SALT MARSH RECOVERY AFTER *IN SITU* BURNING FOR OIL REMEDIATION: EFFECTS OF WATER DEPTH AND BURN DURATION

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Salt Marsh Recovery After *In Situ* Burning For Oil Remediation: Effects of Water Depth And Burn Duration

Abstract

Oil spills pose serious risks to the health of wetland systems. 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. However, burning of wetlands can have detrimental as well as beneficial impacts. Factors such as water depth over the soil surface, the season of the burn, and burning intensity and duration may influence the response of wetlands to the burn. Yet these factors have not been adequately addressed scientifically. A mesocosm scale investigation was conducted to study the effects of water depth, burn duration, and oil application on the relationships between recovery of marsh vegetation, soil temperature, and oil remediation.

Marsh sods, which were collected from a south Louisiana salt marsh dominated by *Spartina alterniflora*, were instrumented with thermocouples and assigned to the following treatments: (a) oil exposure: unweathered diesel (1.5 liters m^{-2}) versus no diesel application, (b) burn duration: five minutes versus 20 minutes, and (c) water depth: 10, 2 and 0 cm over the marsh surface and 10 cm below the marsh surface. 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. After the burns, the mesocosms were returned to the greenhouse where plant recovery was evaluated. Soil samples for total petroleum hydrocarbon and GC/MS analyses were collected 24 hours after oil addition and one day and seven months post-burn.

The water depth over the soil surface during *in situ* burning was a major factor in the 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 almost completely inhibited the post-burn recovery of *S. alterniflora* at this water level. Although poor plant recovery was also apparent at water levels of 2 and 0 cm relative to the soil surface, this result was most likely due to diesel fuel (used to create the fires) entering the sod containers. The high concentration of diesel in the soil at these water levels probably caused greater plant stress than the thermal effect, per se, because the estimated lethal temperature of 60 °C at 2 cm soil depth was not attained at the 2 and 0 cm water depths. Although *in situ* burning effectively removed floating oil from the water surface, thus preventing it from potentially contaminating adjacent habitats, it did not effectively remediate the oil that penetrated the soil.

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 wetland environments is problematic and can do more damage than the oil itself (McCauley and Harrel 1981; DeLaune *et al*. 1984; Kiesling *et al*. 1988). Nonetheless, it is often essential to remove spilled oil before it spreads to other habitats and adjacent waterbodies. Furthermore, it is important to develop less intrusive oil spill cleanup procedures that have few long term impacts 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 often burned on an annual cycle 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 in the scientific literature show that burning of 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, duration and intensity of the burn, season of the burn, and the wetland type can control post-burn recovery (Mallik and Wein 1986; Hess 1975; van der Toor and Mook 1982; Timmins 1992).

Although the factors mentioned above are often cited as controlling recovery success after a prescribed burn, 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 this subject limited, 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 did 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 help oil penetrate into the marsh substrate (Kiesling *et al*. 1988). Recently, 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. However, they emphasized that more information is needed to better predict the environmental conditions that should accompany *in situ* burning in order to promote satisfactory wetland recovery. The present state of knowledge concerning the effects of *in situ* burning on oil spill remediation in wetlands is so rudimentary that sound, scientifically based guidelines for its use cannot be formulated at present.

Goal and Objectives

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 burn duration (fuel load) and wetland characteristics (water level) on soil temperature, oil remediation, and vegetation recovery of salt marshes dominated by *Spartina alterniflora*. This research provides the first quantitative data on the interaction among burn dynamics, oil chemistry, and marsh recovery.

2.0 Materials And Methods

2.1 Experimental Design

Intact salt marsh sections, 30 cm in diameter and 30 tall, were collected from a *Spartina alterniflora dominated* intertidal salt marsh in southeast Louisiana. The sections were placed in five gallon metal buckets. *Spartina alterniflora*, commonly called smooth cordgrass, dominates intertidal salt marshes along the Atlantic and Gulf coasts of the United States. Results from this study are therefore applicable to marshes outside the northern Gulf of Mexico. After collection, the 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 (1.5 liters m-2) versus no diesel application, (b) burn duration: five minutes versus 20 minutes, and (c) water depth: 10, 2 and 0 cm over the marsh surface and 10 cm below the marsh surface. The experimental design was a completely randomized block with a 4 x 2 x 2 factorial arrangement of treatments (four water depths, two oil levels, and two burn durations, respectively). Each treatment level combination was replicated five times for a total of 80 experimental units (marsh sods). Each block [4 (water level) x 2 (diesel level)] was burned separately. In addition, five unburned-oiled and unburned-unoiled sods served as controls. Thus, 90 experimental units were used.

2.2 Experimental Procedures

Forty of the marsh sods were instrumented with thermocouples inserted into the soil to monitor soil temperature during *in situ* burning. Thermocouples were inserted at 0, 0.5, 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 ten burns, a total of eight marsh sods, four instrumented and four uninstrumented, were positioned at 10 cm, 0 cm, -2 cm and -10 cm relative to the water level (Fig. 1). Diesel fuel burns were conducted in a 6 m diameter test tank at Louisiana State University's Fire and Emergency Training Institute. Diesel fuel was added to the water surface, ignited, and allowed to burn for periods of either five minutes or 20 minutes (Fig. 2). The volume of diesel added to the water surface determined burn duration. 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*. 2000).

After the burns, the mesocosms were returned to the greenhouse, where plant recovery 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, 24 hours after the burn, and seven months 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 grass, *S. alterniflora,* was evaluated by determining plant survival rate, live stem density after the burn, live above-ground biomass, and leaf photosynthesis. The latter is a sensitive indicator of plant response to stress (Ewing *et al*. 1997).

2.3 Methods

<u>Leaf CO_2 Assimilation and Transpiration Measurements</u>. CO_2 uptake was determined on representative intact leaves within each mesocosm with an ADC LCA-2 portable IRGA (infrared gas analyzer) system. A fully-expanded leaf was clamped into an ADC Parkinson leaf chamber, and the difference in CO_2 concentration between inlet and outlet air was measured. Sample air was taken at 5 m above the ground surface in order to obtain a relatively stable CO_2 concentration. The air was led through an ADC air supply unit with silica columns to obtain a dry inlet air stream. The flow rate was held constant at 6.25 ml sec^{-1}. Measurements were conducted at light saturated photosynthetic conditions provided by a Kodak slide projector bulb. Gas exchange was determined on a per unit leaf area basis. CO_2 uptake was calculated according to Cammerer and Farquhar (1981).

<u>Plant Growth and Survival.</u> Plant regrowth was assessed by measuring plant survival rate, live plant stem density during the experiment, and live above-ground biomass at the termination of the experiment. Live stem density was determined by counting the number of live stems in each experimental unit. The plant material harvested at the end of the experiment (seven months after burning) was separated into live and dead biomass and dried at 65^oC to a constant weight. Percent sod survival was determined as the number of the experimental units having live vegetation divided by the total number of experimental units per treatment level (five) multiplied by 100%.

<u>TPH Analysis (GC/FID).</u> 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 two 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 to 4 cm and 4 to 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 (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 three minutes. We then increased the temperature to 290 °C at a rate of 5 °C /minute and held the temperature at 290 °C for 15 minutes. The injection temperature was set at 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 are provided in Table 1. 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.

2.4 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 model (GLM) as a 4 X 2 X 2 factorial arrangement of treatments. Duncan's Test was used to evaluate statistical differences of the main factors when no interaction occurred. Least square means (LSD) test was used when an interaction between main factors occurred. Significant differences were reported at the 0.05 probability level, unless otherwise stated.

Figure 1 *Salt marsh sods located in the 6 m burn tank with soil surface at –10, -2, 0 and +10 cm relative to the watersurface before the burn. Half of the sods received 1.5 l m^{-2} of diesel oil 24 hour prior to the burn.*

Figure 2 In situ *burning of salt marsh sods in the 6 m burn tank for either five or 20 minute burn duration.*

Table 1 Target compounds assessed by GC/MS.

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

Sum of these compounds excluding those identified with a * is the TTAH value.
* Used primarily for source-fingerprinting and generally not quantified.

3.0 RESULTS

3.1 Recovery of Marsh Plants after *In Situ* Burning

Recovery of the salt marsh grass, *Spartina alterniflora*, after *in situ* burning mainly depended upon the depth of water over the soil surface. Ten centimeters of water overlying the soil surface were sufficient to protect the plants from burn impacts. In the absence of diesel additions to the soil, percent survival of the experimental units (marsh sods) after *in situ* burning was 100%, with 10 cm of water over the soil surface regardless of burn duration (five versus 20 minutes) (Fig. 3). Sod survival decreased with decreasing surface water. No experimental units survived after a 20 minute burn with 10 cm of soil exposure. When diesel was added to the soil, percentage survival was much lower than in the absence of diesel (Fig. 3). For example, even with 10 cm overlying the water column, a 60% decrease in survival resulted when diesel was present in the soil. No mesocosms survived in the lower water level treatments when the soil contained diesel. There was no significant difference in sod survival between burn durations (five versus 20 minutes).

Stem densities of *Spartina alterniflora* re-grown after the burn (Fig. 4) were consistent with the survival results. Both diesel addition to the soil prior to the burn and water depth over the soil surface during burning significantly ($p<0.0001$) affected regrowth of new stems after the burn. A significant interaction ($p<0.0001$) between diesel addition and water level suggested that diesel addition influenced the effect of water level on plant response to the burn. In the absence of diesel additions to the soil, stem density was significantly higher, with 10 cm of water over the soil surface compared to all other water level treatments regardless of burn duration (five versus 20 minutes).

Stem densities were, however still significantly lower than the control (without burning). Stem density decreased with decreasing surface water. Few stems re-grew with 10 cm of soil exposure. When diesel was added to the soil, stem density was significantly lower, regardless of water level (Fig. 4). For example, with 10 cm of overlying water and diesel present in the soil, live stem density was only 10 to 15% of that observed when diesel was absent. No stems re-grew after the burn in the lower water level treatments (= 2 cm of water over the soil surface) when diesel was applied to the soil prior to the burn. There was no significant difference in live stem density between burn durations (five versus 20 minutes).

Live above-ground biomass and live stem density exhibited similar responses to the experimental treatments. Effects of diesel addition to the soil prior to the burn ($p<0.0001$), water depth over the soil surface during the burn ($p<0.0001$), and the interaction between the diesel addition and water level ($p<0.005$) on live above-ground biomass were significant. In the absence of diesel additions to the soil, live above-ground biomass of the marsh sods was significantly higher with 10 cm of water over the soil surface regardless of burn duration (five versus 20 minutes) (Fig. 5). Live above-ground biomass was, however, still significantly lower than the control (without burning). Live above-ground biomass in treatments with £ 2 cm of water over the soil surface was significantly lower than that with 10 cm of water over the soil surface even in the absence of the diesel additions to the soil. Furthermore, when diesel was added to the soil, live above-ground biomass was significantly lower (Fig. 5). No live above-ground biomass re-grew after burning in the lower water level treatments (-2, 0 and +10 cm) when diesel was added to the soil. There was no significant difference in live above-ground biomass between burn durations (5 versus 20 minutes).

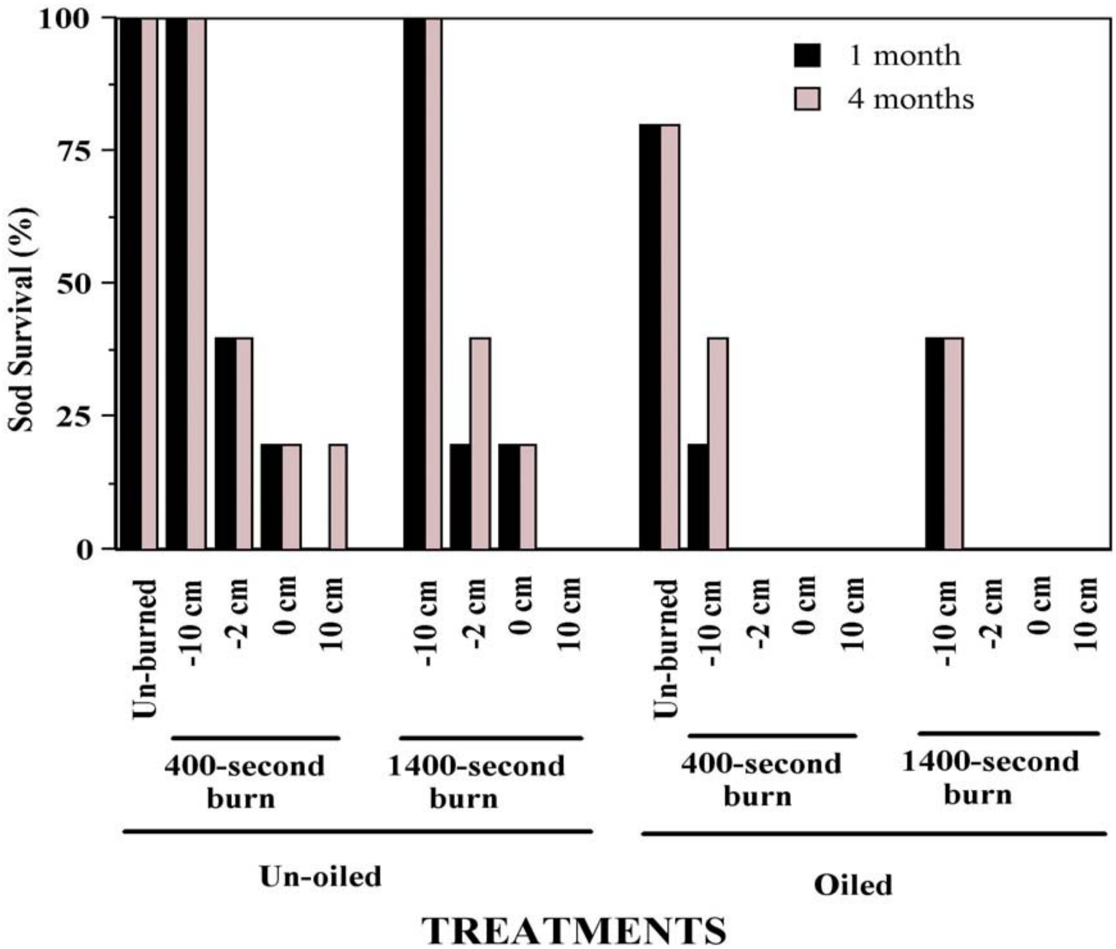

Figure 3 *Effects of burning duration, water table level, and oil dosage on the percentage of sods exhibiting post-burn regrowth. -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Sod survival was also determined seven months after the burn, but it was not different than the four month survival rate.*

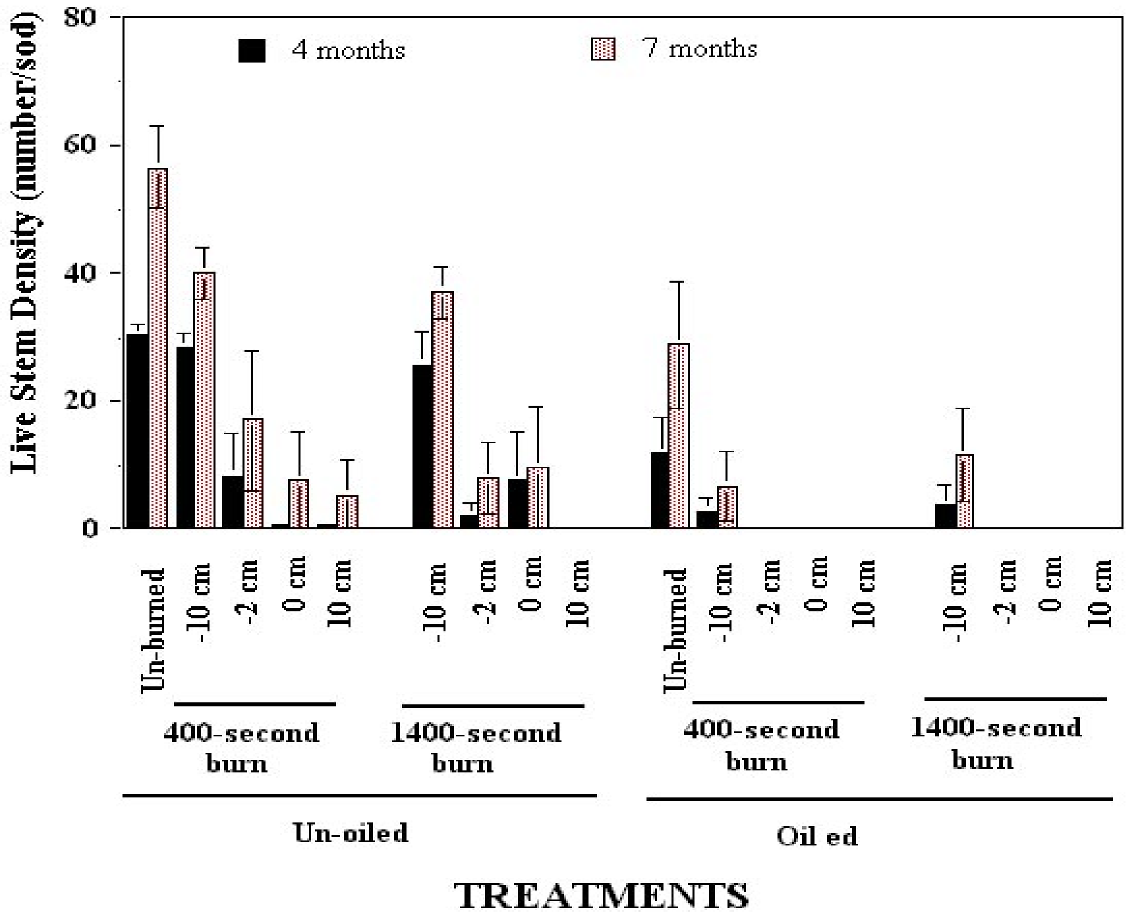

Figure 4 *Effects of burning duration, water table level, and oil dosage on the live stem density four and seven months after the burn. -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Error bars represent standard errors.*

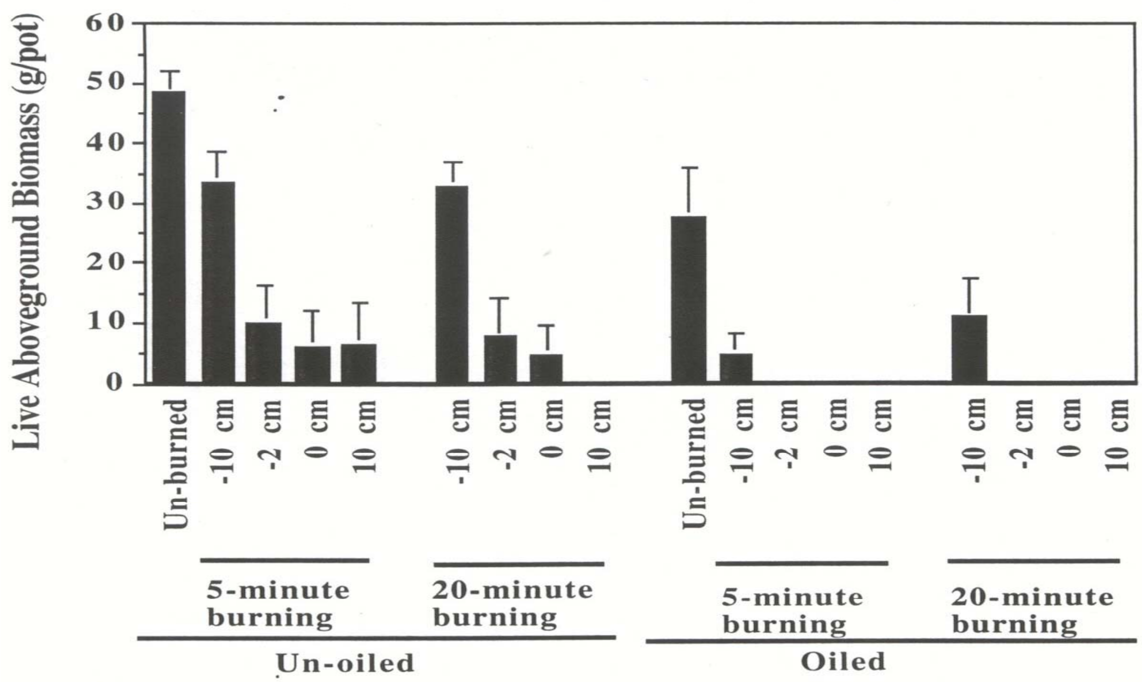

Figure 5 *Effects of burning duration, water table level, and oil dosage on the live above-ground biomass of S. alterniflora seven months after the burn. -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Error bars represent standard errors.*

Interestingly, leaf photosynthetic rates of *S. alterniflora* at the termination of the experiment were high and similar for all mesocosms with surviving individuals, regardless of treatment (Fig. 6). These results imply that any residual effects of the diesel and/or the thermal stresses were absent seven months after burning. Hence, surviving marsh sods, even those with low stem densities, would likely eventually recover via vegetative propagation.

3.2 Petroleum Hydrocarbons Concentrations

The experimental treatments affected the total petroleum hydrocarbons (TPH) in the soil. It was not surprising that the TPH in the soil was significantly ($p<0.0001$) higher in the treatments with diesel addition than in treatments without (Fig. 7). In addition, water level over the soil surface during the burn significantly ($p<0.0001$) affected TPH in the soil. In the absence of diesel additions to the soil, TPH concentration was lowest in the soil with 10 cm of water overlying the soil surface and with the water table 10 cm below the soil surface regardless of burn duration (five versus 20 minutes) (Fig. 7). TPH concentrations in these treatments were not significantly different from the overall control (unburned and unoiled). However, after *in situ* burning, TPH concentrations in the soil with 2 and 0 cm of water overlying the soil surface was significantly higher than in treatments with 10 cm of water over the soil surface and 10 cm below the soil surface regardless of burn duration (Fig. 7). When diesel was added to the soil, the trend of the water level effect on soil TPH was similar to water level effect trends in the absence of diesel additions. But TPH concentrations were generally higher than in comparable treatments without diesel addition. There was no significant difference in TPH in the soil between burn duration (five versus 20 minutes). *In situ* burning did not remove the oil that had penetrated the soil. With diesel addition to the soil, TPH concentrations in all burning treatments were equal to or higher than the un-burned treatment. In addition, average TPH concentrations in the 15 random samples from all sods with diesel addition prior to the burn were 226 mg g^{-1} wet soil (± 34 standard error) at 0 to 4 cm of soil and 93 mg g^{-1} wet soil (± 12 standard error) 4 to 8 cm from the soil surface. This was consistent with results in the un-burned treatment with diesel addition (Figs. 7 and 8). The effect of treatments on TPH concentrations in the soil 4 to 8 cm below the soil surface (Fig. 8) was similar to the effect of treatments on TPH concentrations of 0 to 4 cm below the soil surface (Fig. 7), but the concentration was generally lower in the latter. Seven months after burning, about 45% of the TPH remained in the soil at the 0 to 4 cm depth, compared to the concentration one day after the burn. The TPH concentration in the soil was significantly ($p<0.0001$) higher in the treatments with diesel addition prior to the burn than in treatments without diesel (Fig. 9).

The total targeted aromatic hydrocarbons (TTAH) in the soil after *in situ* burning showed a similar trend to the TPH in the soil. In the absence of diesel addition to the soil, TTAH in the soil with 10 cm of water overlying the soil surface and with the water table 10 cm below the soil surface was negligible regardless of burn duration (five versus 20 minutes) one day after burning (Fig. 10). Furthermore TTAH was not different from the overall control (unburned and unoiled). However, TTAH in the soil with 2 and 0 cm of water overlying the soil surface was higher than TTAH in the treatments with 10 cm of water over the soil surface and 10 cm below the soil surface regardless of burn duration. In the presence of diesel additions to the soil, the TTAH concentrations in the treatments with burning were higher than concentrations without burning except in the treatment with a 10 cm water table below the soil surface.

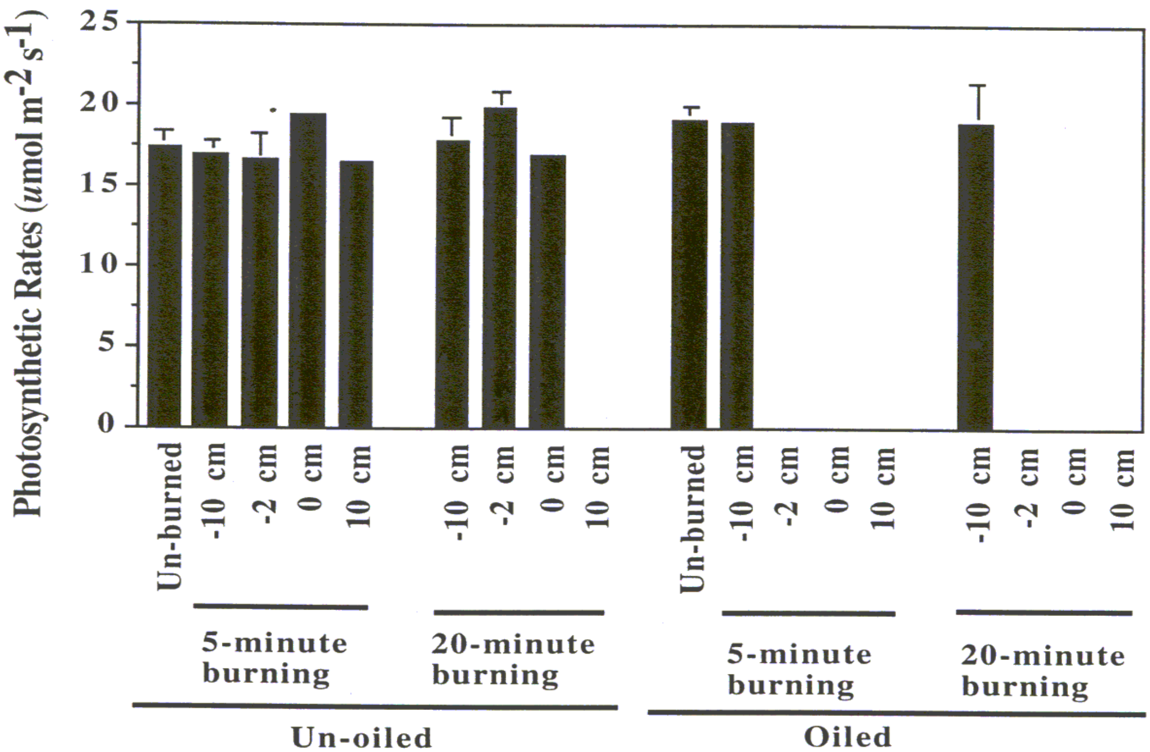

Figure 6 *Effects of burning duration, water table level, and oil dosage on the photosynthetic rate of live leaves of S. alterniflora seven months after the burn. -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Error bars represent standard errors.*

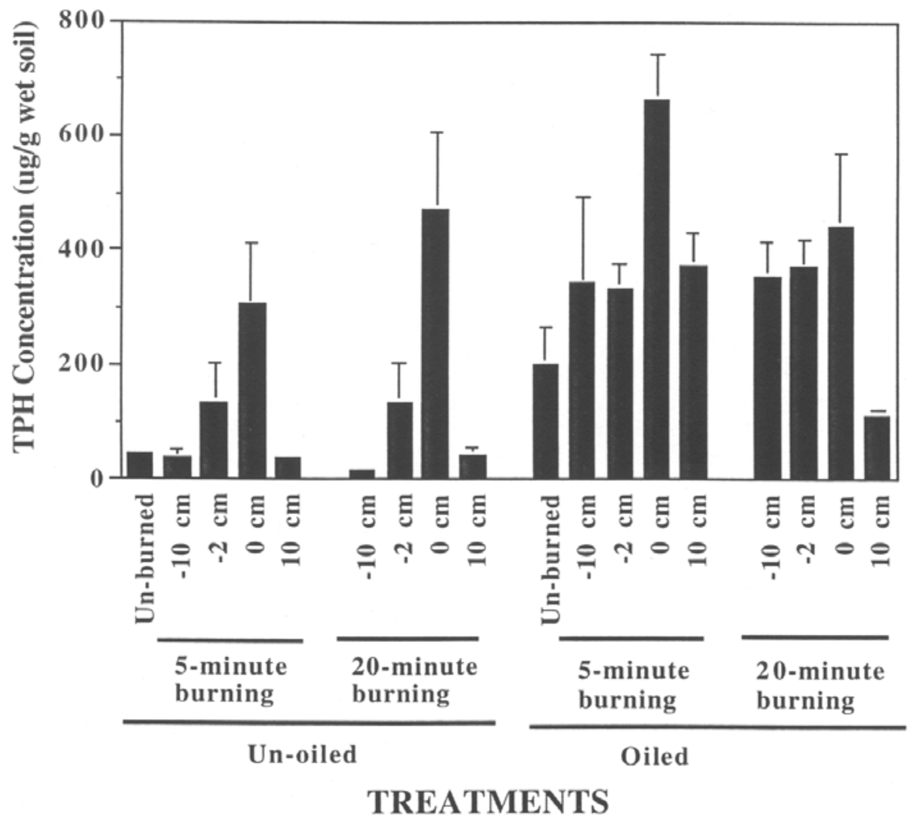

Figure 7 *Effects of burning duration, water table level, and oil dosage on the total petroleum hydrocarbons in the soil 0 to 4 cm below the soil surface one day after the burn. -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Error bars represent standarderrors.*

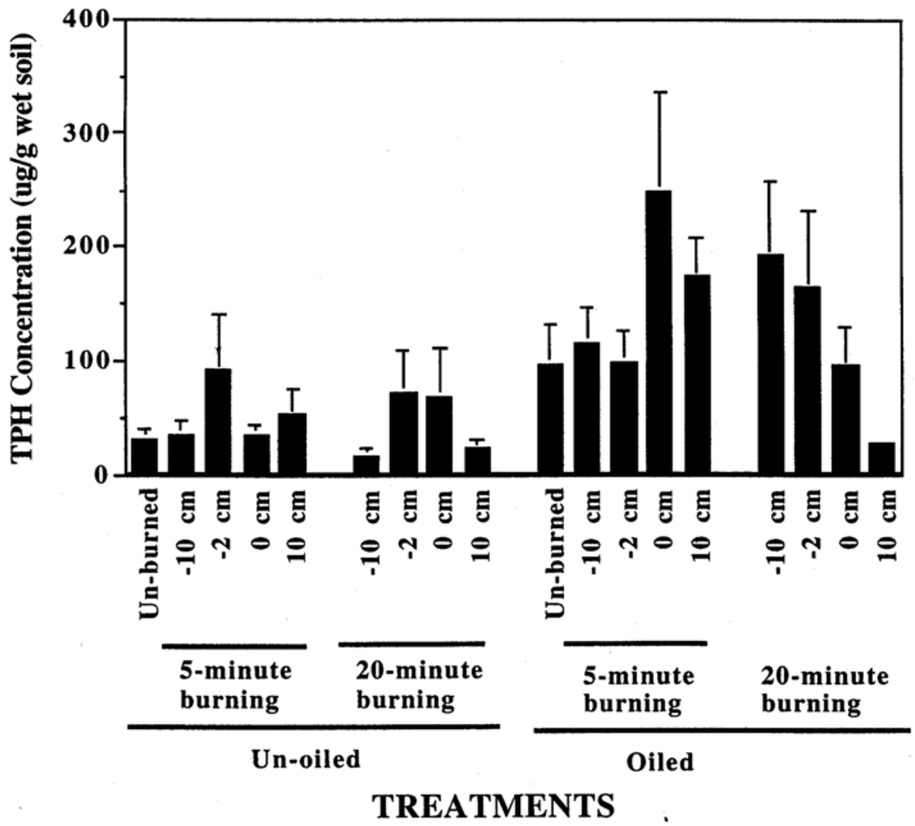

Figure 8 *Effects of burning duration, water table level, and oil dosage on the total petroleum hydrocarbons in the soil 4 to 8 cm below the soil surface one day after the burn. -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Error bars represent standard errors.*

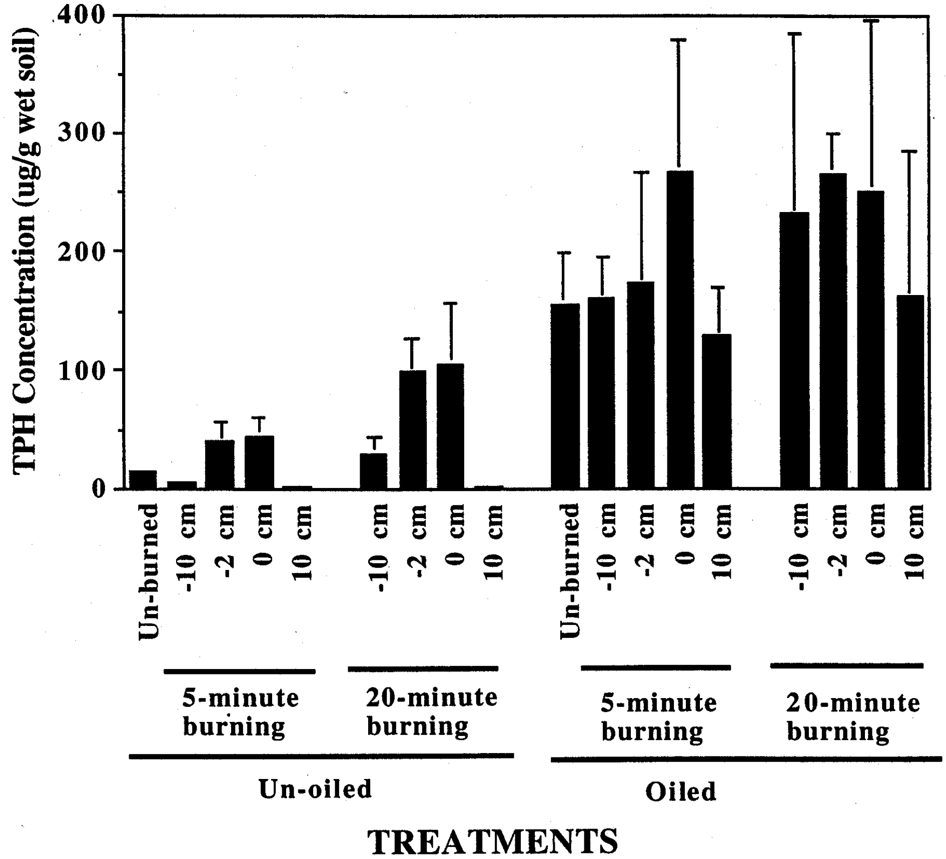

Figure 9 *Effects of burning duration, water table level, and oil dosage on the total petroleum hydrocarbons in the soil 0 to 4 cm below the soil surface seven months after the burn. -10 cm, -2 cm, 0 cm, and 10 cm representsoil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Error bars represent* standard *errors.*

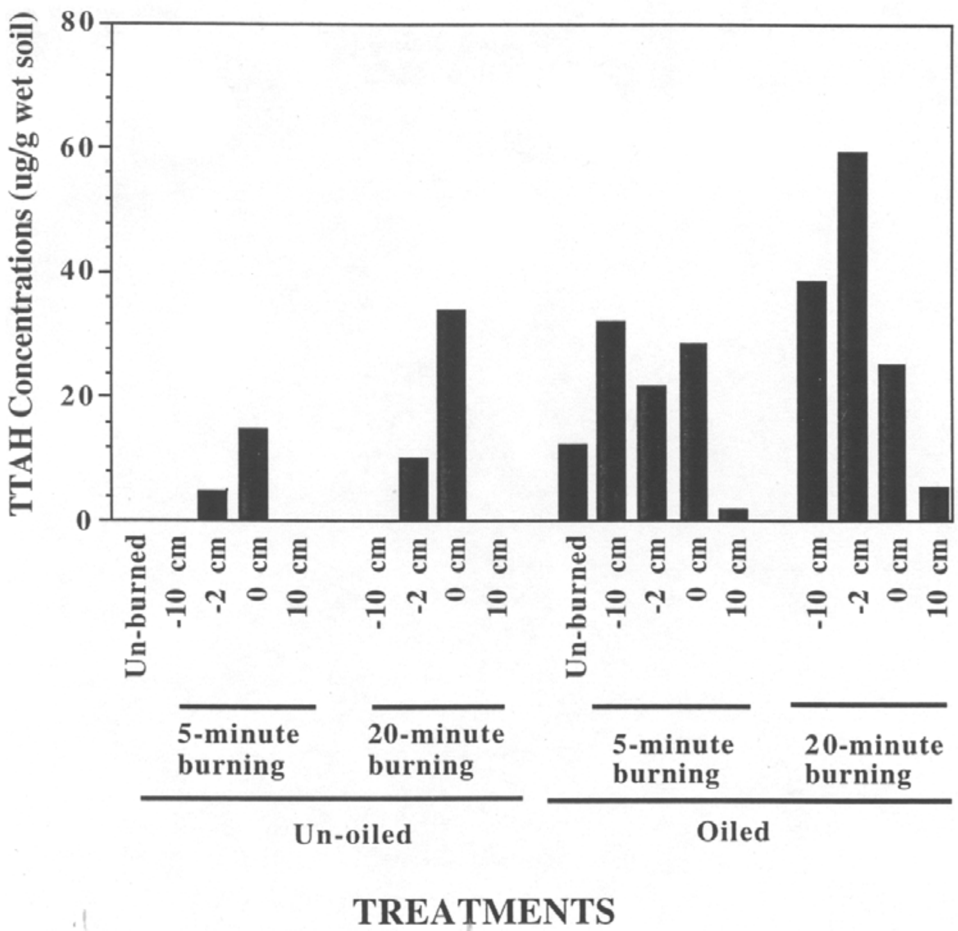

Figure 10 *Effects of burning duration, water table level, and oil dosage on the total targeted aromatic hydrocarbons (TTAH) in the soil 0 to 4 cm below the soil surface one day after the burn. Values are derived from an analysis of five replicates composited. -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn.*

The TTAH concentrations in the residual oil floating on the water surface after burning did not decrease compared to concentrations in original diesel fuel before the burn (Table 2). After burning, the TTAH concentration was somewhat higher than before the burn (119% vs. 100%), although changes in concentrations varied with individual compounds. However, *in situ* burning greatly reduced the thickness and amount of the oil on the water surface, with only a thin film (< 1 mm or < 5% of the original amount) of residue regardless of the original amount of diesel fuel added to the water surface (³ 20 mm of oil layer initially). Thus, *in situ* burning also greatly reduced the amount of toxic components, such as TTAH.

3.3 Soil Temperature and Plant Recovery

Peak soil temperature at 0, 0.5, 2, and 5 cm below the soil surface was documented during *in situ* burning (Fig. 11). Water levels over the soil surface significantly ($p<0.0001$) affected soil temperature. The peak temperature also decreased rapidly with soil depth. At 0, 0.5, and 2 cm soil depths, average peak soil temperature of the treatment with 10 cm of soil exposure during the burn was above 100 °C, ranging from 120 to 500 °C. Average peak soil temperature of the treatment with 0 cm overlying water during the burn was below 80 °C even at the soil surface, ranging from 40 to 80 °C at the 0 to 5 cm soil depth. Average peak soil temperature at all soil depths, including the soil surface, was below 60 °C for the treatment with 2 cm of overlying water. Temperature at all soil depths was below 37 °C for the treatment with 10 cm of overlying water (see Bryner *et al.* 2000 for detailed soil temperature data).

In addition, burn duration significantly affected soil temperature. Average peak soil temperature during the 20 minute burn was significantly ($p<0.0001$) higher than that of the five minute burn at 0.5, 2, and 5 cm soil depths (Fig. 12). Interestingly, oil application to the soil prior to the burn affected the soil temperature. Average peak soil temperature in the treatment with diesel applied to the soil prior to the burn was significantly lower than average peak soil temperatures in treatments without added diesel at both 2 cm ($p<0.0001$) and 5 cm ($p=0.054$) soil depths (Fig. 13).

The relationship between live above-ground biomass of *S. alterniflora* and soil temperature at 0, 0.5, 2, and 5 cm below the soil surface was analyzed to determine the thermal effect on plant recovery after *in situ* burning. At 0 cm (Fig. 14-1) and 0.5 cm (Fig. 14-2) of soil depths, soil temperature had a very wide range. Most *S. alterniflora* exhibited mortality when the soil temperatures exceeded 55 °C at 0.5 cm soil depth. In one sod, *Spartina alterniflora* survived soil temperatures as high as 110 °C and 80 °C at 0 and 0.5 cm below the soil surface, respectively (Figs. 14-1 and 14-2). The soil temperatures at 2 cm soil depth in most marsh sods were below 70 °C. Generally, *Spartina alterniflora* recovered from temperatures £ 50 °C at 2 cm soil depth. No plants survived at temperature > 60 °C at 2 cm soil depth (Fig. 14-3) and > 40 °C at a depth of 5 cm (Fig. 14-4).

Table 2 Comparison of TTAH concentrations in the residue after *in situ* burning compared to concentrations before burning.

	Before Burn (ug/kg)	After Burn (ug/kg)
ITAH (sum of the following compounds)	**485,117**	**578,231**
Compounds		
NAPHTHALENE	7,893	2,641
C1-NAPHTHALENE	39,725	7,753
C2-NAPTHALENE	123,405	63,202
C3-NAPTHALENE	98,966	85,383
ACENAPHTHYLENE	593	4,152
ACENAPHTHENE	3,749	1,901
FLOURENE	15,610	14,923
C1-FLOURENE	19,813	27,078
C2-FLOURENE	24,474	43,885
C3-FLOURENE	14,630	36,964
DIBENZOTHIOPHENE	0	0
C1-	2,317	3,282
DIBENZOTHIOPHENES	5,618	12,287
C2-	4,198	11,613
DIBENZOTHIOPHENES	20,420	39,490
C3-	25,863	52,863
DIBENZOTHIOPHENES	31,863	76,729
PHENANTHRENE	9.835	25,161
C1-PHENANTHRENE	0	0
C2-PHENANTHRENE	0	0
C3-PHENANTHRENE	9,612	18,925
C4-PHENANTHRENE		
ANTHRACENE	0	1,046
o-TERPHENYL	2,839	9,685
	1,159	3,566
FLOURANTHENE	0	0
PYRENE	0	0
C1-PYRENE	0	0
C2-PYRENE		
C3-PYRENE	0	0
C4-PYRENE	1,290	1,857
	0	0
BENZ (a) ANTHRACENE-	0	0
d12	0	0
BENZO (a)	0	0

ANTHRACENE CHRYSENE C1-CHRYSENE C2-CHRYSENE C3-CHRYSENE C4-CHRYSENE BENZO (b) FLOURANTHENE BENZO (k) FLOURANTHENE BENZO (e) PYRENE BENZO (a) PYRENE PERYLENE INDENO (1,2,3 - cd) PYRENE DIBENZO (a,h) ANTHRACENE BENZO (g,h,i) PERYLENE	0 0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0 0

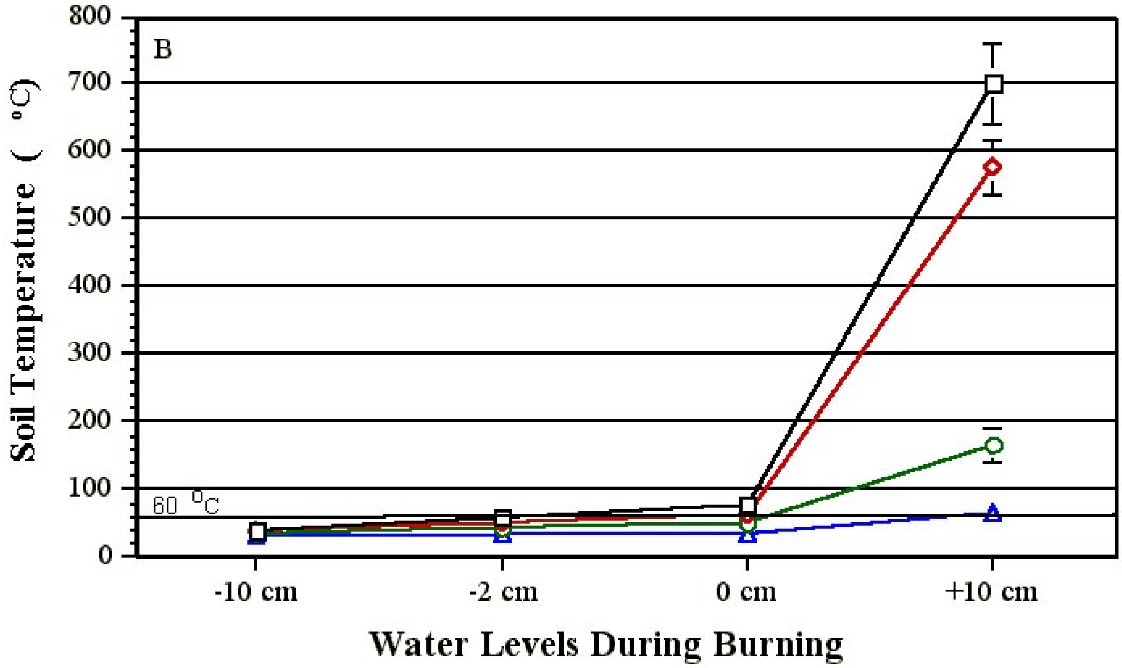

Figure 11 *Average peak soil temperature as a function of water level over the soil surface during the burn. -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surfaceduring the burn.*

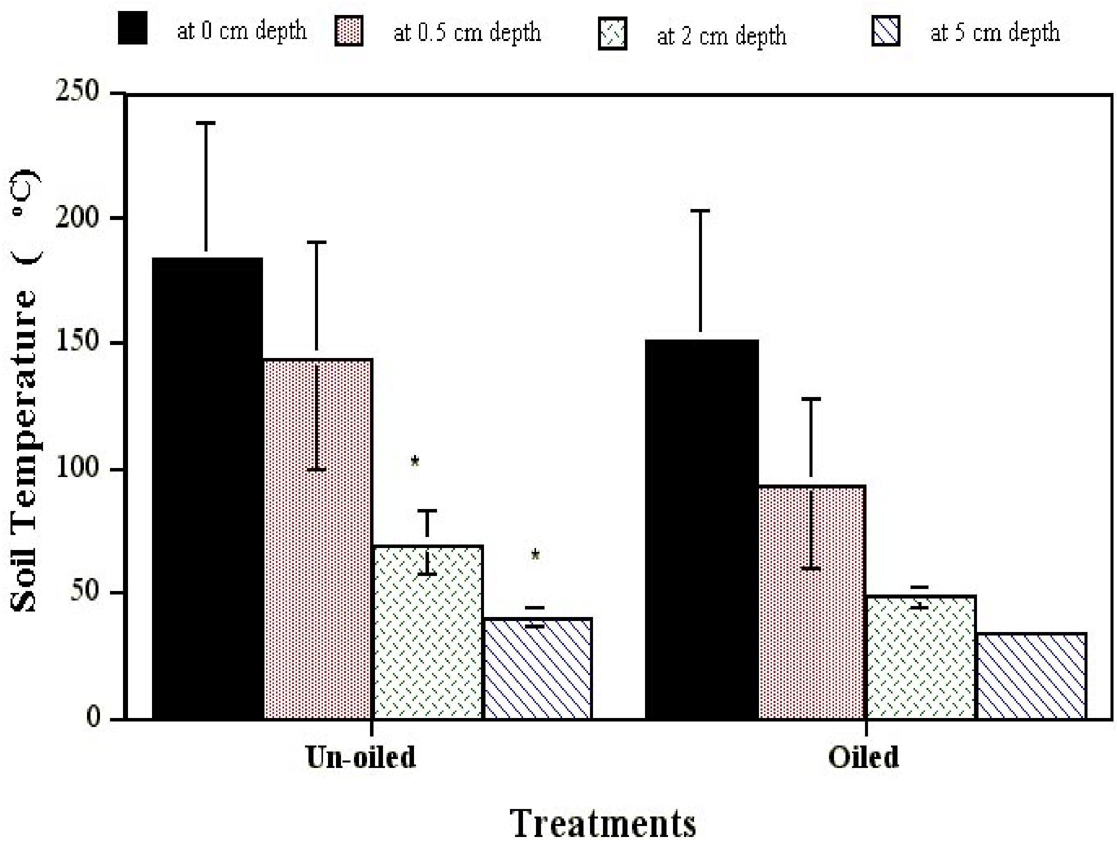

Figure 12 *Average peak soil temperature during in situ burning as a function of oil added to the soil prior to the burn.*
** indicates a significant difference between un-oiled and oiled treatment at the same soil depth.*

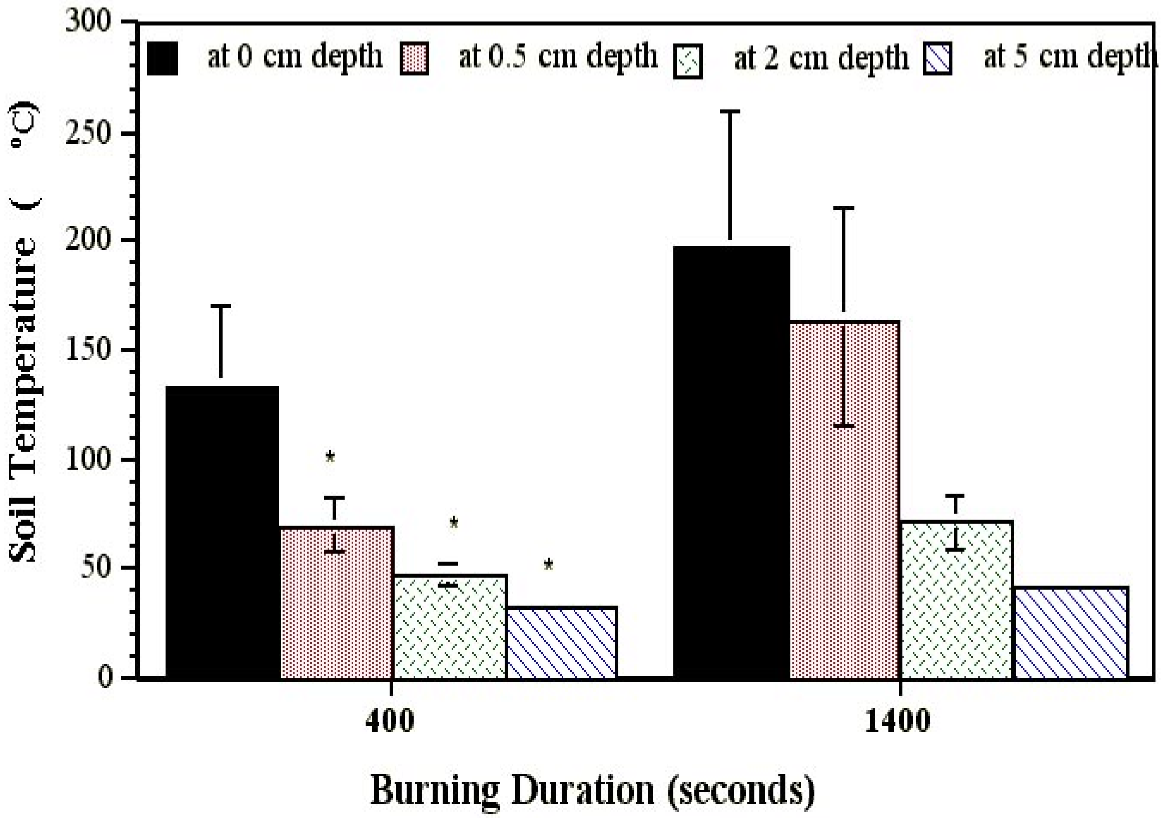

Figure 13 *Average peak soil temperature during* in situ *burning as a function of burn duration.*
** indicates a significant difference between burn duration at the same soil depth.*

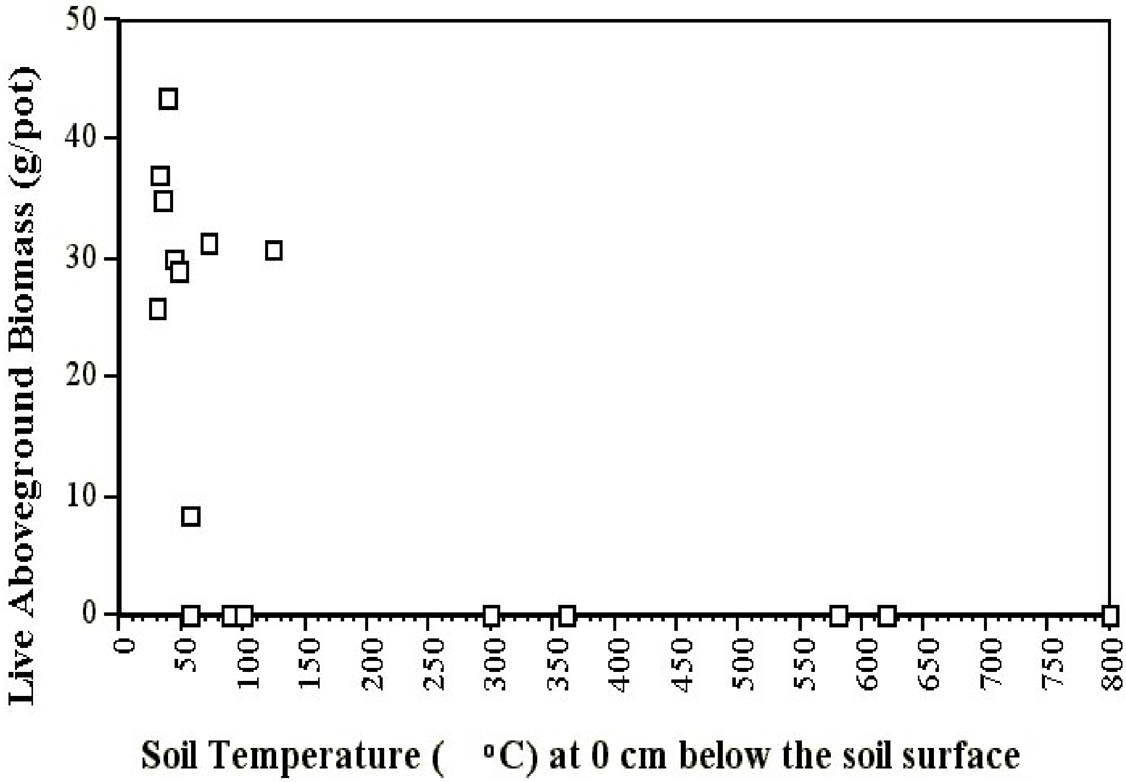

Figure 14-1 *Relationship between live above-ground biomass produced seven months after the burn and soil temperature at 0 cm below the soil surface during the burn.*

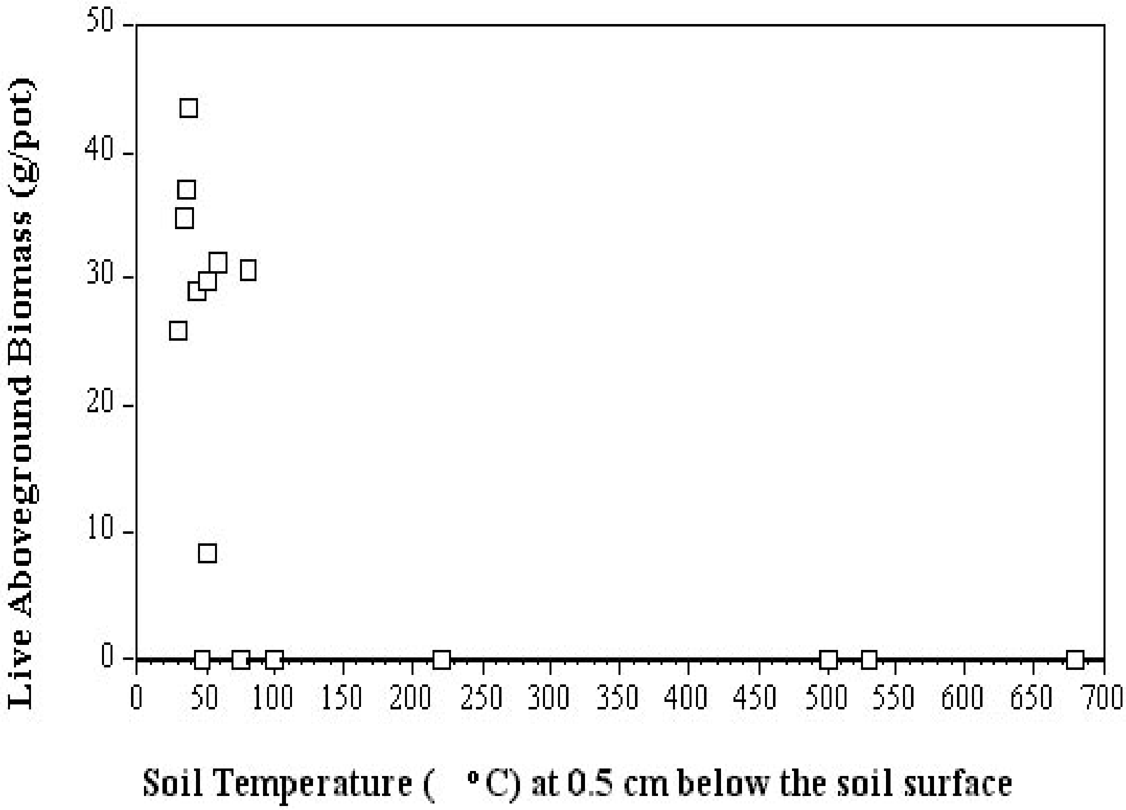

Figure 14-2 *Relationship between live above-ground biomass produced seven months after the burn and soil temperature at 0.5 cm below the soil surface during the burn.*

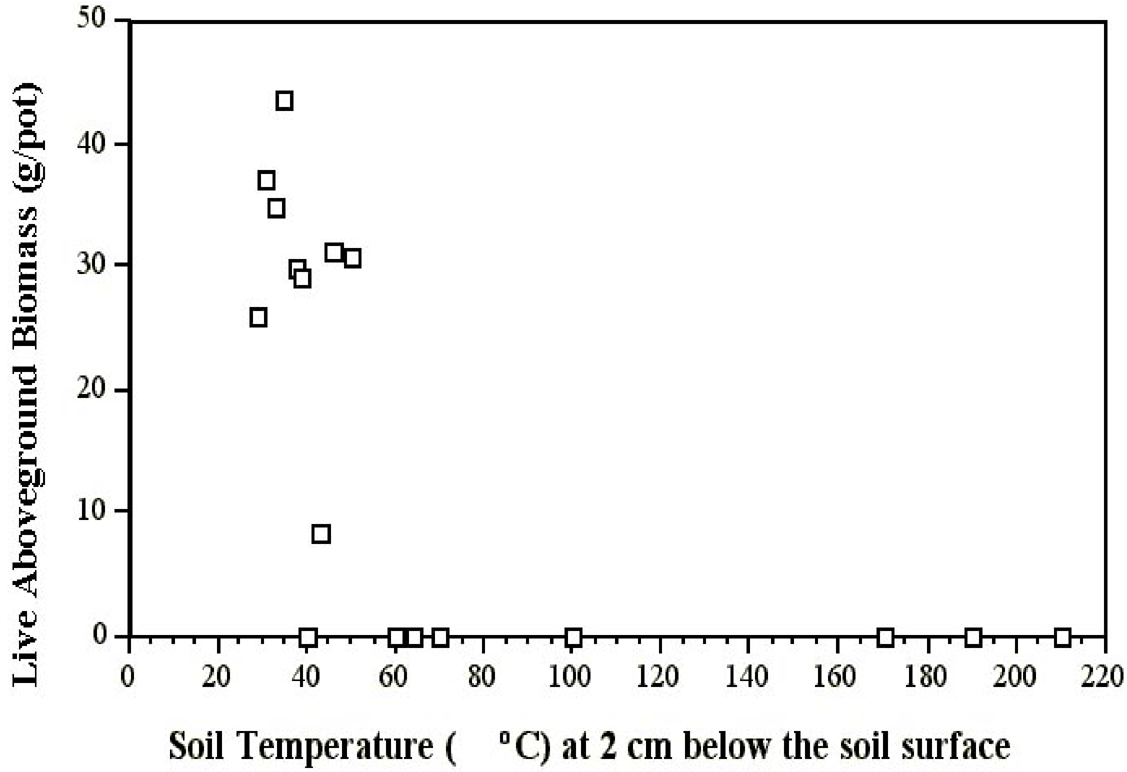

Figure 14-3 *Relationship between live above-ground biomass produced seven months after the burn and soil temperature at 2 cm below the soil surface.*

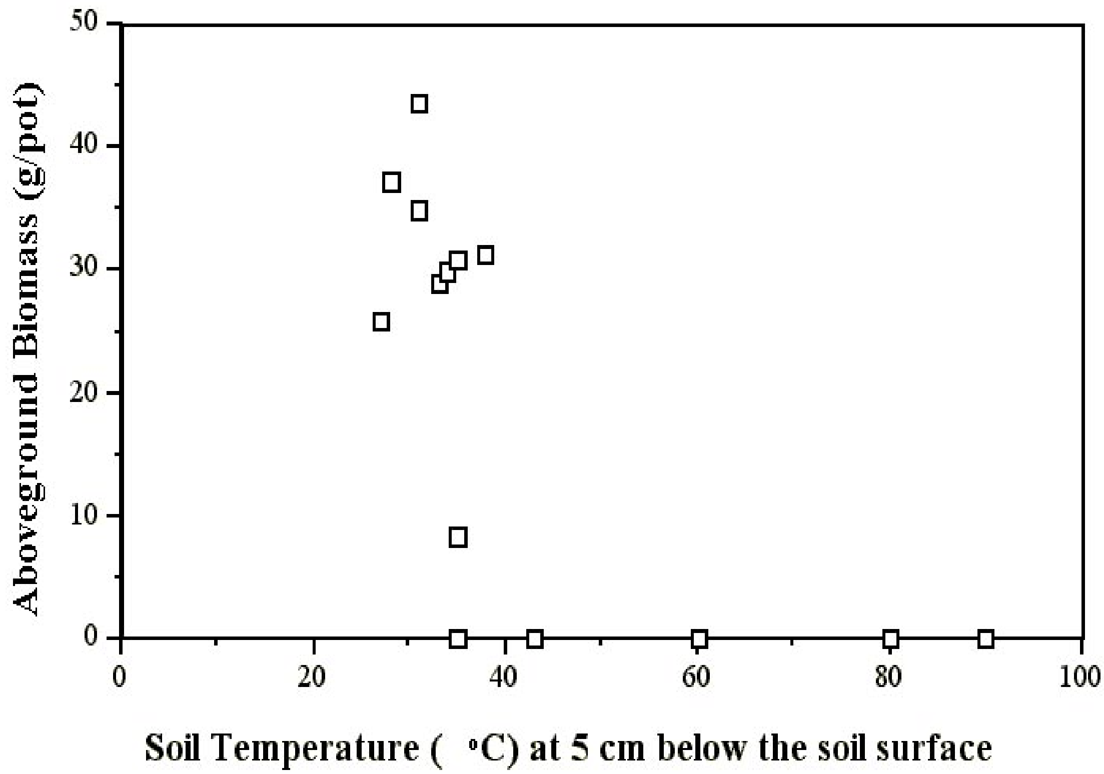

Figure 14-4 *Relationship between live above-ground biomass produced seven months after the burn and soil temperature at 5 cm below the soil surface during the burn.*

4.0 Discussion

Recovery of the salt marsh grass, *Spartina alterniflora*, to *in situ* burning of diesel mainly depended upon the depth of water over the soil surface during the *in situ* burn and the residual oil content in the soil. Greater water depth over the marsh surface provided greater protection to the marsh vegetation during the burn, resulting in lower soil temperature and higher survival rates. In addition, the less diesel that penetrated the soil, the better the plant recovery.

Ten centimeters of water over the soil surface were sufficient to protect the marsh sods from burn impacts. Soil surface temperature 10 cm below the water did not exceed 40 °C for either five or 20 minute burn durations. Thermal stress on plant below-ground organs was negligible. The plant survival and growth responses to the water level treatments support the temperature data. However, plant survival was much reduced when diesel was added to the soil before the burn. In the treatments with 10 cm of overlying water and diesel addition to the soil, poor recovery was obviously due to the stress of the added petroleum hydrocarbons. Also, the degree of diesel penetration into the soil may have been enhanced by the fire. This was shown by higher TPH and TTAH in the treatments with 10 cm of overlying water during the burn compared to unburned treatments receiving diesel.

Marsh sods with surfaces located 2 cm below the water level and equal to the water level exhibited poor recovery, probably due to the entry of diesel into the sod containers. The diesel likely caused the main stress to the vegetation, as evidenced by the significantly higher TPH and TTAH concentrations in the 0 and 2 cm water level treatments compared to the control. This occurred even when diesel was not added to the soils prior to the burn (Figs. 7 and 10). Average peak soil temperatures in the 0 and 2 cm water level treatments at soil depth of 2 cm were 42 and 48 °C. Since these temperatures were probably not high enough to severely stress the plants, the diesel was likely the primary reason for the high mortality and poor regrowth in these treatments.

Ten cm of soil exposure during *in situ* burning impeded the post-burn recovery of the marsh grass, *S. alterniflora*. Burning with the water table 10 cm below the soil surface resulted in average peak soil temperatures of about 500 °C at the soil surface and 120 °C at a depth of 2 cm below the soil surface. Thermal stress on plant below-ground organs was severe and resulted in little recovery of *S. alterniflora* even in the absence of diesel addition. The marsh sods with soil surfaces 10 cm above the water line, which were too high above the waterline to be contaminated by the diesel used to create the fire, showed poor vegetative recovery due to the temperature effect alone. The oil played no role.

Research on prescribed burning has also demonstrated that water level during the burn can affect post-burn recovery. Mallik and Wein (1986) found that burning the drained portion of an impoundment resulted in lower plant cover than the control. However, burning in the flooded portion of an impoundment stimulated plant cover above the controls. Hess (1975) demonstrated that prescribed burning during higher water levels produced greater stem density and height of *Scirpus olneyi*. In a New Zealand bog, burning also resulted in a more favorable response in wet sites compared to drier sites (Timmins 1992). In the present study, burning of marsh sods with a 10 cm soil exposure almost completely inhibited recovery of *S. alterniflora*. In contrast, burning at a water level 10 cm above the soil surface resulted in a significant recovery of *S. alterniflora*, further demonstrating that standing water over the marsh surface during *in situ* burning is important for post-burn recovery.

Burn duration affected soil temperatures at depths $\geq$ 2 cm below the soil surface. Although a 20 minute burn resulted in significantly higher soil temperatures at 2 and 5 cm below the soil surface than a five minute burn, both burn durations had similar effects on plant survival and post-burn recovery of marsh vegetation. The soil temperature during a five minute burn was high enough to kill *S. alterniflora* when the water level was 10 cm below the soil surface. However, soil temperature during a 20 minute burn was not high enough to affect *S. alterniflora* when water level was 10 cm above the soil surface. In the 0 and 2 cm water level treatments, diesel contents in the soil played a more important role in plant recovery than did thermal effects (or burning duration). The diesel contamination in the soil was a remnant of the diesel used to create the fire at these two water levels. Diesel is much more toxic to plants than crude oil. In general, petroleum hydrocarbon toxicity increases from alkanes to aromatics; within each series of hydrocarbons, the hydrocarbons with small molecular weights are more toxic than the hydrocarbons with large molecular weights. Alexander and Webb (1985) demonstrated that 1.5 l m^{-2} of No. 2 fuel oil significantly reduced live above-ground biomass of *S. alterniflora*, while 2 l m^{-2} of crude oil did not. The compositions and toxicities 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 above-ground biomass of *S. alterniflora* four and nine months after oiling. This supports the contention that No. 2 fuel oil and diesel have a greater toxicity on plants than does crude oil.

Soil temperatures differed with soil depth during the *in situ* burns. Lower temperatures were found with greater depth in the soil. Two important questions regarding *in situ* burning are: (1) what soil temperature will result in plant mortality? and (2) at what depth can soil temperature help predict lethal effects on plants? In the present study, some *Spartina alterniflora* recovered in sods with soil temperatures as high as 110 and 80 °C at 0 and 0.5 cm below the soil surface, respectively. Therefore, surface soil temperature (0 and 0.5 cm below the soil surface) may not accurately predict thermal effects on plants. Plant reproductive organs, such as rhizomes, are located below the soil surface. In contrast, in sods that exhibited regrowth after burning, soil temperatures 5 cm below the soil surface were < 37 °C. This temperature was not high enough to kill the below-ground rhizomes. Furthermore, no *S. alterniflora* recovered at temperatures > 60 °C at the 2 cm depth. In addition, almost all *S. alterniflora* recovered at temperatures below 60 °C at 2 cm below the soil surface. It appears that the critical temperature for survival of *S. alterniflora* is 60 °C at a 2 cm soil depth. Since lethal temperatures for most vascular plants have been cited in the range of 60 °C to 65 °C (Byram 1948, Ahlgren 1974, and Levitt 1980), we suggest that plant recovery may be predicted based on the temperatures recorded at 2 cm below the soil surface. Effects of soil temperature during *in situ* burning of wetlands may vary with plant species and soil characteristics. This is currently being investigated.

The effectiveness of *in situ* burning on oil cleanup may differ if the oil is floating on the water surface or has penetrated the soil. *In situ* burning can effectively reduce floating diesel from the water surface, thus preventing it from penetrating the soil when the water recedes, or from drifting and contaminating adjacent habitats. In an *in situ* diesel burn in Mobile Bay, AL, Wang *et al.* (1994) estimated that the average destruction efficiencies for total targeted diesel PAHs, including five alkylated PAH series and other EPA priority unsubstituted PAHs, were greater than 99%. 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. Thus, in the present study, although concentrations of some hydrocarbon constituents increased, the total mass of diesel was greatly reduced.

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

5.0 Conclusions

Water depth over the soil surface during *in situ* burning is one of the most important factors controlling recovery of the salt marsh grass, *Spartina alterniflora*. Ten centimeters of water overlying the soil surface were sufficient to protect the marsh soil from burn impacts, with lower soil temperature, higher survival rates, and live plant biomass. In contrast, a water table 10 cm below the soil surface (10 cm of soil exposure to fire) resulted in high soil temperatures, with 120 °C even at 2 cm below the soil surface. Thermal stress almost completely inhibited the post-burn recovery of *S. alterniflora* in this water level treatment. The poor recovery of marsh sods with soil surfaces located 2 cm below and equal to the water surface was most likely due to hydrocarbon stress induced by diesel entry into the sod containers used to create the fire. The high concentration of diesel in the soil at these water levels most likely caused greater stress on the plants than the thermal stress. The soil temperature at 2 cm deep was not greater than 60 °C for marsh sods with surfaces located 0 and 2 cm below the water surface in the present study. This finding further supports the conclusion that oil stress on these plants was the primary reason for poor recovery. In addition, the lethal temperature for *S. alterniflora* appeared to be 60 °C at 2 cm below the soil surface, although it may vary with plant species. Although *in situ* burning appeared not to remediate oil that had penetrated into the soil, it effectively removed floating oil from the water surface, thus preventing it from potentially contaminating adjacent habitats and penetrating the soil when the water receded. 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 a *Spartina alterniflora* marsh, 10 cm of overlying water is certainly sufficient. Lower water levels may also be adequate, but diesel stress at these lower water level treatments (0 and 2 cm of water over the soil surface) prevented a definitive conclusion regarding the causes for low plant recovery at these water levels, (i.e. thermal stress or oil stress). Ongoing research will separate the thermal effect from the oil effect at these lower water levels.

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