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

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ABSTRACT

Oil spills pose a serious risk 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, the burning of wetlands can have beneficial as well as detrimental 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 relationship 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 l/m^2) versus no diesel application, (b) Burn duration: 400 s (seconds) versus 1400 s (seconds), and (c) Water depth: -10, -2, 0, and 10 cm of the marsh surface relative to the water level. Soil temperature, as a function of soil depth and sod elevation, was continuously recorded during the burn and for a total of 5400 s post-burn. After the burns, the mesocosms were returned to the greenhouse where plant recovery was monitored. Soil samples for total petroleum hydrocarbon and gas chromatography/mass spectrometry (GC/MS) analyses were collected 24 hours after oil addition and 1 day and 7 months post-burn.

The water depth over the soil surface during *in-situ* burning was a major factor controlling recovery of the salt marsh grass, *Spartina alterniflora.* Ten centimeters of water overlying the soil surface (-10 cm) 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 0 and -2 cm water levels (0 and 2 cm of water over the soil surface), this result was most likely due to chemical stress induced by the entry of diesel fuel, used to create the fire, into the marsh sods. The high concentration of diesel fuel hydrocarbons 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 was not attained at the 0 and -2 cm water levels. Although *in-situ* burning effectively removed floating oil from the water surface, thus preventing it from potentially contaminating adjacent habitats, it did not appear to effectively remediate the oil that penetrated into the soil.

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, and 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). 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 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 along the northern Gulf of Mexico, examples exist in the scientific literature showing that burning of wetlands can have beneficial, detrimental, or no impact. For example, prescribed burns in salt water 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 water 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 likely are controlling 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 successful recovery after a prescribed burn, little is known about the primary variables determining the successful recovery of wetlands subjected to *in-situ* burning of an oil spill. The impacts of the two types of burns are likely to be different due to the much greater fuel load in most petroleum burns. Not only is the literature on *in-situ* burning of oil contaminated wetlands limited, but it is often contradictory. 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). Recently, Lindau *et al.* (1999) and Pahl and Mendelssohn (1999) observed rapid recovery of salt water marsh vegetation in Louisiana after *in-situ* burning. Mendelssohn *et al.* (1995) reviewed *in-situ* burning and concluded that burning is suitable for oil spill cleanup in wetlands. However, they emphasized that more information is needed to better predict under what environmental conditions *in-situ* burning should be attempted and would likely result in satisfactory wetland recovery. 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 can not be presently formulated.

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 water marshes dominated by *Spartina alterniflora.* This research provides the first quantitative data on the interaction among burn dynamics, oil chemistry, and marsh recovery.

MATERIALS AND METHODS

Experimental Design

Intact salt marsh sections, 30 cm in diameter and 30 cm tall, were collected from a *Spartina alterniflora*-dominated intertidal salt marsh in southeast Louisiana and placed in 5-gallon metal buckets. *Spartina alterniflora*, commonly called smooth cordgrass, dominates intertidal salt marshes along the Atlantic and Gulf coasts of the United States, and therefore results from this study are applicable to marshes outside of the northern Gulf of Mexico. After collection, half of the marsh sods were instrumented with vertical arrays of thermocouples, allowed to acclimate under greenhouse conditions for a period of five weeks, and randomly assigned to the following treatments: (a) Oil exposure: unweathered diesel fuel (1.5 l/m^2) versus no diesel fuel application, (b) Burn duration: 400 s versus 1400 s, and (c) Water depth: 10, 2 and 0 cm over the soil surface and 10 cm below the soil surface. The experimental design was a completely randomized block with a 4 x 2 x 2 factorial arrangement of treatments (4 water depths, 2 oil levels and 2 burn durations, respectively). Each treatment - level combination was replicated five times for a total of 80 experimental units (marsh sods). Each block [4 (water level) 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 in the experiment.

Experimental Procedures

Forty of 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 surface. 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 (FETI). Diesel fuel was added to water surface, ignited, and allowed to burn for periods of either 400 s or 1400 s (Figure 2). For the 400 s burn duration, sufficient diesel fuel for the entire 400 s burn exposure was added to the water surface before ignition. For the longer 1400 s burn exposure, sufficient diesel fuel was added to allow for 400 s of burn, and as the diesel fuel burned, additional fuel oil was added via inlets below the water surface. The soil temperature, as a function of soil depth and sod elevation, was continuously recorded during the burn, 400 s or 1400 s, and monitored for total of 5400 s (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 (TTAH) 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 burn exposure were evaluated in representative mesocosms. Recovery of the salt marsh grass, *S. alterniflora*, was assessed by determining plant survival rate, live stem density after the burn, live above-ground biomass and leaf photosynthesis, the latter a sensitive indicator of plant response to stress (Ewing *et al.* 1997).

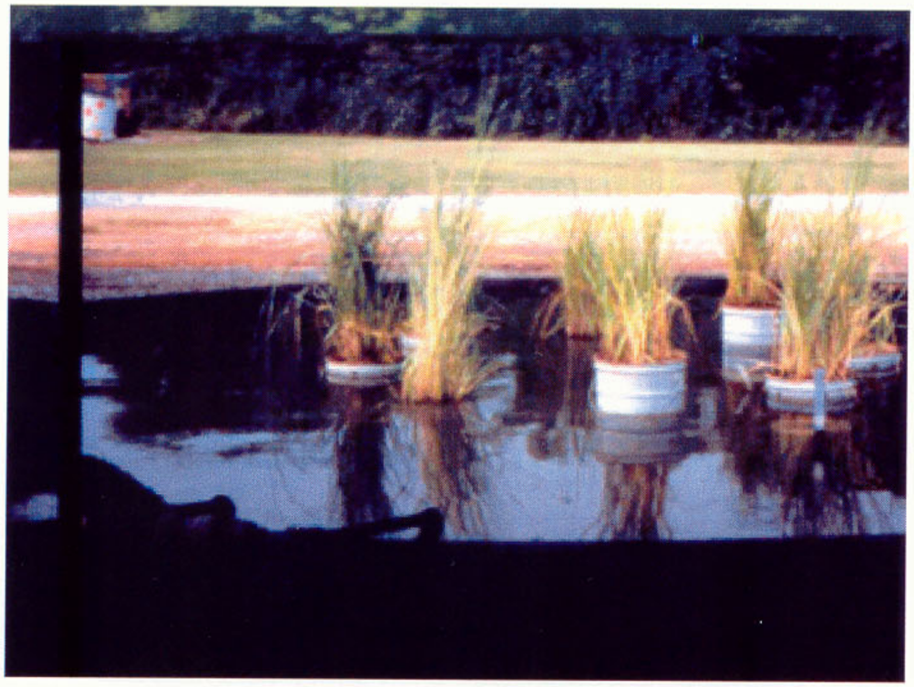

Fig. 1. Salt marsh sods located in the 6 m burn tank with soil surface at –10, -2, 0 and +10 cm relative to the water surface before the burn. Diesel fuel (1.5 liter/m^2) was added to half of the sods 24 hours prior to the burn exposure.

Fig. 2. *In-situ* burning of salt marsh sods in the 6 m burn tank for either 400 s or 1400 s burn duration.

Methods

Leaf Carbon Dioxide Assimilation and Transpiration Measurements Carbon dioxide (CO_2) uptake was determined on representative intact leaves within each mesocosm with a 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 measured. Sample air, taken at 5 m above ground surface in order to obtain a relatively stable CO_2 concentration, 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/s. 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. Carbon dioxide uptake will be calculated according to Cammerer and Farquhar (1981).

Plant Growth and Survival   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 (7 months after burn exposure) was separated into live and dead biomass and dried at 65 C to a constant weight. Also, 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 (5) and multiplied by 100 to convert to percent.

Total Petroleum Hydrocarbons (TPH) Analysis by GC/FID   TPH 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. Gas chromatographic separations used a 30 m, 0.25 mm inner diameter column with a 5 percent phenyl-95 percent 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 to 4 cm and 4 to 8 cm depth of soil) were determined shortly after the burn to assess any migration of the oil residue into the soil.

Detailed Oil Chemical Analysis by GC/MS   All samples were analyzed by gas chromatography/mass spectrometry (GC/MS) to confirm and expand the GC-FID results. A GC/MS profile of the initial oil material was obtained for comparison with the burn 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 μm 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 minutes. 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 diesel fuel. The instrument was operated such that the selected ions for each acquisition window were scanned at a rate greater than 1.4 Hz. The targeted constituents and the quantitative ions monitored for each is provided in Table 1. An internal standard mix composed of nitrobenzene-d5, 2-flurobiphenyl, and terphenyl-d14 was co-injected with each analysis to monitor instrument performance during each run.

Statistical Analysis

Statistical analysis was conducted with the Statistical Analysis System (SAS, 1985). 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 (SAS, 1985) was used to evaluate statistical differences of the main factors when no interaction occurred. Least square means (LSD) test (SAS, 1985) was used when interaction between main factors occurred. Significant differences were reported at the 0.05 probability level, unless otherwise stated.

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.

RESULTS

Recovery of Marsh Plants after *in-situ* Burning

Recovery of the salt marsh grass, *Spartina alterniflora* after exposure to *in-situ* burning mainly depended upon the depth of water over the soil surface. Ten centimeters of water overlying the soil surface was sufficient to protect the plants from thermal stress. In the absence of diesel additions to the soil, percent survival of the experimental units (marsh sods) after *in-situ* burning was 100 percent with 10 cm of water over the soil surface regardless of burn duration (400 s versus 1400 s, Figure 3). Sod survival decreased with decreasing surface water. No experimental units survived after a 1400 s 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 fuel (Figure 3). For example, even with a 10-cm overlying water column, a 60 percent decrease in survival resulted when diesel oil was present in the soil compared to when it was absent. No mesocosms survived in the lower water level treatments when the soil contained diesel fuel. There was no significant difference in sod survival between burn durations, 400 s versus 1400 s.

Stem densities of *Spartina alterniflora* re-grown after the burn (Figure 4) were consistent with the survival results. Both diesel fuel added 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 exposure. A significant interaction ($p<0.0001$) between diesel fuel addition and water level suggested that diesel fuel addition influenced the effect of water level on plant response to the burn exposure. 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 (400 s versus 1400 s), although they were still significantly lower than the control (without burn exposure). Stem density decreased with decreasing water layer thickness. Few stems re-grew with 10 cm of soil exposure. When diesel fuel was added to the soil, stem density was significantly lower than in the absence of diesel, regardless of water level (Figure 4). For example, with 10 cm of overlying water, when diesel fuel was present in the soil, live stem density was only 10 to 15 percent of that when diesel was absent. No stems re-grew after the burn exposure 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 exposure durations (400 s versus 1400s).

Live aboveground biomass and live stem density exhibited similar responses to the experimental treatments. Effects of diesel fuel added 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 fuel addition and water level ($p<0.005$) on live aboveground biomass were significant. In the absence of diesel fuel additions to the soil, live aboveground biomass of the marsh sods was significantly higher with 10 cm of water over the soil surface regardless of burn duration (400 s versus 1400 s) (Figure 5), although live aboveground biomass was still significantly lower than the control (without burn exposure). Live aboveground 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 fuel additions to the soil. Furthermore, in the presence of diesel fuel added to the soil, live aboveground biomass was significantly lower than in the absence of diesel fuel (Figure 5). No live aboveground biomass re-grew after burn exposure in the lower water level treatments (-2, 0 and +10 cm) in the presence of diesel fuel addition to the soil. There was no significant difference in live aboveground biomass between burn duration (400 s versus 1400 s).

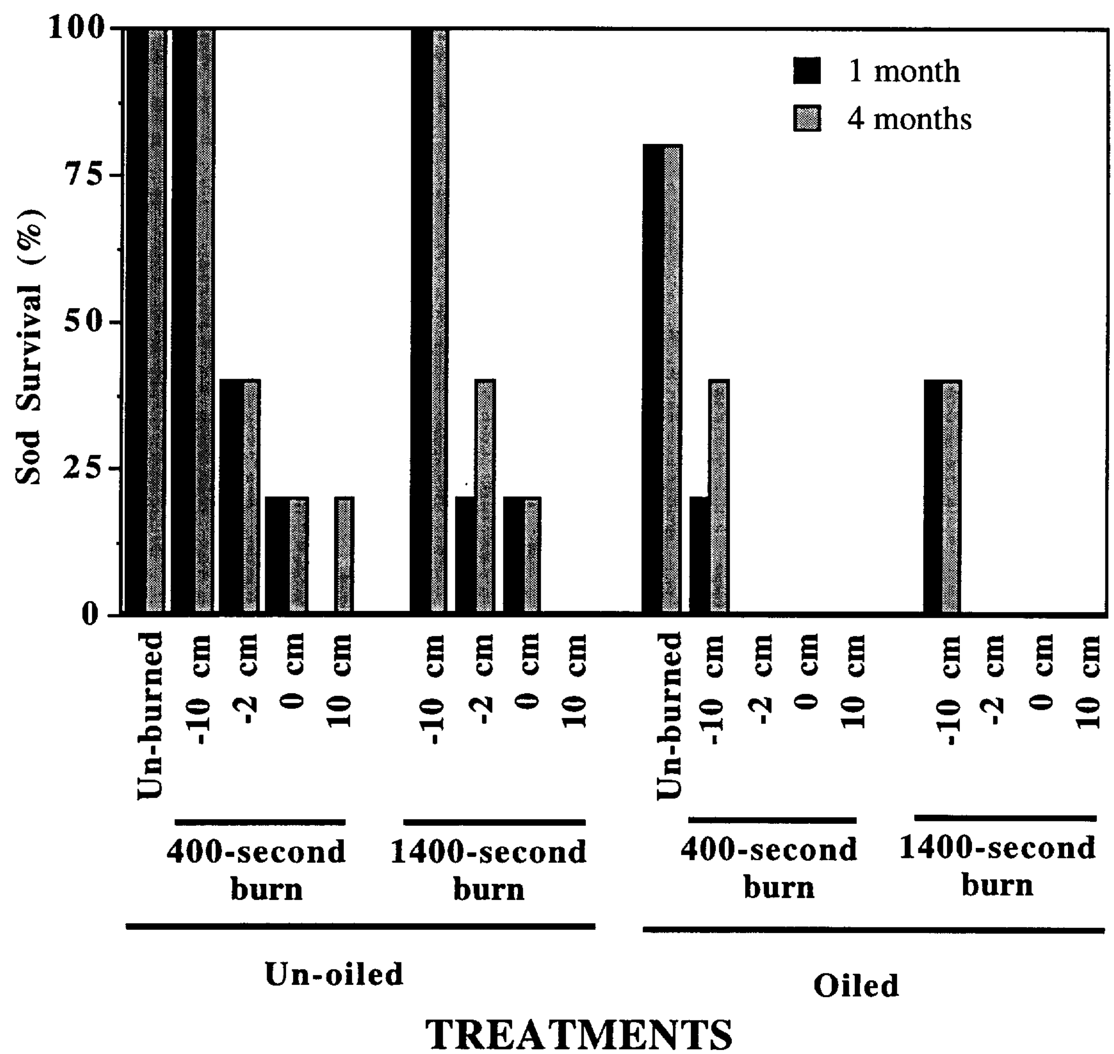

Fig. 3. Effects of burn exposure duration, water table level, and diesel fuel application on percentage of sods exhibiting post-burn regrowth. Notation of -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Sod survival was also determined 7 months after the burn, but it was not different than for the 4 month survival.

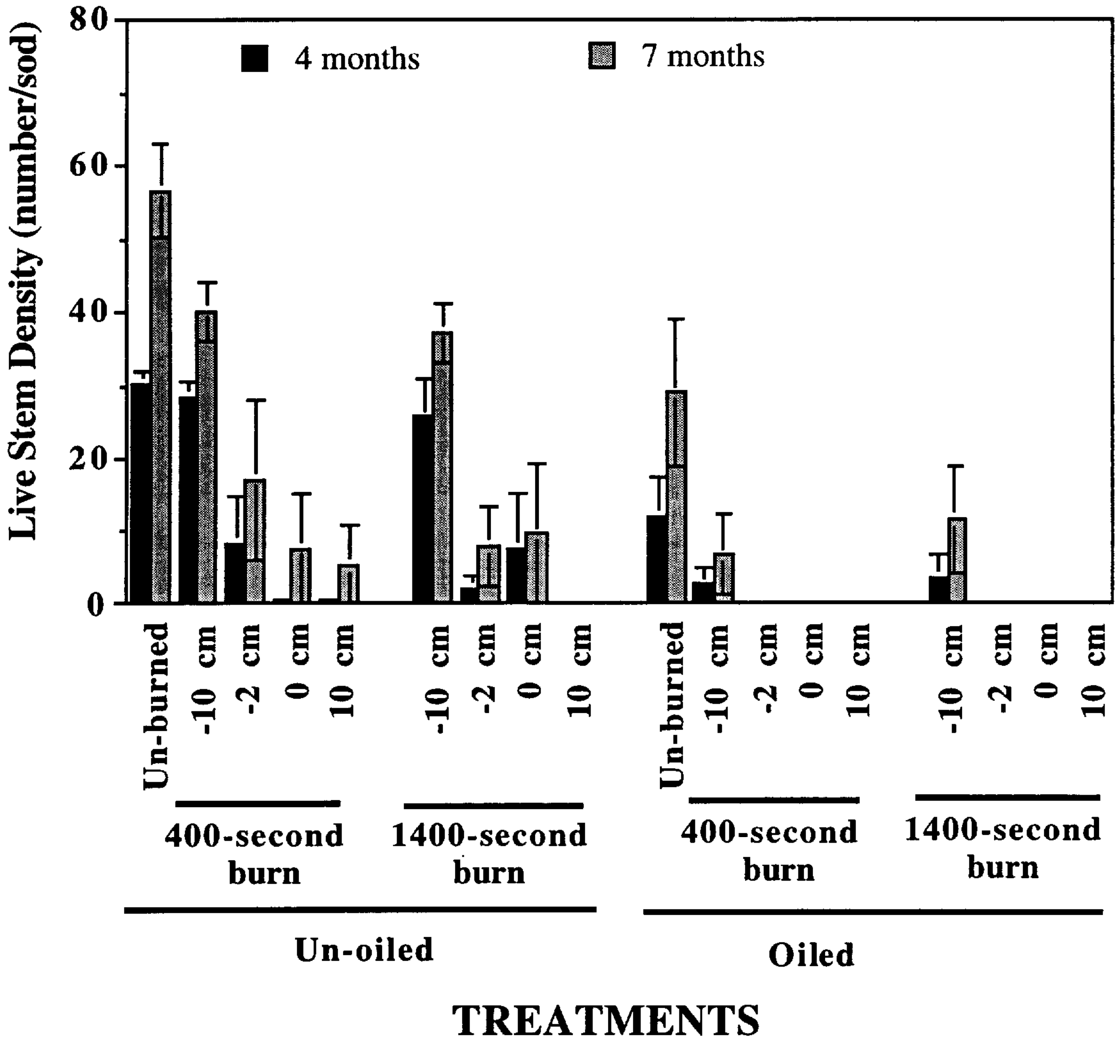

Fig. 4. Effects of burn exposure duration, water table level, and diesel fuel application on live stem density 4 and 7 months after the burn. Notation of -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Error bars are standard errors.

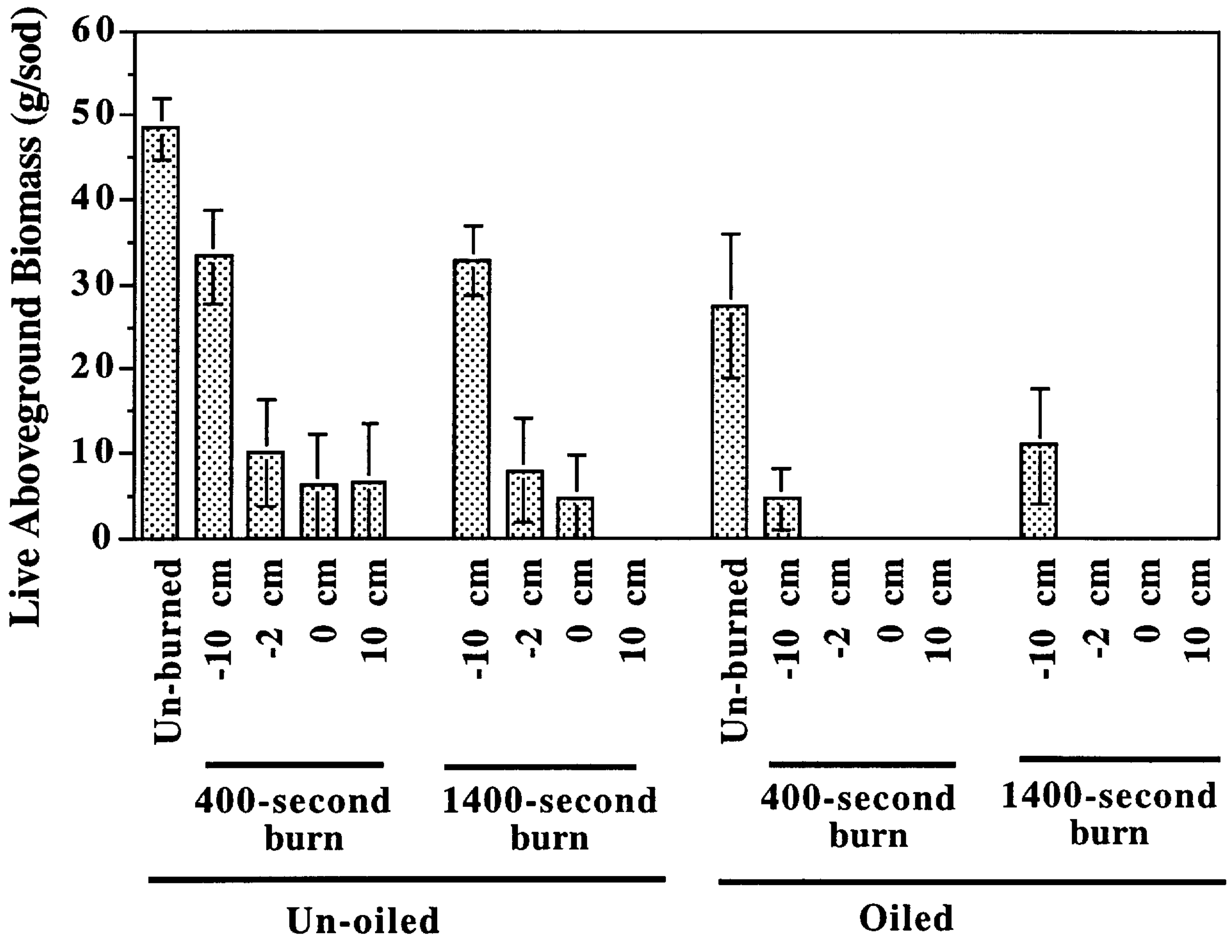

Fig. 5. Effects of burn exposure duration, water table level, and diesel fuel application on live aboveground biomass of *S. alterniflora* 7 months after the burn. Notation of -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Error bars are standard errors.

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 (Figure A1). 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.

Interestingly, diesel fuel application increased the interstitial nitrogen concentration (Figure A2). Average interstitial nitrogen concentration in the treatments with diesel oil application prior to the burn was 3.7 ppm, significantly higher than that (2.0 ppm) in the treatment without oil application. A significant interaction between the diesel fuel addition and water level ($p=0.05$) on interstitial nitrogen concentration indicated that water level affected the nitrogen concentration greater in the treatments without oil application. For example, interstitial nitrogen concentrations of the treatments with 0 and -2 cm water levels were more than 30 and 70 fold higher than that with -10 cm water level in the absence of fuel added to the soil, however, there was no significant difference in the interstitial nitrogen among the same treatments in the presence of diesel addition.

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 fuel added to the soil than without (Figure 6). In addition, water level over the soil surface during the burn significantly ($p<0.0001$) affected TPH in the soil. In the absence of diesel fuel added to the soil, TPH concentration in the soil with 10 cm of water overlying the soil surface and with the water table 10 cm below the soil surface was lowest regardless of burn duration (400 s versus 1400 s) (Figure 6), and was not significantly different from the overall control (un-burned and un-oiled). However, after *in-situ* burning, TPH concentration in the soil with 2 cm and 0 cm of water overlying the soil surface was significantly higher than that in the treatments with 10 cm of water over the soil surface and 10 cm below the soil surface regardless of burn duration (Figure 6). In the presence of diesel fuel added to the soil, the trend of the water level effect on TPH in the soil was similar to that in the absence of diesel additions, but TPH concentrations were generally higher than the comparable treatments without diesel addition. There was no significant difference in TPH in the soil between burn duration (400 s versus 1400 s). *In-situ* burning did not appear to remove significant amounts of diesel fuel that had penetrated into the soil. With diesel addition to the soil, TPH concentration in all burning treatments was 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 µg/g wet soil (± 34 standard error) in the 0 to 4 cm soil depth and 93 µg/g wet soil (± 12 standard error) in the 4 to 8 cm soil depth, which were similar to that in the treatment with diesel addition but un-burned (Figures 6 and 7). The effect of the water level treatments on TPH concentrations in the 4 to 8 cm soil depth (Figure 7) was similar to that in the 0 to 4 cm soil depth (Figure 6), but the concentration was generally lower in the later. Seven months after burning, there was about 45 percent of TPH left in the soil at the 0 to 4 cm depth compared to that one day after the burn exposure. The TPH concentration in the soil was significantly ($p<0.0001$) higher in the treatments with diesel addition to the soil prior to the burn than without (Figure 8).

The total targeted aromatic hydrocarbons (TTAH) in the soil one day after *in-situ* burning showed a similar trend to the soil TPH. 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 (400 s versus 1400 s) (Figure 9), and was not different from the overall control (un-burned and un-oiled). However, TTAH in the soil with 0 to 2 cm of water overlying the soil surface was higher than that in the treatments with 10 cm of water over the soil surface and 10 cm below the soil surface regardless of burn exposure duration. In the presence of diesel fuel added to the soil, the TTAH concentrations in the treatments with burn exposure was higher than without burn exposure except in the treatment with a 10 cm water table below the soil surface.

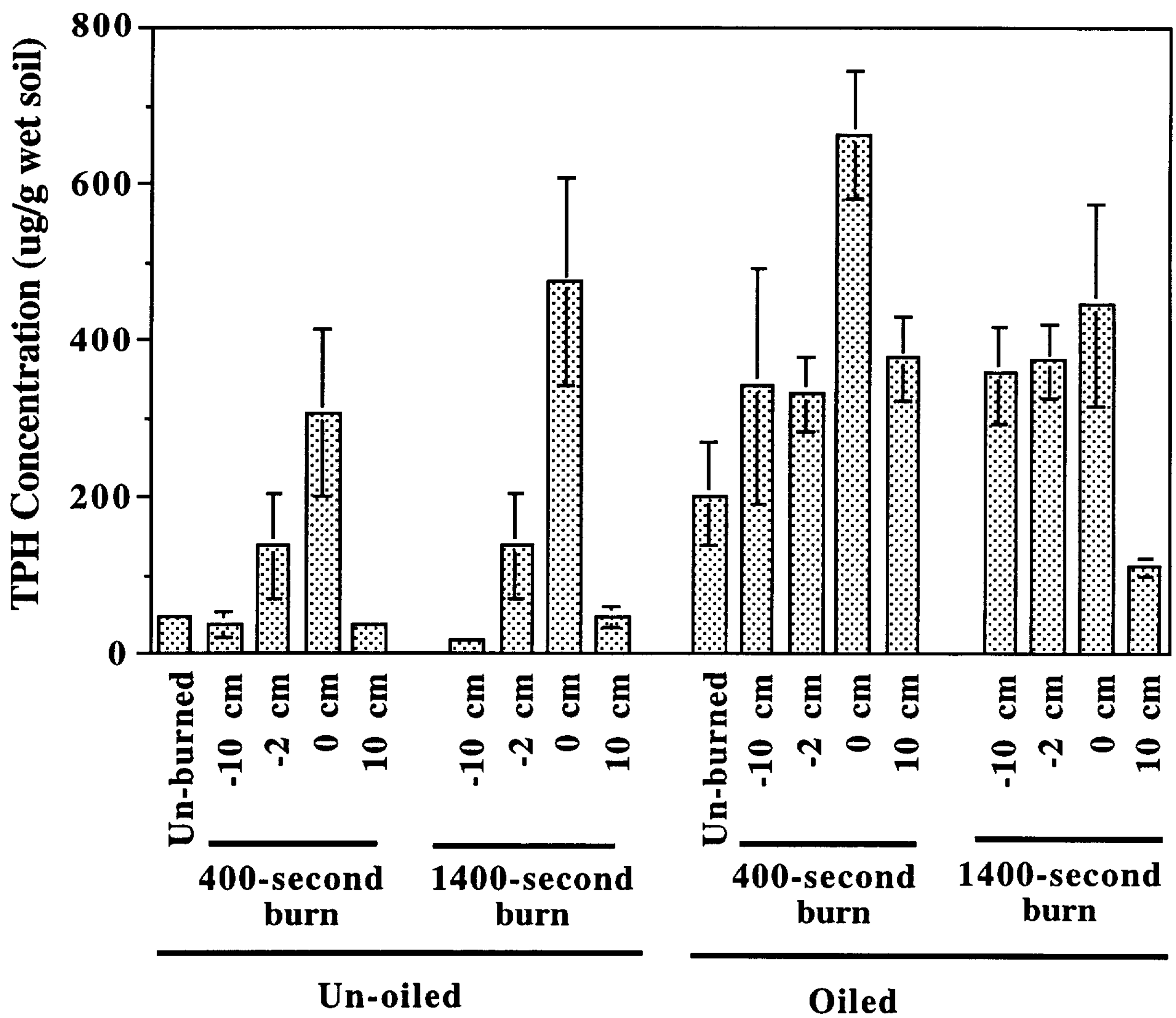

Fig. 6. Effects of burn exposure duration, water table level, and oil application on total petroleum hydrocarbons in the soil 0 to 4 cm below the soil surface one day after the burn. Notation of -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Error bars are standard errors.

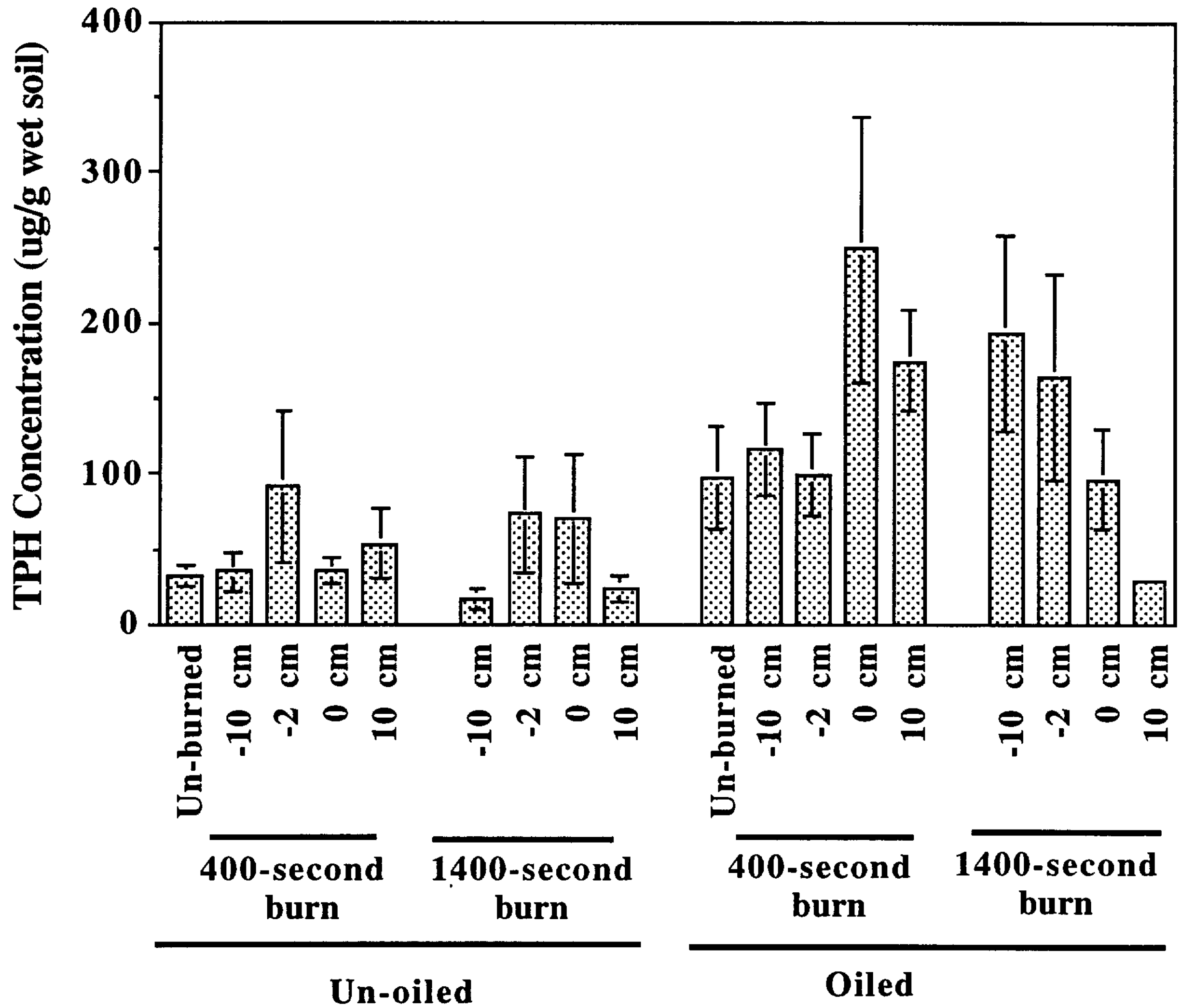

Fig. 7. Effects of burn exposure duration, water table level, and diesel fuel application on total petroleum hydrocarbons in the soil 4 to 8 cm below the soil surface one day after the burn. Notation of -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Error bars are standard errors.

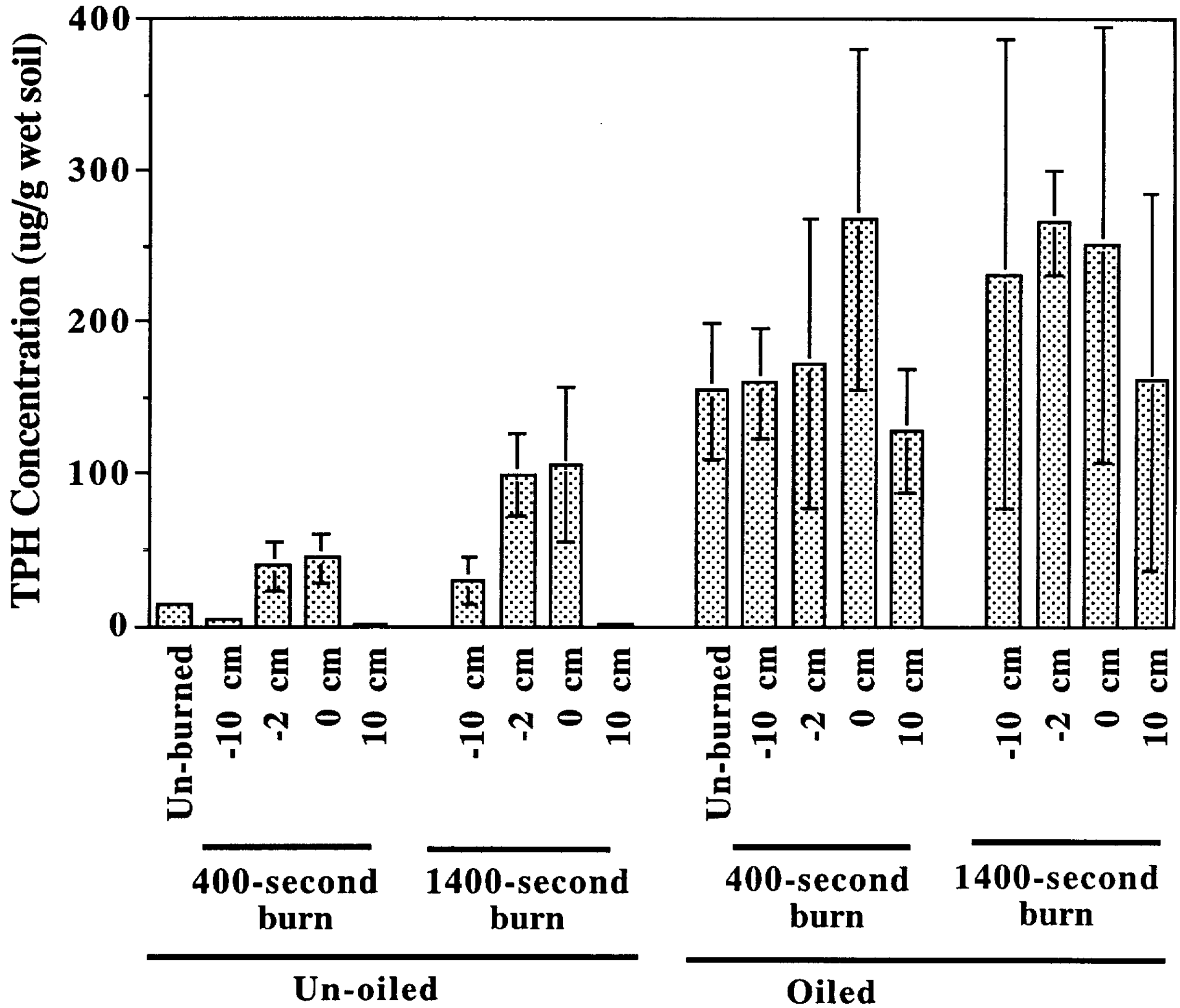

Fig. 8. Effects of burn exposure duration, water table level, and diesel fuel application on total petroleum hydrocarbons in the soil 0 to 4 cm below the soil surface 7 months after the burn. Notation of -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Error bars are standard errors.

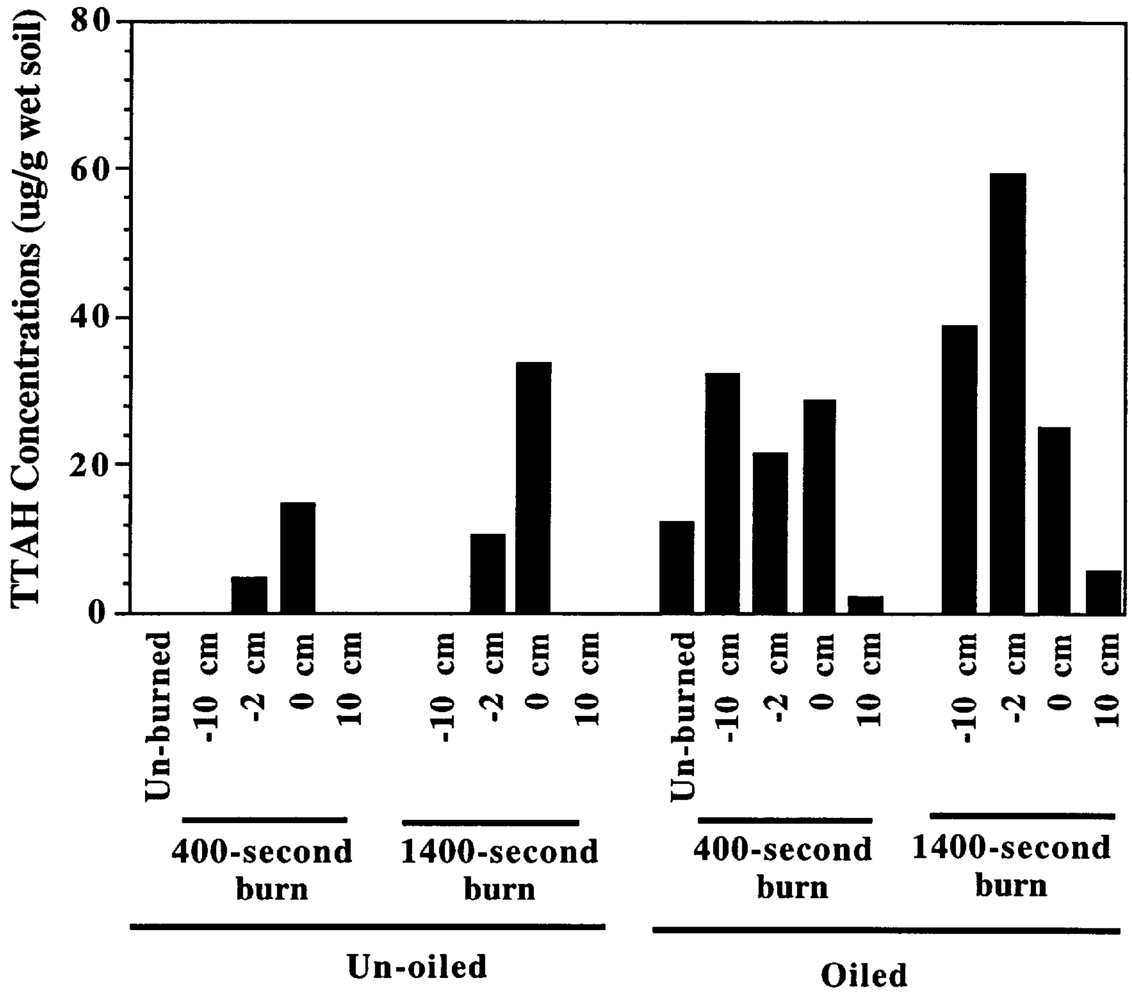

Fig. 9. Effects of burn exposure duration, water table level, and oil application on total targeted aromatic hydrocarbons (TTAH) in the soil 0 to 4 cm below the soil surface one day after the burn. Values are derived from a analysis of five replicates composited. Notation of -10 cm, -2 cm, 0 cm, and 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 residue oil floating on the water surface after burning did not decrease when compared to that in the original diesel fuel before the burn (Table A1). After burning, TTAH concentration was somewhat higher than before the burn (119 percent versus 100 percent) although changes in concentrations varied with individual compounds. However, *in-situ* burning appeared to reduce greatly the thickness and amount of the oil on the water surface. Only a thin layer of residual oil covered a portion of the water surface. Although determining the thickness of residual oil is extremely difficult, it is estimated that the oil layer was less than 1 mm. *In-situ* burning appeared to remove more than 95 percent of the diesel fuel regardless of the original amount of diesel fuel added to the water surface (≥ 18 mm of oil layer initially). Thus, by reducing the total amount of diesel fuel in the marsh environment, *in-situ* burning significantly reduced the total amount of toxic compounds, such as TTAH in the marsh ecosystem.

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 (Figure 10). 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 160 to 700 °C during the 1400 s burn (Figure 10B), and 75 to 370 °C during the 400 s burn (Figure 10A). Average peak soil temperature of the treatment with 0 cm overlying water during the burn was below 80 °C even at soil surface, ranging from 40 to 80 °C at the 0 to 5 cm soil depth, respectively (Figures 10A and 10B). Average peak soil temperature at all soil depths, including at the soil surface, was below 60 °C for the treatment with 2 cm of overlying water. Temperature at all soil depths was below 40 °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 1400 s burn was significantly ($p<0.0001$) higher than that of the 400 s burn at 0, 0.5, 2 and 5 cm soil depths (Figures 10A and 10B). Interestingly, oil application to the soil prior to the burn appeared to affect the soil temperature. Although average peak soil temperature in the treatment with diesel applied to the soil prior to the burn was lower than those without added diesel at the 2 and 5 cm soil depths, the uncertainty which we estimated for soil temperature was –16% to +21% (see Bryner *et al.* 2000) was of the same magnitude as the difference analyzed by statistics. Thus, effect of the applied oil in the soil on soil temperature during the burn cannot be determined in this study.

The relationship between live aboveground biomass of *S. alterniflora* and soil temperature at 0, 0.5, 2, and 5 cm below the soil surface was analyzed to determine the thermal effect on plant recovery after *in-situ* burning. At the 0 cm (Figure A3) and 0.5 cm (Figure A4) soil depths, the soil temperature varied greatly. Most *S. alterniflora* exhibited mortality when the soil temperatures exceeded 55 °C at 0.5 cm soil depth except in one sod where *S. alterniflora* survived soil temperatures as high as 110 °C and 80 °C at 0 and 0.5 cm below the soil surface, respectively (Figures A3 and A4). The soil temperatures at the 2 cm soil depth in most marsh sods were below 70 °C. Generally, *Spartina alterniflora* recovered from temperatures ≤ 50 °C at the 2 cm soil depth. No plants survived at temperature > 60 °C at 2 cm soil depth (Figure 11) and > 40 °C at the 5 cm soil depth (Figure A5).

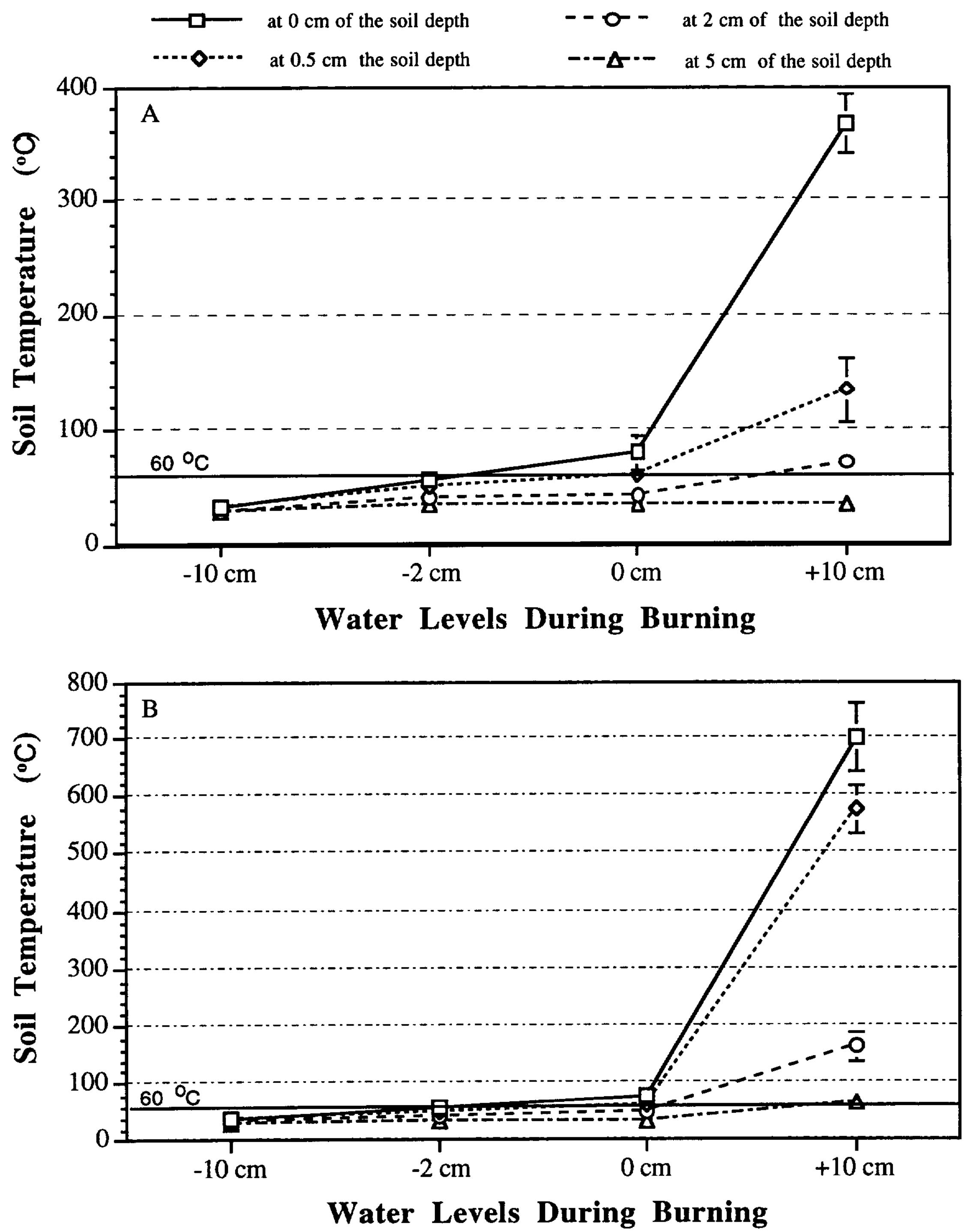

Fig. 10. Average peak soil temperature as a function water level over the soil surface during 400 s (A) and 1400 s (B) burn durations. Notation of -10 cm. -2 cm. 0 cm. and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn.

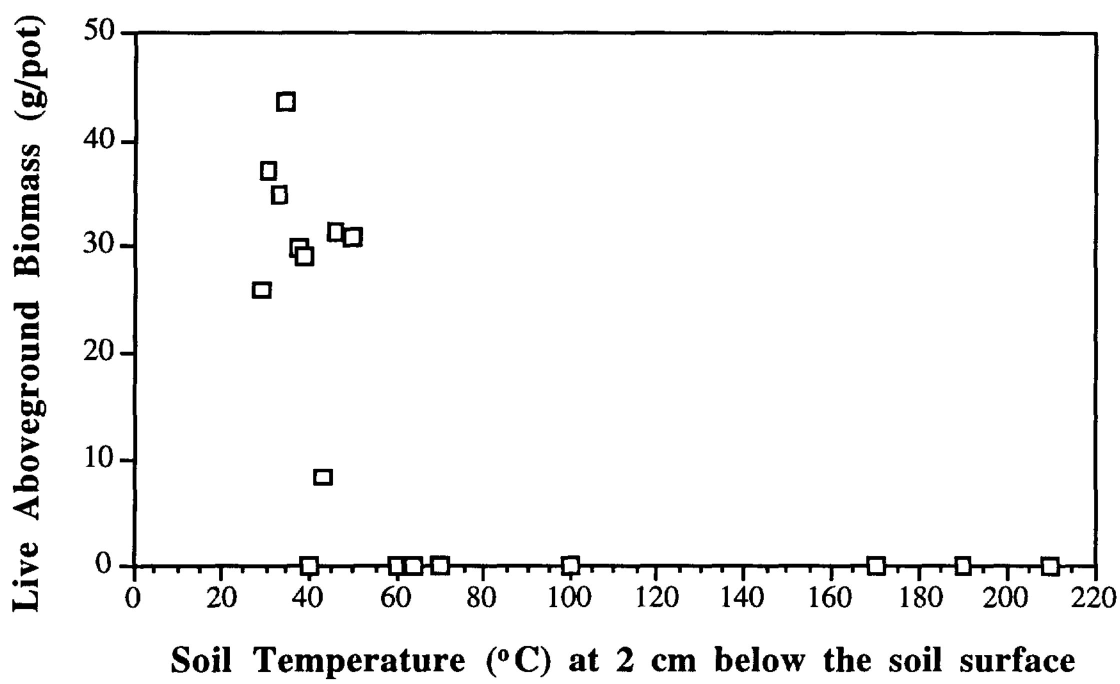

Fig. 11. Relationship between live above-ground biomass produced 7 months after the burn exposure and soil temperature at 2 cm below the soil surface.

DISCUSSION

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

Ten centimeters of water over the soil surface was sufficient to protect the marsh sods from burn impacts. Soil surface temperature 10 cm below the water did not exceed 40 °C for either 400 s or 1400 s 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 greatly reduced when diesel was added to the soil before the burn. The poor recovery in the treatments with 10-cm of overlying water and diesel fuel added to the soil was obviously due to the stress of the added petroleum hydrocarbons prior to the burn. In addition, the degree of diesel penetration into the soil may have been enhanced by the fire as evidenced by higher TPH and TTAH in the treatments with 10 cm of overlying water during the burn than those for unburned treatments receiving diesel.

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

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 400 °C (400 s exposure) to 700 °C (1400 s exposure) at the soil surface and 120 °C at a depth of 2 cm below the soil surface. However, concentration of TPH and TTAH was low at this water level, causing little chemical stress to the marsh plant. Thus, thermal stress on the plants appeared to be the main factor, which resulted in little recovery of *S. alterniflora* even in the absence of diesel fuel addition.

The contamination of sods with the diesel used to create the burn exposure referred to as 'rogue diesel fuel' was likely the primary reason for the high mortality and poor re-growth in the treatments with soil surfaces located at 2 cm and 0 cm below the water level. For these two water level treatments, four access holes, each 1 cm in diameter, were drilled at the water line to allow the water in the marsh sod to equilibrate with the water level in the tank. However, the holes also allowed the rogue diesel fuel to enter the sod containers. This is evidenced by the significantly higher TPH and TTAH concentrations in the 0 and 2 cm water level treatments compared to the control even in the absence of diesel addition to the soils prior to the burn (Figures 7 and 10). Thus, chemical stress induced by the entry of the rogue diesel fuel into containers at the 0 and 2 cm water levels and contamination of these sods likely caused the main stress to the vegetation and played the key role in preventing the post-burn recovery of these marsh sods. However, the marsh sods with soil surfaces 10 cm above the water line, which were too high above the waterline to be contaminated by the rogue diesel fuel, showed poor vegetative recovery due to the thermal stress alone. The chemical stress caused by the oil appeared to play no role in the sods with soil surfaces 10 cm above the water line. For the marsh sods with soil surfaces 10 cm below the water line, the 10 cm water layer separated the floating rogue diesel fuel from the soil surface, thus, minimizing contamination by the rogue diesel.

Research on prescribed burning has also demonstrated that water level during the burn can affect post-burn recovery. Mallik and Wein (1986) found that burning the drained portion of an impoundment resulted in lower plant coverage than the control. However, burning in the flooded portion of the impoundment stimulated plant coverage 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 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, burn exposure with 10 cm of water overlying 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.

Duration of burn exposure affected soil temperatures at depths ≥ 2 cm below the soil surface. Although a 1400 s burn resulted in significantly higher soil temperatures at 2 and 5 cm below the soil surface than a 400 s burn, both burn exposures had similar effects on plant survival and post-burn recovery of marsh vegetation. The soil temperature during a 400 s exposure was high enough to kill *S. alterniflora* when water level was 10 cm below the soil surface. However, soil temperature during a 1400 s exposure was not high enough to affect *S. alterniflora* when water level was 10 cm over the soil surface. In the 0 and 2 cm water level treatments, the concentration of diesel fuel in the soil played a more important role in plant recovery than thermal effects (or burn duration) because of contamination by the 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; 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.

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 of soil is the temperature appropriate to predict lethal effects on plants? In the present study, some *Spartina alterniflora* recovered in sods with the soil temperatures as high as 110 and 80 °C at 0 and 0.5 cm below the soil surface, respectively. Therefore, surface soil temperature (0 and 0.5 cm below the soil surface) may not be appropriate to predict thermal effects on plants. Plant reproductive organs, such as rhizomes, are located below the soil surface. In contrast, soil temperatures 5 cm below the soil surface of sods that exhibited regrowth after burning were < 37 °C, which was not high enough to kill the belowground rhizomes. Furthermore, no *S. alterniflora* recovered at temperatures > 60 °C at the 2 cm depth. In addition, almost all *S. alterniflora* recovered at temperatures < 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, and 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 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. 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 were increase in mass in the smoke. Unfortunately, the 4 and 5 ringed PAHs are likely to be the most carcinogenic, so the trade off is less total PAH, but slightly more of the more harmful PAHs. Thus, in the present study, although concentrations of some hydrocarbon constituents increased, the total mass of diesel was greatly reduced since we estimated that 95% of the floating rogue diesel was consume by fire. Aromatic hydrocarbon release in the smoke was not evaluated.

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

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 was sufficient to protect the marsh soil from burn impacts, with lower soil temperature caused by burning and higher survival rates and live biomass of the plants. In contrast, 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 fuel entry into the sod containers used to create the burn exposure. The high concentration of diesel fuel in the soil at these water levels most likely caused greater plant stress than the thermal stress. The soil temperature at a 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, which further supports the conclusion that chemical stress by diesel on these plants was the primary factor causing 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 did not appear to remediate oil that had penetrated into the soil, it did effectively remove floating oil from the water surface, thus preventing it from potentially contaminating adjacent habitats and penetrating the soil when the water recedes. 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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APPENDIX

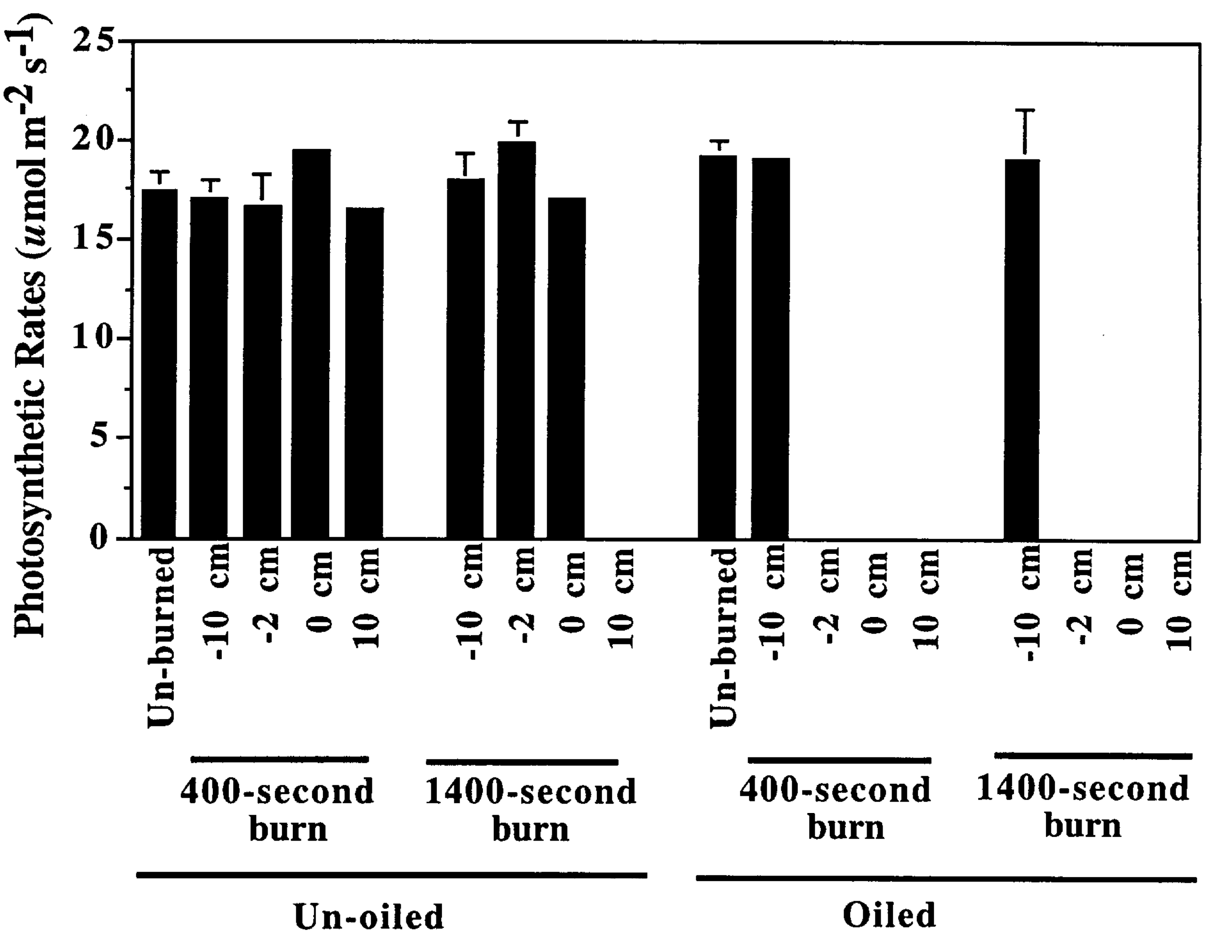

Fig. A1. Effects of burn exposure duration, water table level, and diesel fuel application on the photosynthetic rates of live leaves of *S. alterniflora* 7 months after the burn. Notations of -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Error bars are standard errors.

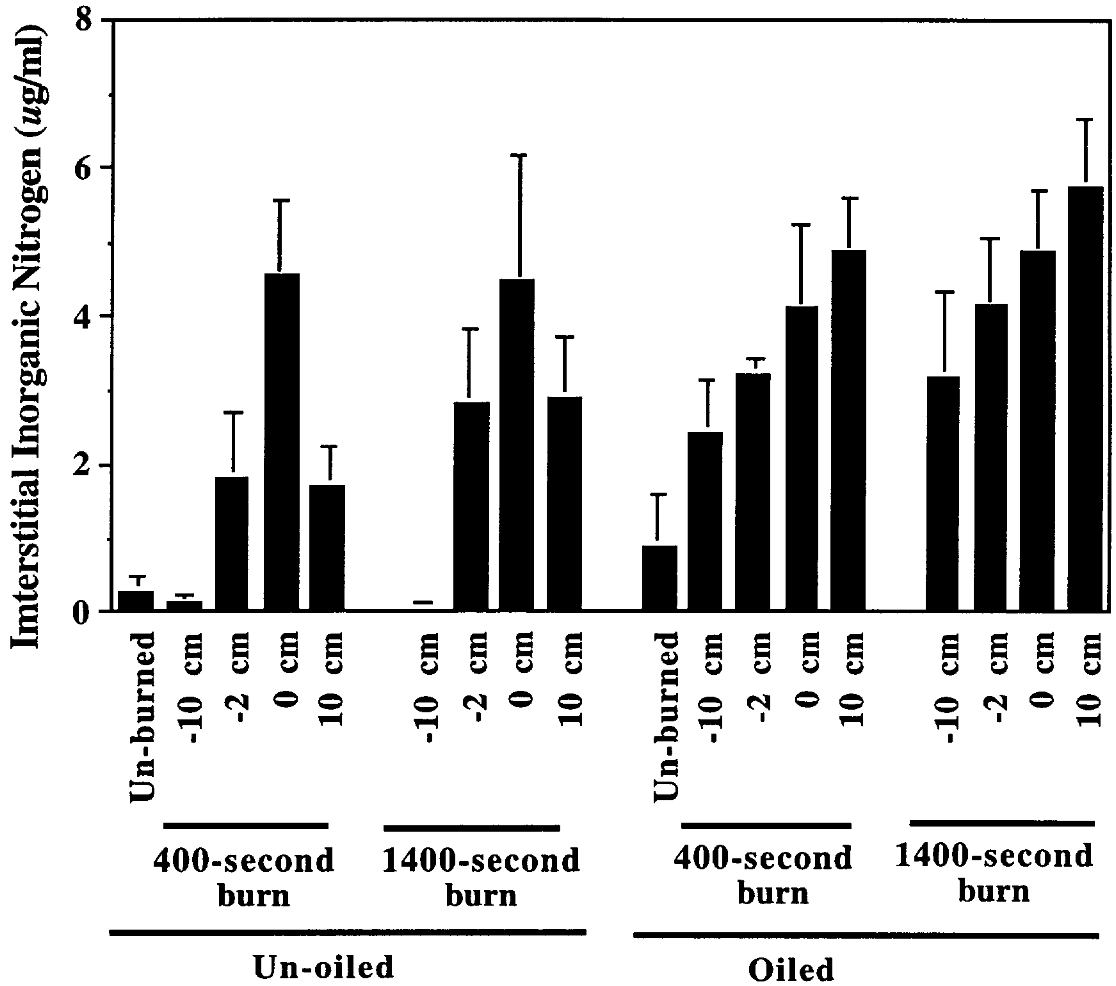

Fig. A2. Effects of burn exposure duration, water table level, and diesel fuel application on the interstitial water nitrogen concentration 7 months after the burn. Notations of -10 cm, -2 cm, 0 cm, and 10 cm represent soil surfaces at -10 cm, -2 cm, 0 cm, and 10 cm relative to the water surface during the burn. Error bars are standard errors.

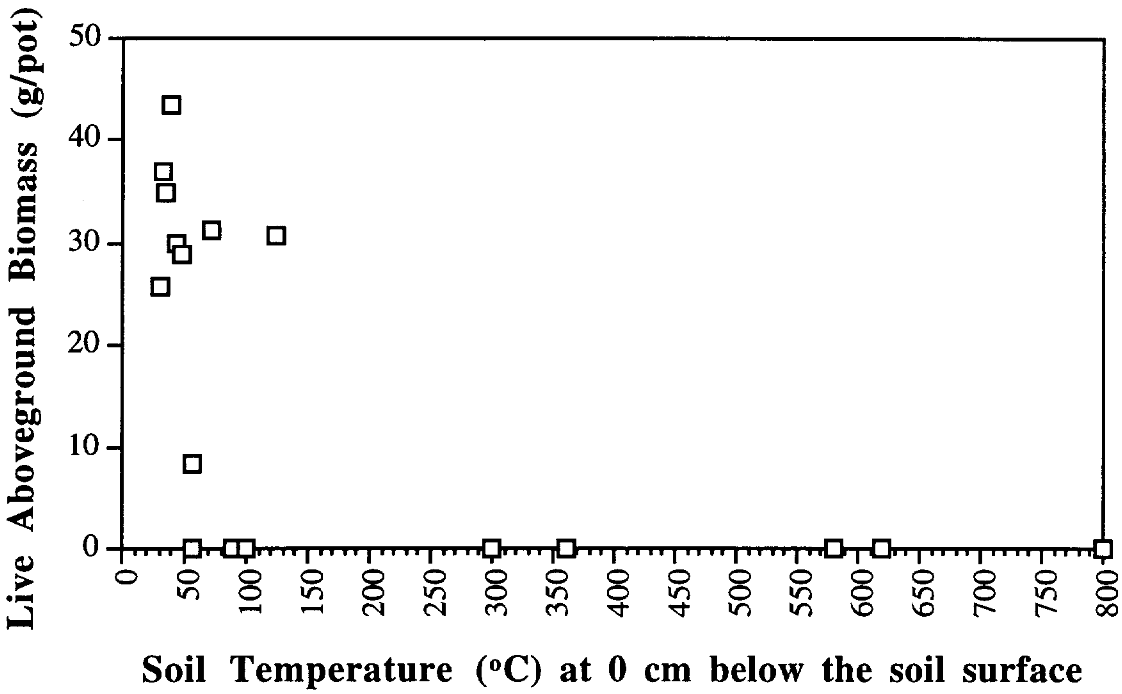

Fig. A3. Relationship between live above-ground biomass produced 7 months after the burn and soil temperature at 0 cm below the soil surface during the burn.

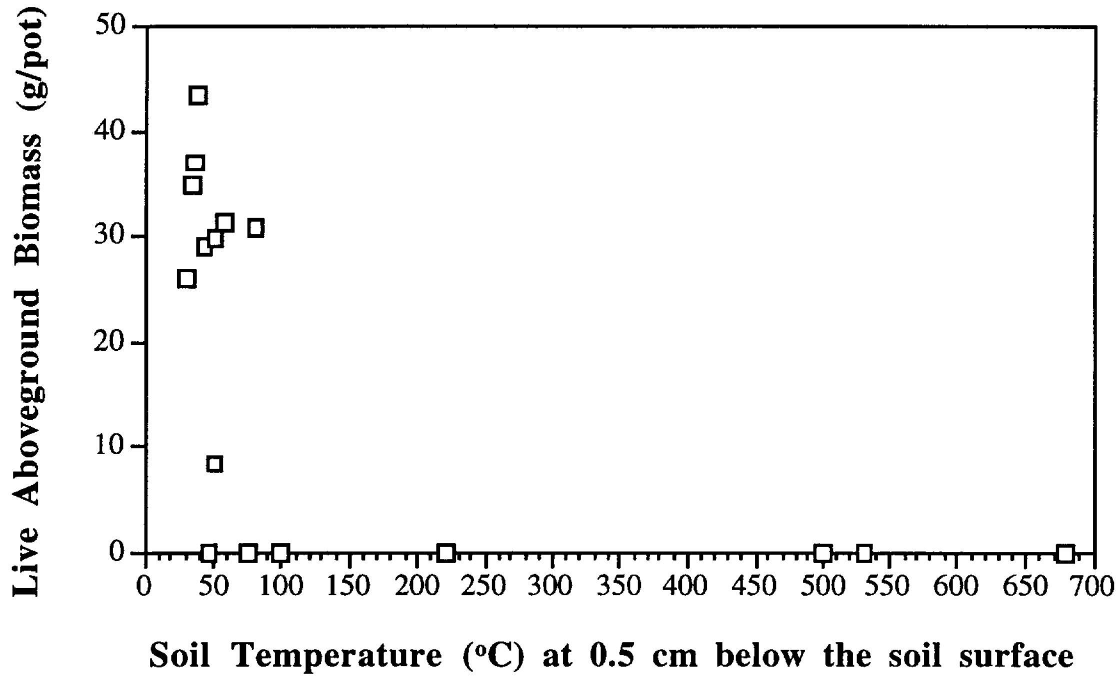

Fig. A4. Relationship between live above-ground biomass produced 7 months after the burn exposure and soil temperature at 0.5 cm below the soil surface during the burn.

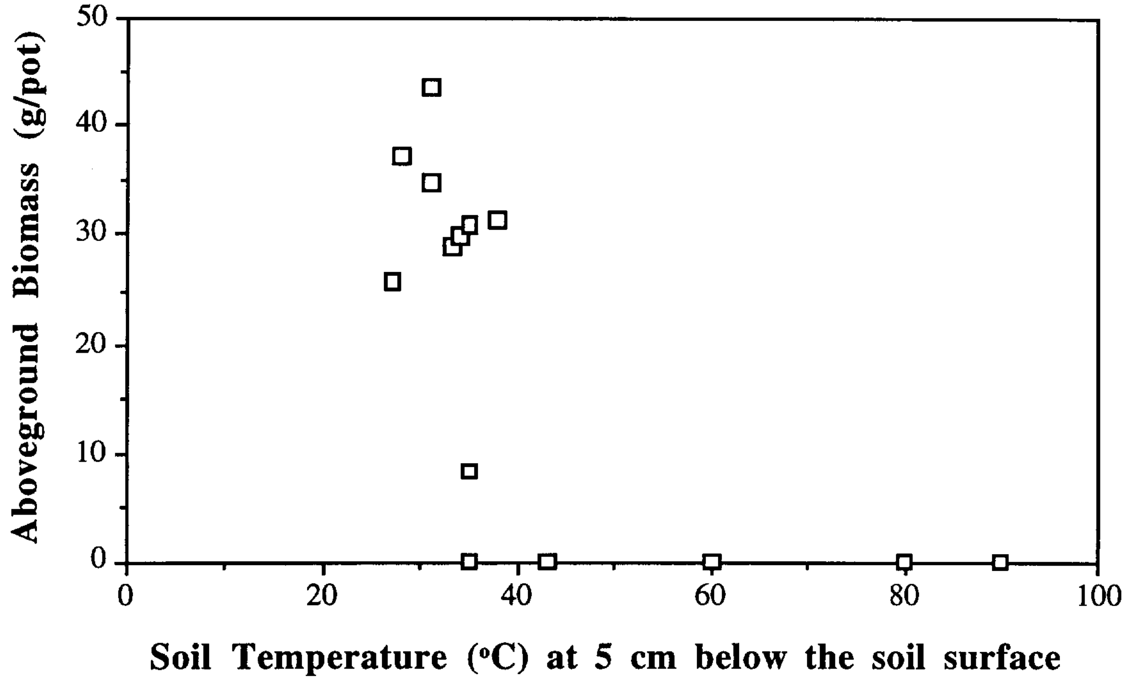

Fig. A5. Relationship between live above-ground biomass produced 7 months after the burn exposure and soil temperature at 5 cm below the soil surface during the burn.

Table A1. Effect of *in-situ* burning on TTAH concentrations in the residue after *in-situ* burning compared to that before burning.

	Before Burn (ug/g)	After Burn (ug/g)
TTAH (sum of all following compounds)	**485.1**	**578.2**
Compounds		
NAPHTHALENE	7.89	2.64
C1-NAPHTHALENE	39.72	7.75
C2-NAPTHALENE	123.40	63.20
C3-NAPTHALENE	98.96	85.38
C4-NAPTHALENE	21.24	33.84
ACENAPHTHYLENE	0.593	4.15
ACENAPHTHENE	3.74	1.90
FLOURENE	15.61	14.92
C1-FLOURENE	19.81	27.07
C2-FLOURENE	24.47	43.88
C3-FLOURENE	14.63	36.96
DIBENZOTHIOPHENE	0	0
C1-DIBENZOTHIOPHENES	2.31	3.28
C2-DIBENZOTHIOPHENES	5.61	12.28
C3-DIBENZOTHIOPHENES	4.19	11.61
PHENANTHRENE	20.42	39.49
C1-PHENANTHRENE	25.86	52.86
C2-PHENANTHRENE	31.86	76.72
C3-PHENANTHRENE	9.83	25.16
C4-PHENANTHRENE	0	0
ANTHRACENE	0	0
o-TERPHENYL	9.61	18.92
FLOURANTHENE	0	1.04
PYRENE	2.83	9.68
C1-PYRENE	1.15	3.56
C2-PYRENE	0	0
C3-PYRENE	0	0
C4-PYRENE	0	0
BENZ (a) ANTHRACENE-d12	0	0
BENZO (a) ANTHRACENE	1.29	1.85
CHRYSENE	0	0
C1-CHRYSENE	0	0
C2-CHRYSENE	0	0
C3-CHRYSENE	0	0
C4-CHRYSENE	0	0
BENZO (b) FLOURANTHENE	0	0
BENZO (k) FLOURANTHENE	0	0
BENZO (e) PYRENE	0	0
BENZO (a) PYRENE	0	0
PERYLENE	0	0
INDENO (1.2.3 - cd) PYRENE	0	0
DIBENZO (a.h) ANTHRACENE	0	0
BENZO (g.h.i) PERYLENE	0	0