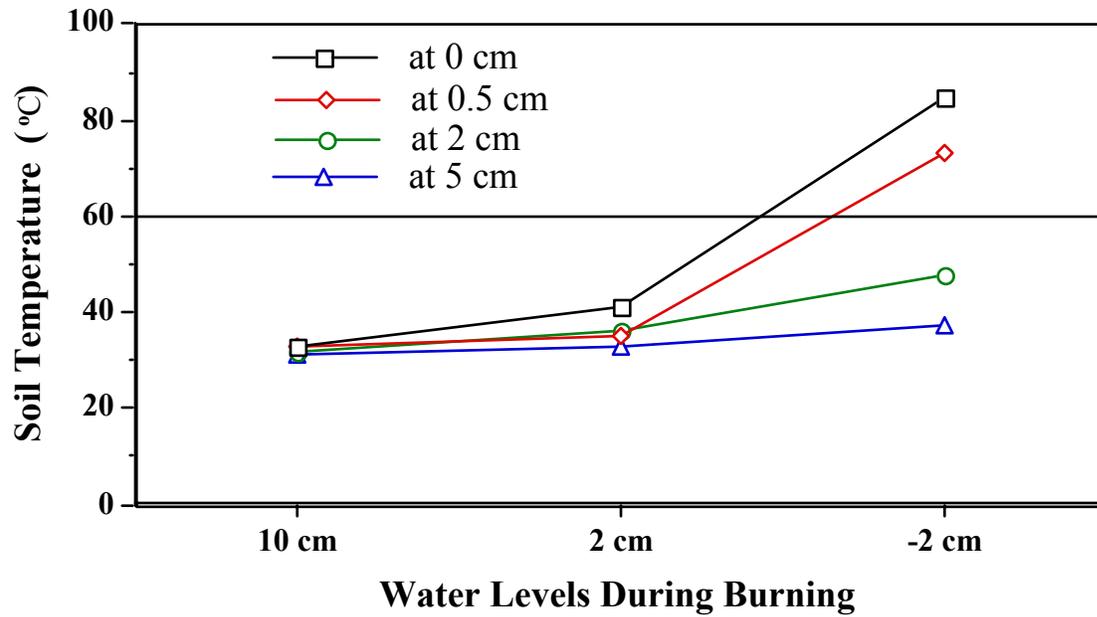
Fig. 17. Average peak soil temperature as a function water level over the soil surface during the crude oil fresh marsh burns. Notation of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn.

3.3. Petroleum Hydrocarbons Concentrations

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

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 un-burned 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 that in original diesel fuel before the burn (Table 5), with 75% reduction in concentration for the diesel burn and 56% reduction in concentration for the crude oil burn. In addition, the TTNH concentrations in the residue oil floating on the water surface after the burn decreased compared to that in original crude oil before the burn (Table 6), with 77.5% reduction in concentration for the diesel burn and 88.2% reduction in concentration for the crude oil burn. Interestingly, changes in concentrations varied with individual compounds of the petroleum. The removal efficacy of petroleum compounds during *in-situ* burning generally decreased with increasing carbon number of compounds. For example, reduction in concentrations of alkanes remaining in the residual oil after the burn was 99% for nC-11 undecane, while concentrations remaining in the residue after burning were higher for compounds with number of carbon > nC-22 and nC-26 for the diesel and crude burn, respectively (Table6). For aromatic hydrocarbons, 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 number of carbon > fluoranthene (4 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 the residual oil compared to that added to the water surface (> 40 mm of oil initially). 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 diesel and crude burn; 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 the original oils (Tables 7 and 8).
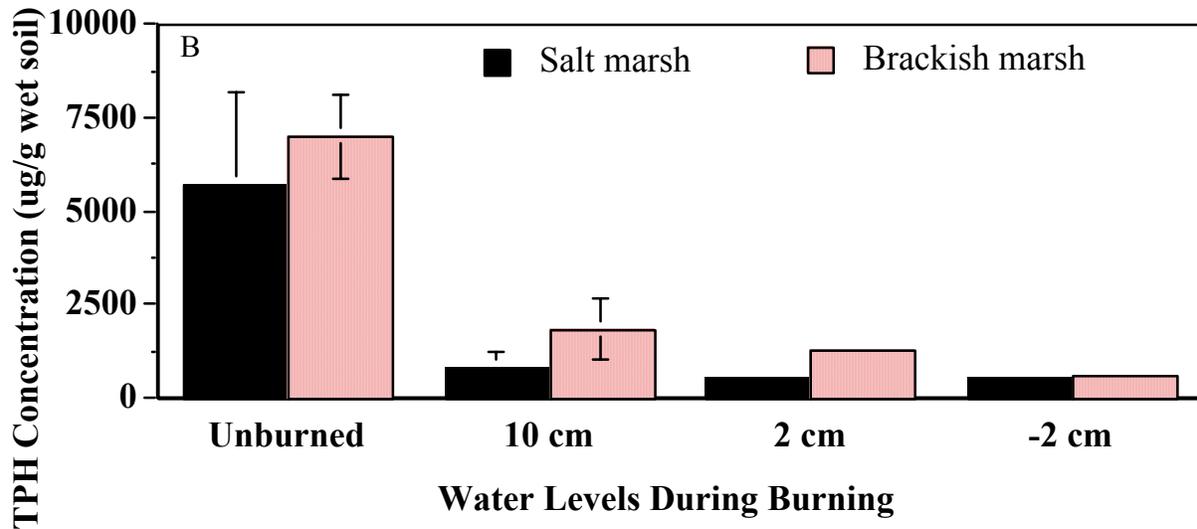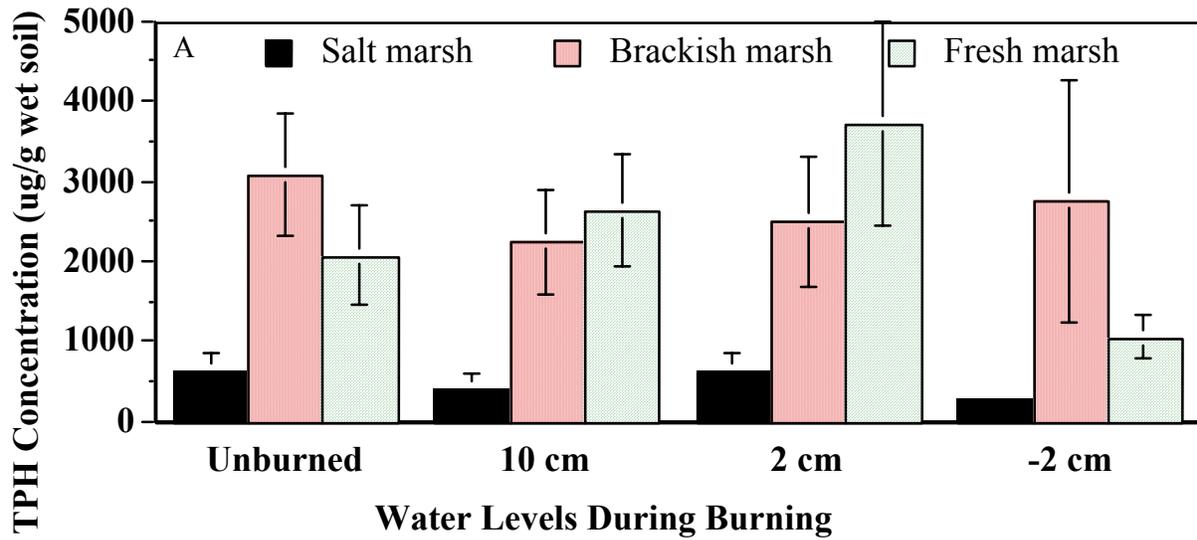
Fig. 18. Effects of water table level and burning type on total petroleum hydrocarbons in the soil 0 to 4 cm below the soil surface one day after the crude oil (A) and diesel fuel (B) burns. Notation of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn. Error bars are standard errors (n=4). Oil was applied to all treatments prior to the burn.
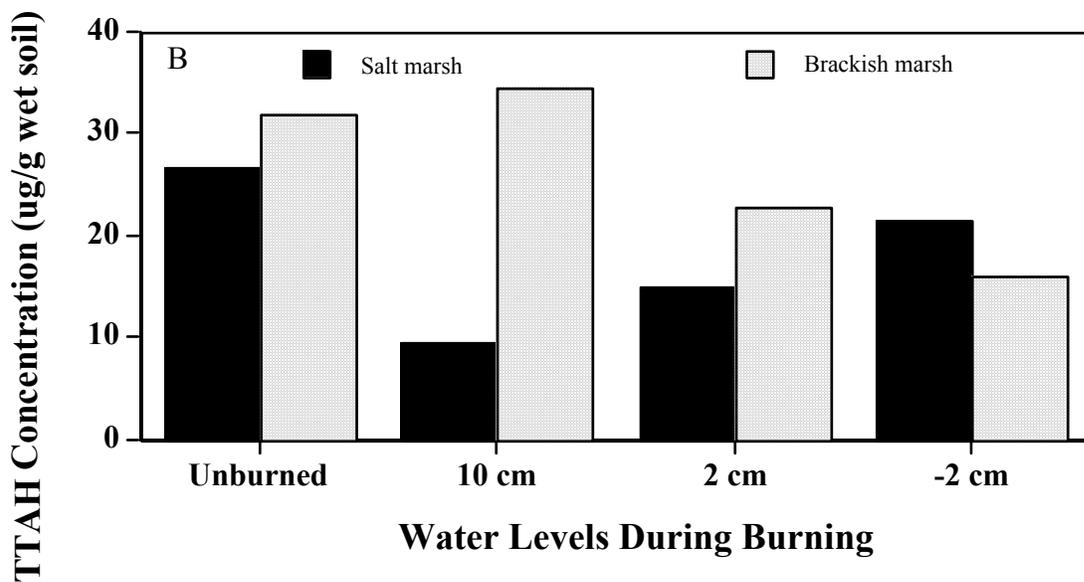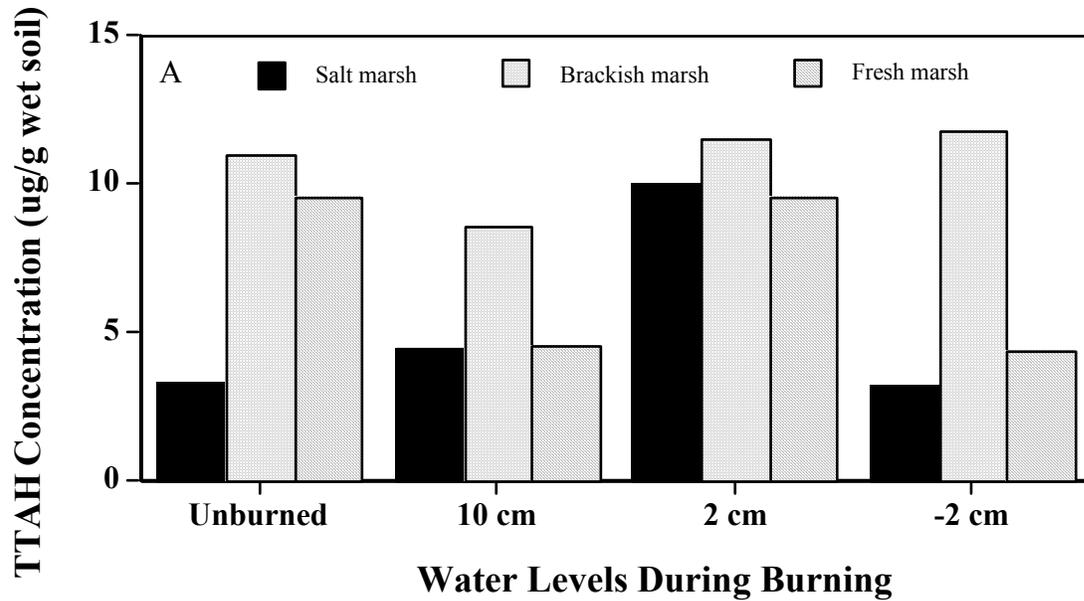
Fig. 19. Effects of water table level and burning type on the total target aromatic hydrocarbons (TTAH) in the soil 0 to 4 cm below the soil surface one day after the crude oil (A) and diesel fuel (B) burns. Values are derived from an analysis of four replicates composited. Notation of 10 cm, 2 cm, and -2 cm indicate the water surface relative to the soil surface during the burn. Oil was applied to all treatments prior to the burn.
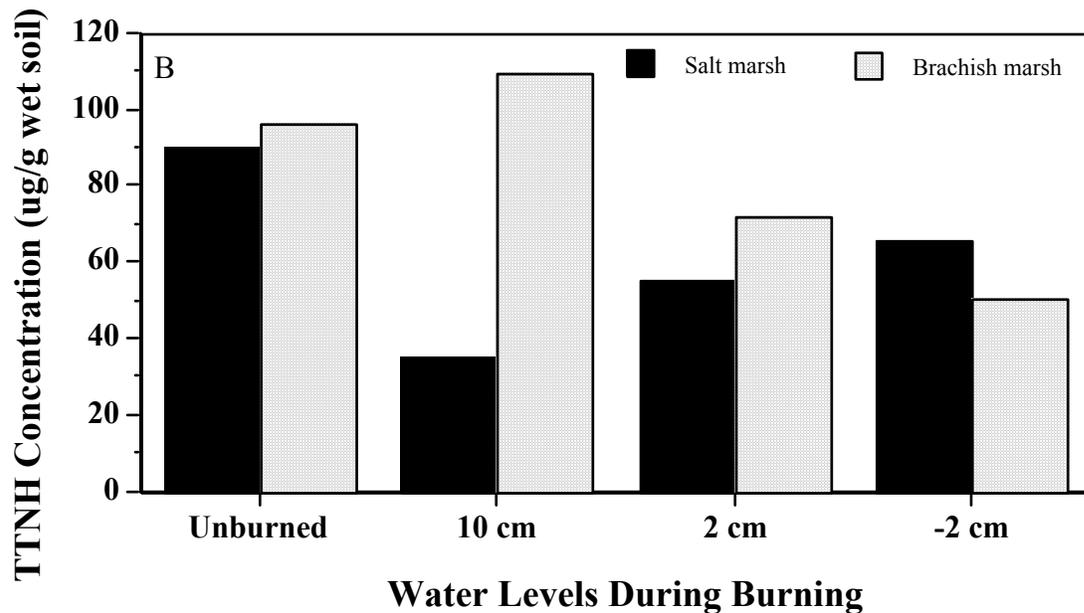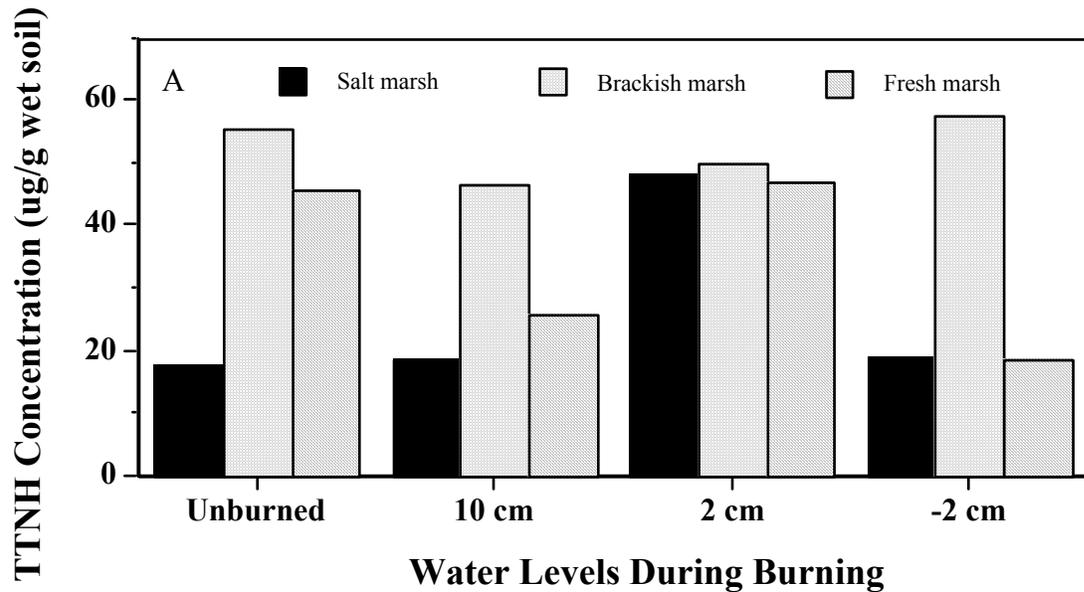
Fig. 20. Effects of water table level and burning type on the total target normal hydrocarbons (TTAH) in the soil 0 to 4 cm below the soil surface one day after the crude oil (A) and diesel

fuel (B) burns. Values are derived from an analysis of four replicates composited. Notation 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-situ* burning on aromatic hydrocarbon concentrations in the residual oil after *in-situ* burning compared to that before burning.

	Diesel			Crude Oil		
Compound	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 burn
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 Fluorene	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**	**55.4%**

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

	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 burn
nC-10 Decane	15	3	82.6%	5,644	18	99.7%
nC-11 Undecane	2,410	29	98.8%	5,207	22	99.6%
nC-12 Dodecane	3,600	137	96.2%	4,093	24	99.4%
nC-13 Tridecane	4,517	336	92.6%	3,173	39	98.8%
nC-14 Tetradecane	5,550	587	89.4%	2,539	69	97.3%
nC-15 Pentadecane	5,828	890	84.7%	2,058	101	95.1%
nC-16 Hexadecane	5,863	1,211	79.3%	1,730	134	92.3%
nC-17 Heptadecane	4,963	1,275	74.3%	1,358	151	88.9%
Pristane	3,290	852	74.1%	257	28	89.2%
nC-18 Octadecane	3,521	1,177	66.6%	1,076	165	84.7%
Phytane	1,725	520	69.8%	413	64	84.5%
nC-19 Nonadecane	2,463	1,078	56.2%	904	188	79.2%
nC-20 Eicosane	1,442	828	42.6%	792	209	73.6%
nC-21 Heneicosane	799	621	22.4%	622	219	64.8%
nC-22 Docosane	383	416	-8.5%	472	208	56.1%
nC-23 Tricosane	191	246	-28.9%	372	200	46.3%
nC-24 Tetracosane	103	149	-43.9%	317	220	30.6%
nC-25 Pentacosane	46	90	-94.0%	237	195	17.7%
nC-26 Hexacosane	18	40	-125.0%	200	207	-3.8%
nC-27 Heptacosane	6	16	-173.0%	163	168	-3.0%
nC-28 Octacosane	2	5	-253.6%	137	170	-23.6%
nC-29 Nonacosane	0	2	-415.1%	111	152	-37.5%
nC-30 Triacontane	0	1	n/a	111	154	-38.2%
nC-31 Hentriacontane	0	0	0	109	158	-45.5%
nC-32 Dotriacontane	0	0	0	95	147	-55.0%
nC-33 Tritriacontane	0	0	0	69	120	-75.3%
nC-34 Tetratriacontane	0	0	0	56	107	-90.5%
nC-35 Pentatriacontane	0	0	0	51	127	-146.4%
nC-30 17a, 21b-Hopane	0	0	0	36	66	-86.8%
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 *in-situ* burn compared to that before the burn.

Compound	Diesel Fuel			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 after 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 Fluorene	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	84.4%	684	67	90.2%
Perylene	544	23	95.7%	1,083	21	98.1%
TTAH	**13,320,637**	**83,704**	**99.4%**	**2,919,864**	**32,524**	**98.9%**

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

	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 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	66,816	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%
TTNH	**45,578,838**	**256,202**	**99.4%**	**31,597,690**	**93,362**	**99.7%**

4.0. Discussion

The recovery of coastal marsh plants to *in-situ* burning mainly depended upon the depth of water over the soil surface during the *in-situ* burn and specific marsh plant species. Standing water over the marsh surface during *in-situ* burning was important to protect the marsh vegetation during the *in-situ* burn. 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. However, the impact of *in-situ* burning on marsh plants was species-specific.

Ten centimeters of water over the soil surface was sufficient to protect the marsh vegetation of all 3 types of marshes from burning impacts. Soil surface temperature 10 cm below the water did not exceed 40 °C. Thermal stress on plants was absent. The plant survival and growth responses to the water level treatments support the temperature data. Two centimeters 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 °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 °C at the soil surface and 50 to 60 °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 water level during the 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, burn in the flooded portion of the 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 recently study (Lin et al. 2002) demonstrated that burning of 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 was 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 for controlling post-burn recovery.

Soil temperatures during the *in-situ* burns, generally, depended upon the water depth over the soil surface during the burns. 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 at 10 and 2 cm of water over the soil surface, with soil temperature < 40 and 50 °C at soil surface, respectively. Therefore, a 50 °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 °C to 65 °C (Byram 1948; Ahlgren 1974; and Levitt 1980).

However, 2 cm of soil exposure during *in-situ* burning resulted in wide range of soil temperatures (100 °C at 0 cm of soil depth to <40 °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. In addition, 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 these species are perennial, and reproduce new plants mainly from belowground rhizomes. Rhizomes of *S. lancifolia* are large, and shallowly located. It is not rare that parts of the *S. lancifolia's* rhizome are located at the soil surface or even extrude above the soil surface. Thus, 80 to 100 °C temperatures 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 °C. At 2 cm soil depth, a mean temperature of 55 °C with large standard error means that temperature of some experimental units were > 60 °C, and they may affect the survival of reproductive organs of *S. alterniflora*. Lethal temperatures for most vascular plants have been cited in the range of 60 °C to 65 °C (Byram 1948; Ahlgren 1974; and Levitt 1980). 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 reach the level of the unburned control rapidly. Pahl et al. (1997 and 1999) indicated that response to burning impact differed with marsh plant species after a *in-situ* burn of a hydrocarbon product spill 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 3 years (Pahl and Mendelssohn, 1999), *D. spicata and S. patens* co-dominated the site and *S. robutus* was only a minor constituent.

Application of oil (diesel or crude oil) 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 ones (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* 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. In the present study, application of oil (diesel or crude oil) at rate of 0.5 L/m2 prior to the burn was not high enough to detrimentally affect plant survival.

The effectiveness of *in-situ* burning on 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 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 were greater than 99% (Wang et al., 1994), and 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 4 and 5 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, there was more than a 50% reduction in concentration of total targeted aromatic hydrocarbons (TTAH) after the burns, although concentrations remaining in the residual oil after the burn were higher for compounds with molecular weight > fluoranthene (4 rings). The total mass of diesel and crude oil was greatly reduced. We estimated that greater 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 high efficiency of *in-situ* burning for the clean-up 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 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 the *in-situ* burn. However, *in-situ* burning more effectively removed diesel fuel added prior to the burn compared the crude oil added. 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 centimeters of water overlying the soil surface was sufficient to protect marsh vegetation of all 3 types of marshes from burning impacts. Soil surface temperature 10 cm below the water did not exceed 40 °C. The plant survival rate was 100%, and growth responses after the burn with 10 cm of water over the soil surface was not significantly different from the unburned control. Two centimeters of water overlying the soil surface provided similar protection to marsh vegetation of all 3 types of marshes from burning impacts as 10 cm of water, with < 50 °C soil surface temperature 2 cm below the water, 100% plant survival rate, and similar plant growth responses as 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 80-100 °C at 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 prevent the hydrocarbons from potentially 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. 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 certainly sufficient. Lower water levels, such as 2 cm of overlying water also to be adequate. However, a water table below the soil surface, such as a 2 cm soil exposure during *in-situ* burning in this experiment, should be avoided for most marshes.

6.0. References

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