In-Situ **Oil Burning in the Marshland Environment - Recovery and Regrowth of** ***Spartina alterniflora, Spartina patens*****, and** ***Sagittaria lancifolia*** **Plants**

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Abstract

In a series of *in-situ* burns involving 330 plant mesocosms, including *Spartina alterniflora*, *Spartina patens*, *Distichlis spicata,* and *Sagittaria lancifolia* sods, were exposed to burning diesel fuel or crude oil. Oil spilled in sensitive wetlands pose unique problems associated with cleanup because mechanical recovery in a marsh may result in more damage to the wetland than the oil itself. *In-situ* burning of oiled wetlands may provide a less damaging alternative than traditional mechanical recovery. After exposure to burning fuel for either 400 s, 700 s or 1400 s, the plants were returned to a greenhouse where the recovery and regrowth of the plants were monitored.

One-third of the plants were instrumented with thermocouples to monitor the soil temperatures at different soil depths. Before each burn, the soil lines of the plant mesocosms were positioned at different elevations: +10 cm, +2 cm, 0 cm, -2 cm, and -10 cm relative to the water level. The water depth over the soil surface during *in-situ* burning was a key factor controlling marsh-plant recovery. Ten and two centimeters of water overlying the soil surface were sufficient to protect marsh vegetation of all 3 types of marshes from burning impacts. Soil surface temperatures did not exceed 50 °C and 70 °C for 10 and 2 centimeters of water overlying the soil surface, respectively. Plant survival rate was 100 %, and growth responses after the burn with 10 and 2 cm of water over the soil surface was not significantly different from the unburned control. In contrast, a water table 2 cm below the soil surface (+ 2 cm of soil exposure to the fire) during the burn resulted in high soil temperatures, with 70 °C to 103 °C at 0 to 0.5 cm below the soil surface. The effect of thermal stress on plant survival differed with species at 2 cm of water over the soil surface. Two centimeters of soil exposure impeded the post-burn recovery of the salt marsh grass, *S. alterniflora*, and fresh marsh species, *S. lancifolia*. However, 2 cm of soil exposure during *in-situ* burning did not detrimentally affect the post-burn recovery of the brackish marsh grasses, *S. patens* and *D. spicata*.

1.0 Introduction

Wetland ecosystems are considered among the most valuable, as well as the most fragile, of natural systems (Costanza et al. 1998). Oil pollution from pipeline ruptures, tanker accidents, exploration and production blowouts poses a serious risk to the health of wetland systems. The cleanup of oil spills in the wetland environment is problematic and can do more damage than the oil itself (McCauley and Harrel 1981; DeLaune et al. 1984; Kiesling et al. 1988). None-the-less, it is often essential to remove spilled oil before it spreads to other habitats and to adjacent water bodies. Furthermore, it is important to develop less intrusive oil spill cleanup procedures that exert little to no long term impact to the wetland system. A cleanup technique that is compatible with the wetland environment and is consistent with present wetland management procedures would be highly valued.

In-situ burning or intentional burning of spilled oil at the site of the oil release offers the spill response community an alternative that may avoid much of the damage caused by mechanical reclamation while still removing most of the oil from the marshland environment and preventing the spread of the oil to environmentally sensitive areas. The initial spill has already imposed a chemical toxicity or stress on the wetland ecosystem. The intentional burning of spilled hydrocarbons introduces another insult; the fire or thermal stress of an *in-situ* burn. For example, if the soil temperatures exceed 60 EC, most plants would suffer permanent damage (Byram 1948, Levitt 1980, and Ahlgren 1974), but water levels within the marsh could provide significant protection against the thermal stress of an *in-situ* burn. The impact of these two stresses, fire and chemical, on plant regrowth and recovery needs to be more fully characterized and understood before *in-situ* burning can be widely implemented as an oil spill remediation technique.

In a series of 10 burns in 1999 and 11 burns in 2000 , twenty-one full-scale *in-situ* burn experiments were utilized to simulate the thermal and chemical stresses which marshland plants experience during *in-situ* burning of oil spills (Bryner *et al*. 2000 and 2001; Lin *et al.* 2002). Marsh sods were collected from a *Spartina alterniflora* dominated salt marsh, a *Spartina patens* and *Distichlis spicata* co-dominated brackish marsh, and a *Sagittaria lancifolia* dominated fresh marsh in southeast Louisiana. A total of 332 plant sods were included in two series of full-scale experiments that exposed 264 plant sods to burning hydrocarbon fuel, either diesel fuel or crude oil. The duration of the *in-situ* burn exposure ranged from 400 s to 1400 s. Individual plant mesocosms were instrumented with thermocouples to track soil temperatures throughout each burn. Some of the plant sods were "pre-oiled" with small amounts of diesel fuel or crude oil to simulate exposure to the spilled oil before the arrival of oil spill response teams. Plant specimens were positioned at different elevations, +10 cm, + 2 cm, 0 cm, -2 cm, and -10 cm. After exposure to burning fuel, plant mesocosms were returned to greenhouses where the regrowth and recovery of the specimens could be carefully monitored for up to a year.

The overall goal of these burns was to characterize and understand the relationship between the fire dynamics of an *in-situ* burn and the ecological impact and recovery of the marshland system. This study collected data from two series of burn experiments and uses the results to describe how the regrowth and recovery of marsh-plants are effected by 1) soil, water, and air temperatures, 2) different soil line elevations, 3) levels of thermal exposure from different fuels, 4) response of different plant species, and 5) pre-burn oil exposure. This report will focus on linking the soil temperatures that were experienced by the plant sods during a simulated *in-situ* burn to the subsequent regrowth and recovery of plants from salt, brackish, and freshwater marshlands.

2.0 Experimental Apparatus and Procedure

Two hundred and sixty-four marsh-plant sods were exposed to the combined chemical and thermal insult that marsh-plants would encounter during an *in-situ* burn. An additional 68 mesocosms that were not exposed to the *in-situ* burn were used as controls. In a 6 m diameter burn tank, plant sods were positioned at five elevations ranging from +10 cm to -10 cm relative to the water level. These different water level/ soil elevations were designed to mimic the natural variation in water level /soil heights in a salt marsh. One hundred and four specimens were pre-oiled with either diesel fuel or crude oil to simulate exposure to spilled oil before spill response team initiates clean-up or an *in-situ* burn. Ninety-seven of the plant specimens were instrumented with thermocouples arrays that were inserted into the soil in order to monitor soil temperature. Water and air temperature as well as total heat flux above the water surface were also recorded. More detailed descriptions of the experimental apparatus and procedure were included in Bryner *et al.* (2000 and 2001).

2.1 *In-Situ* Burn Exposure

In-situ burning of an oil spill in wetlands was simulated by igniting and subsequently burning a 1.8 cm thick layer of diesel fuel or crude oil. After each group of plants was positioned in the burn tank, the tank was filled to a depth of 71 cm with fresh water (Figures 1 and 2). An initial charge of fuel (either diesel fuel or crude oil) was floated on the surface of the water and ignited (Figures 3, 4 and 5). For burns greater than 400 s, fresh fuel was added throughout the burn to achieve the desired burn exposure of 700 s or 1400 s. Once ignited, the diesel fuel or crude oil was allowed to burn until it extinguished itself.

Each burn in this series was conducted in the 6 m diameter round tank facility at the Fire and Emergency Training Institute at Louisiana State University (LSU). Within this tank, each plant sod was positioned on a plant support stand that allowed the elevation of the specimen to be adjusted (Figures 1 and 2). Each stand supported one of the plant specimens at either - 10 cm , - 2 cm, 0 cm, + 2 cm, and + 10 cm relative to the surface of the water. After being transported from the greenhouses to the burn tank, plant specimens were arranged in concentric circles in order to provide uniform exposure to all plant specimens. Each plant was placed on its assigned stand, adjusted to the proper elevation, and then leveled. A "0 cm" plant was placed so that the soil line was at the surface of the water within the burn tank. A +10 cm plant elevation positioned the soil line 10 cm above the water surface while a -10 cm location placed the soil line 10 cm below the water surface.

2.2 Plant Specimens

Three-hundred thirty-two marsh specimens were collected from a *Spartina alterniflora* dominated salt marsh, a *Spartina patens* and *Distichlis spicata* co-dominated brackish marsh, and a *Sagittaria lancifolia* dominated fresh marsh in southeast Louisiana. In the first series of burns, 100 sods, 80 specimens to burn and 20 specimens for controls, were collected from a *Spartina alterniflora* dominated

Figure 1. The 6 m Burn Tank, Containing Salt and Brackish Marsh Sods With Soil Surface at Different Elevations, Was Filled With Water Before the Burn.

Figure 2. Fine Adjustment of the Soil Surface of the Sods to –10 cm, -2 cm, and +2 cm Relative to the Water Surface in the 6 m Burn Tank Was Conducted Before the Burn.

Figure 3. Diesel Fuel Was Added to the 6 m Burn Tank Before the Burn.

Figure 4. The Fire Intensity in the Burn Tank Was Similar to That of an *In-Situ* Burn in the Field.

Figure 5. Most Diesel Fuel Was Consumed by the Fire After a 700 s Burn.

intertidal salt marsh in southeast Louisiana. In the second set , 232 specimens, 91 *S. alterniflora*, 99 *S. patens and D. spicata*, and 42 *S. lancifolia* sods, were collected from three separate locations in southeast Louisiana. After collecting a 30 cm diameter and 30 cm deep section, each specimen was placed into a 20 liter (five gallon) container and transported to LSU greenhouses. Each plant specimen was assigned a unique number and randomly assigned to different elevations, specific burns, and whether or not to be pre-oiled. The specimens were collected in early July and transferred to the LSU greenhouses. Sods were exposed to *in-situ* burns in late August of each year during each test series.

Control sods were included for burn / no burn, oil / no oil, and cut / no cut for *S. alterniflora*, *D. spicata* and *S. patens* species. *S. lancifolia* sods were included as burn / no burn and oil / no oil control sods. The burn / no burn and oil / no oil controls were used in assessing the impact of thermal and chemical stress, respectively. The cut / no cut controls were included to examine the effect of a sod's foliage being burned off during exposure to an *in-situ* burn. The foliage of each "cut" control was manually trimmed so that it's regrowth and recovery could be compared to plant sods "trimmed" by exposure to an *in-situ* burn.

In order to simulate the exposure to spilled oil before a remediation team might arrive, sods were oiled 24 hours before being exposed to *in-situ* burning. Pre-oiling was implemented at the rate of 1.5 l/m^2 for the first series of 10 burns and 0.5 l/m^2 for the second set of 11 experiments. Twenty-four hours before thermal exposure, the water within the container was increased to a point above the soil and the required volume of diesel fuel or crude oil was added to the surface of the water. After the oil dispersed evenly across the water surface, the water level was dropped to approximately 15 cm below the soil surface. After allowing the oil to intermingle with the soil for about eight hours, the water within the sod was returned to the level that existed before oiling was initiated.

2.3 Soil Instrumentation

After several weeks of acclimatization in the greenhouses, ninety-seven of the plant specimens were instrumented with thermocouple arrays in order to track the temperature gradients within the soil. Specimens were instrumented with the arrays consisting of either four or eight thermocouples. An eight thermocouple array consisted of thermocouples positioned at (0, - 0.5, -1, - 2, - 3, - 5, - 7, and - 10) cm below the soil line while a four thermocouple array featured thermocouples at (0, - 0.5, - 2, and - 5) cm. Stainless steel sheathed (0.16 cm diameter) grounded Chromel-Alumel[1] thermocouples were used for the top three positions, (0, - 0.5, and -1.0) cm, and top two locations, (0 and -0.5)cm, of each eight and four thermocouple array, respectively. The lower thermocouples were fabricated using 0.05 cm diameter (24 gauge) Chromel-Alumel wire with FPA Teflon insulation with a 0.09 cm diameter bead. The array was arranged so that the tips of the thermocouples were positioned vertically near the centerline of the bucket.

2.4 Water and Air Temperatures and Total Heat Flux

Two additional arrays of seven thermocouples and four total heat flux gauges were mounted within the burn tank. Thermocouples monitored the temperature of air or combustion products at + 10 cm and + 20 cm above water surface. The water temperature was recorded at (0, - 0.5, - 2, - 5, and - 10) cm. A water-cooled Schmidt-Boelter total heat flux gauge was located near each air/water thermocouple arrays. Two of the gauges were oriented parallel to the water surface and were monitoring thermal fluxes across the pool of burning fuel. The other two gauges were positioned perpendicular (facing upwards) to track the thermal radiation that the fire was radiating to the surface of the pool of burning fuel. Soil, water, and air temperatures and total heat flux measurements were collected at 5 second intervals using Model CR7 Datalogger (Campbell Scientific, Inc. Logan, UT).

2.5 Plant Regrowth and Recovery Evaluation Procedures

After the burns (Figure 6), the mesocosms were returned to the greenhouse where plant regrowth was assessed by measuring plant survival rate and stem density of plants regenerated during the post-burn monitoring (Figure 7). In addition to monitoring plant recovery, samples of soil and fuel were collected before and samples of soil and residue after each burn. Total petroleum hydrocarbon (TPH) analysis by gas chromatography with flame ionization detection (GC/FID) was done on each soil sample. Each sample of unburned fuel and burn residue was analyzed

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[1]* Certain trade names and company products are mentioned in the text or identified in an illustration in order to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

Figure 6. Burned Marsh Sods Were Held in the Greenhouse to Evaluate the Treatment Effects on Vegetation Recovery. Most Aboveground Biomass of the Marsh-plants Was Consumed by the Fire During the *In-Situ* Burns.

Figure 7. Vegetation Recovery Was Apparent 40 Days After *In-Situ* Burning.

by gas chromatography with mass spectrometry (GC/MS) detection to confirm and expand the GC/FID results. The soil, fuel, and residue analysis from the first series of *in-situ* burns is described in more detail in Lin *et al.* (2002).

Stem density was determined by counting the number of stems of each species in each experimental unit. Also, percent sod survival was determined as the number of the experimental units having regenerated dominant plant species divided by the total number of experimental units per treatment level (4 sods) times 100%.

Statistical analysis was conducted with the Statistical Analysis System (SAS 1989). Plant parameters, total petroleum hydrocarbons, and soil temperature were analyzed with general linear models (GLM). Duncan's test (SAS, 1989) was used to evaluate statistical differences of the main factors when no interaction occurred. The least square means test was used to evaluate statistical differences between treatment-level combinations when interaction occurred. Significant differences were reported at the 0.05 probability level, unless otherwise stated.

3.0 Results

For each of the 21 *in-situ* burns, soil temperatures were monitored in approximately one-third of the sods that were exposed to burning oil. Temperature plots for individual soil thermocouples for different soil depths, as a function of type of fuel and burn duration have been reported by Bryner *et al.* (2000 and 2001). After exposure to the burning oil, plant specimens were monitored for up to a year in order to track post-burn stem density and sod survival. The regrowth and recovery of *S. alterniflora* plant mesocosms from the first 10 burns conducted in 1999 which burned only diesel fuel were discussed by Lin *et al.* (2002a). For the second series of 11 burns completed in 2000 that involved both crude oil and diesel fuel, the regrowth and recovery of *S. alterniflora*, *S. patens* and *D. spicata*, and a *S. lancifolia* as well as soil and oil chemistry are described in more detail in Lin *et al.* (2002b).

3.1 Soil Temperatures

Soil temperatures for each of the 21 burns are summarized in Table 1. As a function of fuel, either diesel fuel or crude oil, and burn duration, the average and range of the peak soil temperature and the estimated depth of the 60 EC have been tabulated. The peak soil temperature was the maximum temperature reported by any of the soil thermocouples. The peak temperatures that were recorded from multiple sods of different species, but all located at the same elevation, were included in the range of peak temperatures. The temperature values at each plant elevation, burn duration, and fuel type were averaged to obtain the average peak temperature tabulated in Table 1.

Each thermocouple array also provided a vertical profile of temperature in the soil. The depth of the 60 EC isotherm was estimated by observing the highest thermocouple which did not exceed 60 EC during or after the burn. The 60 EC isotherm was selected since Byram (1948); Ahlgren (1974); and Levitt (1980) all cite lethal temperatures for most vascular plants in the range of 60 °C to 65 °C . For each test burn, the depth of this thermocouple was recorded as the estimated depth of the 60 EC isotherm. Interpolation was not used to estimate the relative location of the isotherm between two thermocouple locations. For example if the - 2.0 cm thermocouple registered a peak temperature 70 EC and the - 3.0 cm thermocouple recorded 50 EC , the 60 EC was estimated to be at the -3.0 cm depth. This method provides a conservative estimate for the 60 EC isotherm. These isotherm depths that were estimated for multiple plants of different species, but all located at the same elevation, were included in the range of 60 EC isotherm depths. Depth values at each plant elevation, burn duration, and fuel type were averaged to obtain the average 60 EC isotherm depths in Table 1.

Table 1 . Average Peak Soil Temperatures and Estimated Depth of 60 EC .

Plant Elevation	Average Burn Duration s	Peak Soil Temperature		Estimated 60 EC Isotherm**	
		Average * E C	Range E C	Average Depth cm	Range Of Depths cm
Diesel Fuel					
- 10 cm	400	34	31 to 36	0	0
	770	34	32 to 36	0	0
	1400	43	35 to 50	0	0
- 2 cm	400	57	47 to 68	-0.13	-0.5 to 0
	770	46	32 to 66	0	0 to -0.5
	1400	59	51 to 70	-0.13	-0.5 to 0
0 cm	400	66	64 to 70	-0.75	-2 to 0
	1400	72	58 to 90	-1.4	-3 to 0
+ 2 cm	770	91	71 to 103	- 1.5	-0.5 to -2
+ 10 cm	400	360	300 to 400	-3.0	-5 to -2
	1400	700	580 to 800	-6.3	-7 to -5
Crude Oil					
- 10 cm	660	34	32 to 35	0	0
- 2 cm	660	57	36 to 62	0	0 to -0.5
+ 2 cm	660	95	74 to 100	-2	-0.5 to -3

Notes:
* Average Peak Soil Temperature - peak temperature recorded at soil surface thermocouple. Values from all plant specimens at each plant elevation averaged.
** 60 EC Isotherm - depth in soil where temperature which did not exceed 60 EC during or after (90 minutes) burn exposure.

The soil temperature profiles demonstrates that *in-situ* burns of both diesel and crude oil produce similar vertical temperature profiles in the soil of the plant mesocosms. The soil temperature data also demonstrate that 10 cm of water above the soil line prevents the soil temperature from exceeding 60 EC for 400 s, 700 s, and 1400 s burn exposures. Two centimeters of water provides sufficient protection to limit the peak soil temperature to less than 70 EC with the 60 EC isotherm estimated at depth of 0.5 cm. When the soil line was 2 cm above the water surface, peak soil temperatures were significantly higher than 60 EC and exceeded 100 EC in several sods. Without water overlying the soil, the 60 EC isotherm was estimated to reach between 2 cm and 3 cm below the soil surface. The highest temperatures were recorded for plant sods that were 10 cm above the water surface. Peak soil temperatures of 400 EC and 800 EC were observed during the 400 s and 1000 s burn exposures, respectively.

3.2 Post-Burn Regrowth and Recovery of Marsh-plants

The regrowth and recovery data for plants will be presented in two sections. The first section will include the plant regeneration from the first 10 *in-situ* burns where *S. alterniflora* was exposed to burning diesel fuel. The second section will present data from the second 11 *in-situ* experiments which exposed *S. alterniflora*, *S. patens*, *D. spicata*, and a *S. lancifolia* sods to diesel fuel and crude oil fires.

3.2.1 *S. alterniflora* Plants Exposed to Diesel Fuel Burns

Recovery of the salt marsh grass, *S. alterniflora* after exposure to *in-situ* burning mainly depended upon the depth of water over the soil surface. In the absence of pre-oiling of the sods, percent survival of the experimental units after *in-situ* burning was 100 percent with 10 cm of water over the soil surface (-10 cm soil elevation) regardless of burn duration (400 s versus 1400 s, Figure 8). Sod survival was also determined 7 months after the burn, but it was not different than for the 4 month survival. Sod survival decreased with increasing soil exposure.

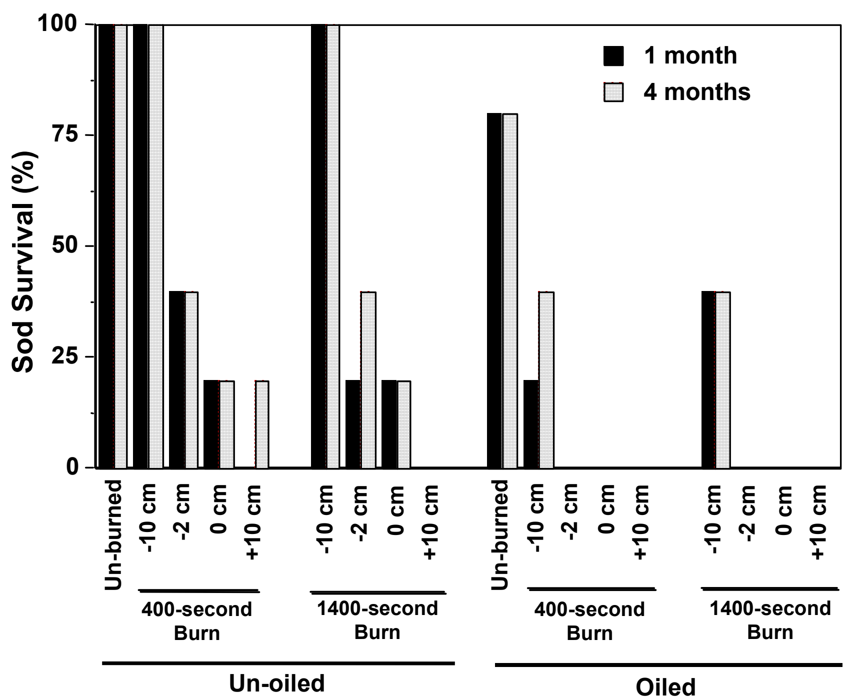


Figure 8. Effects of Burn (Diesel Fuel) Exposure Duration , Soil Elevation, and Pre-Oiling (Diesel Fuel) on Percentage of Sods Exhibiting Post-Burn Regrowth.

No experimental units survived after a 1400 s burn with 10 cm of soil exposure. When sods were pre-oiled with diesel, percentage survival was much lower than in the absence of diesel fuel (Figure 8). 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 *S. alterniflora* re-grown after the burn (Figure 9) 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 pre-oiling the specimens, 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 used to pre-oil the soil, stem density was significantly lower than in the absence of diesel, regardless of water level (Figure 9). 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.

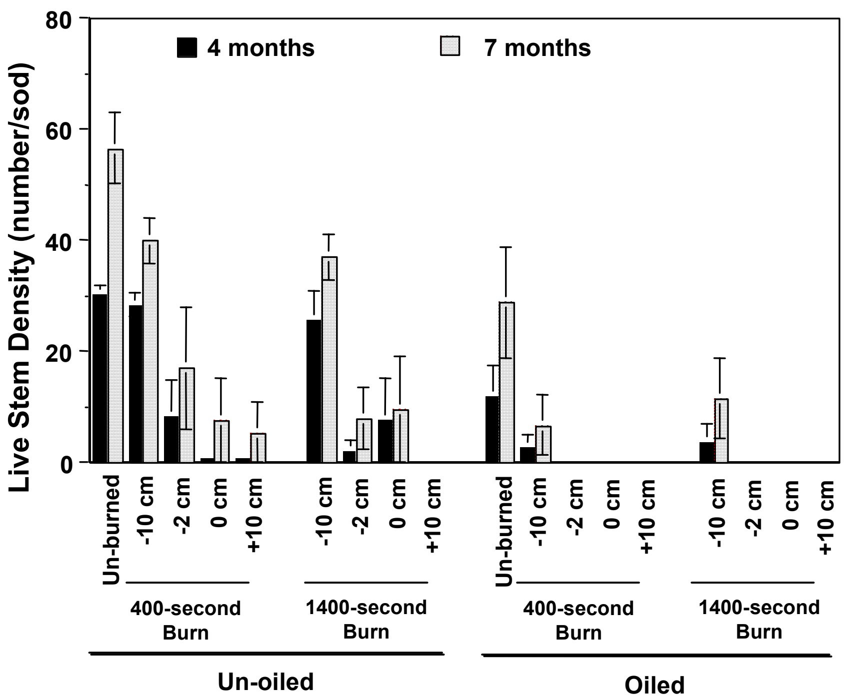


Figure 9. Effects of Burn (Diesel Fuel) Exposure Duration, Soil Elevation, and Pre-Oiling (Diesel Fuel) on Live Stem Density 4 and 7 months after the burn. Error bars are standard errors.

No stems re-grew after the burn exposure in the lower water level treatments (less than 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).

3.2.2 ***S. alterniflora, S. patens, D. spicata,*** **and** ***S. lancifolia*** **Plants Exposed to Diesel Fuel and Crude Oil** ***In-Situ*** **Burns**

Recovery of marsh-plants to *in-situ* burning mainly depended upon the depth of water over the soil surface during the burn and the plant species. Percent survival of the experimental units (marsh sods) after *in-situ* burning was 100% with 10 cm and 2 cm of water over the soil surface (Figure 10). Values were averaged over oil applica-tion and burn type. Sod survival decreased at + 2 cm soil elevation *for S. alterniflora* and *S. lancifolia*, but not for *S. patens* and *D. spicata*. A 30 % decrease in survival resulted for *S. alterniflora* and 50% for *S. lancifolia.*

The effect of *in-situ* burning on stem densities regenerated after the burn varied with marsh-plant species and water depth over the soil surface during burning. For *S. alterniflora*, water depth over the soil surface during burning significantly ($p<0.0001$) affected growth of new stems after the burn (Figure 11). Stem density of *S. alterniflora* was significantly lower at the treatment with + 2 cm soil elevation than the control, while stem densities of the treatments with -10 and - 2 cm soil elevations with 10 cm and 2 cm, respectively, of water overlying the soil surface were not significantly different from the control. Oil addition before the burn and burning type (crude vs. diesel) did not significantly affect the stem density of *S. alterniflora*. Oil addition before the burn and burning type (crude vs. diesel) did not significantly affect the stem density of *S. alterniflora*. For the brackish marsh co-dominated by *S. patens* and *D. spicata*, the effect of water depth over the soil surface during the burn depended upon the plant species (Figure 12). Stem density of *S. patens* was significantly lower at the treatment with + 2 cm soil elevation than the control while the stem densities of the treatments with –10 cm and -2 cm soil elevations were not significantly different from the control. However, water depth over the soil surface during burning did not significantly affect the stem density of *D. spicata* (Figure 13). Oil addition before the burn and burning type (crude vs. diesel) did not significantly affect the stem densities of *S. patens* and *D. spicata*. Although the fresh marsh was dominated by *S. lancifolia*, it also contained several other species. The effect of water depth over the soil surface during the burn also depended upon the plant species. Stem density of *S. lancifolia* (Figure 13A) and *Eleochlis spp.* (Figure 13B) was significantly lower in the treatment with + 2 cm soil elevation than the control while the stem densities of the treatments with -10 cm and -2 cm soil elevations were not significantly different from the control (unburned).

3.3 Uncertainty Analysis

There are different components of uncertainty in the temperatures, plant elevation, stem density, and percent survival data reported here. Uncertainties are grouped into two categories according to the method used to estimate them. Type A uncertainties are those which are evaluated by statistical

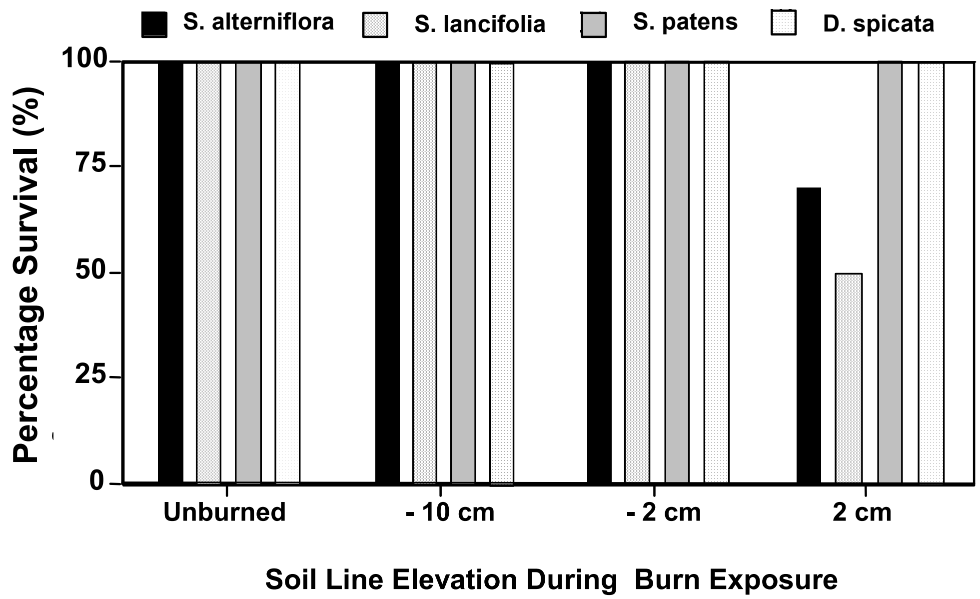


Figure 10. Effects of Soil Elevation on Sod Survival One Year After the Burns.

methods, and Type B are those which are evaluated by other means (Taylor and Kuyatt, 1994). Type B analysis of systematic uncertainties involves estimating the upper (+ a) and lower (- a) limits for the quantity in question such that the probability that the value would be in the interval (± a) is essentially 100 percent. After estimating uncertainties by either Type A or B analysis, the uncertainties are combined in quadrature to yield the combined standard uncertainty. Multiplying the combined standard uncertainty by a coverage factor of two results in the expanded uncertainty which corresponds to a 95 percent confidence interval(2F).

Components of uncertainty are tabulated in Table 2. Some of these components, such as the zero and calibration elements, are derived from instrument specifications, while other components, such as weighing or drying include past experience. The combined standard uncertainty for soil temperature include a component that is related to the position of the thermocouple. Each soil thermocouple array was carefully inserted from above the soil line and pulled down through a slot cut in each plant specimen. While much care was used in positioning the thermocouple array, the insertion method was more likely to cause a thermocouple to be positioned too high in the plant than too low. A thermocouple that ended up a bit too high would be expected to report higher temperatures than one located at its assigned position.

This uncertainty analysis assumed that the thermal conductivity/heat capacity of the soil was relatively uniform and did not include any uncertainty associated with air voids in the soil. Water filled voids were assumed to behave essentially the same as water saturated soil. The total expanded uncertainty was estimated to be - 18% to + 25 % with the largest components estimated as the position and the repeatability. The total expanded uncertainty for stem density and percentage survival was estimated at ± 15% and ± 12%, respectively.

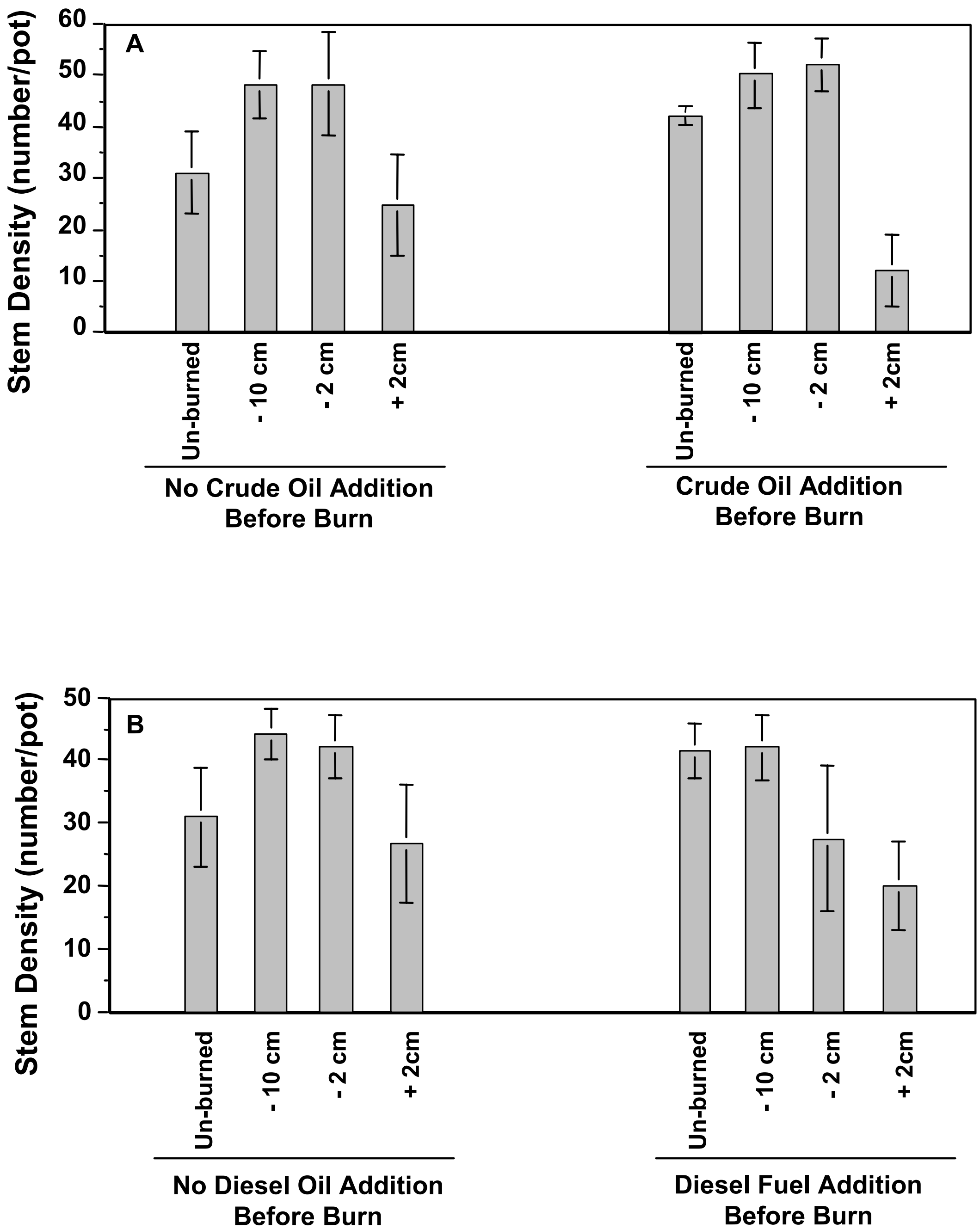
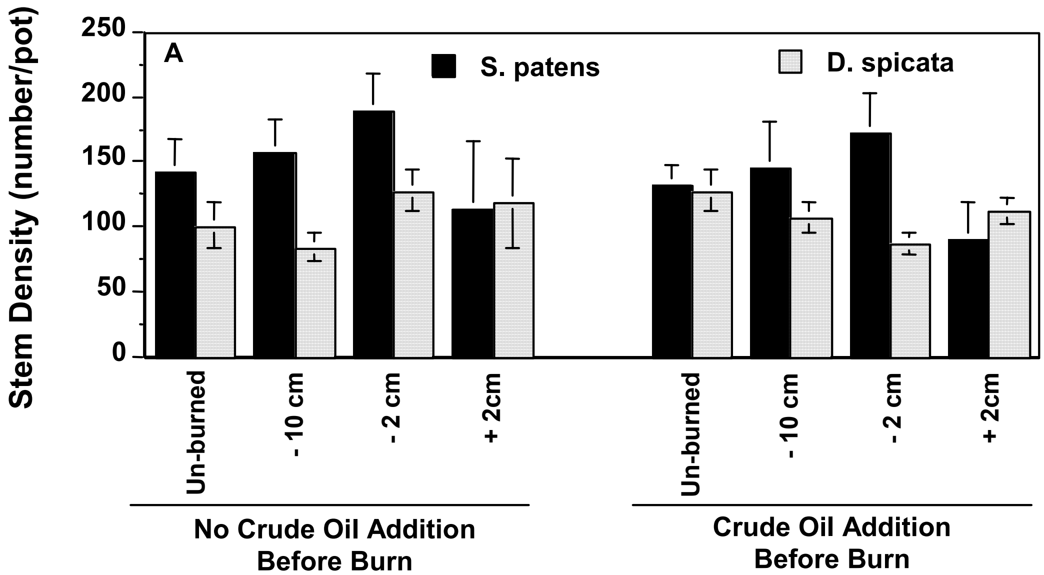


Figure 11. Effects of Soil Elevation and Pre-Oiling on Stem Density of *S. alterniflora* One Year After the Crude Oil (A) and Diesel (B) Burn. Error Bars are Standard errors (n=4).

4.0 Discussion

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



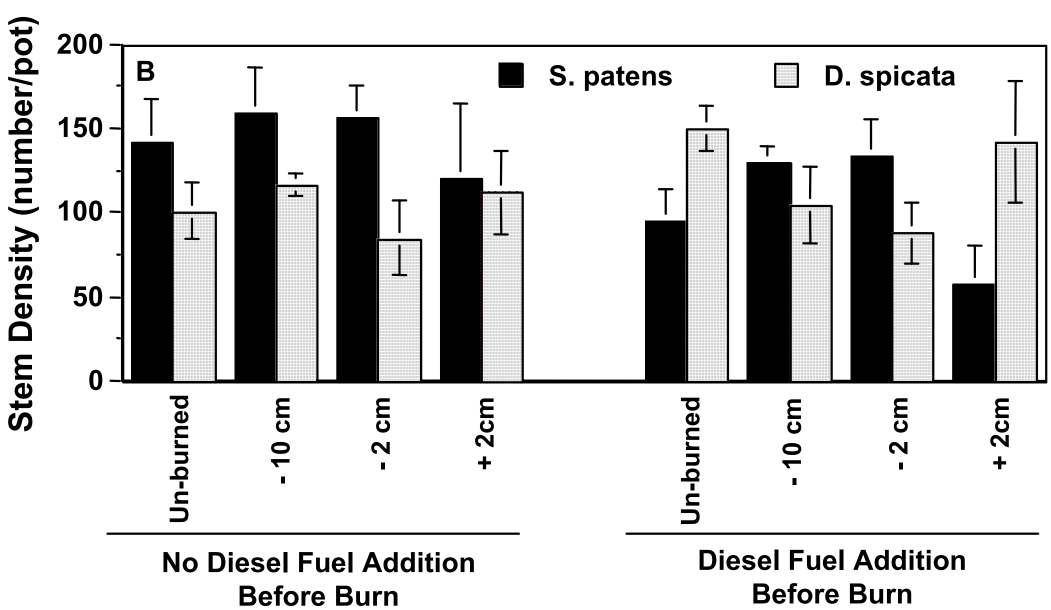
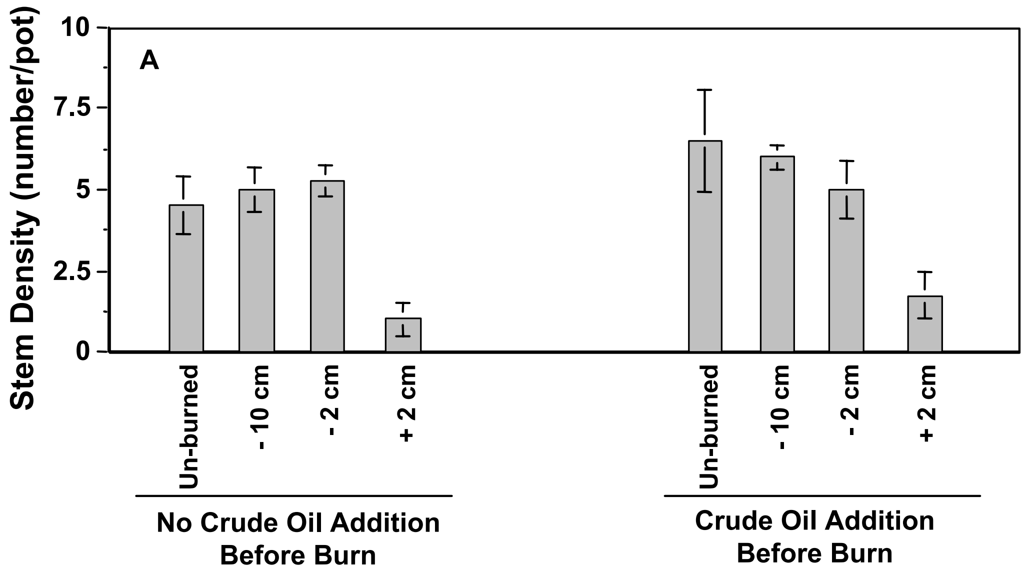


Figure 12. Effects of Soil Elevation and Pre-Oiling on Stem Density of *S. patens* and *D. spicata* One Year After the Crude Oil (10) and Diesel (B) Burns. Error Bars are Standard Errors (n=4).



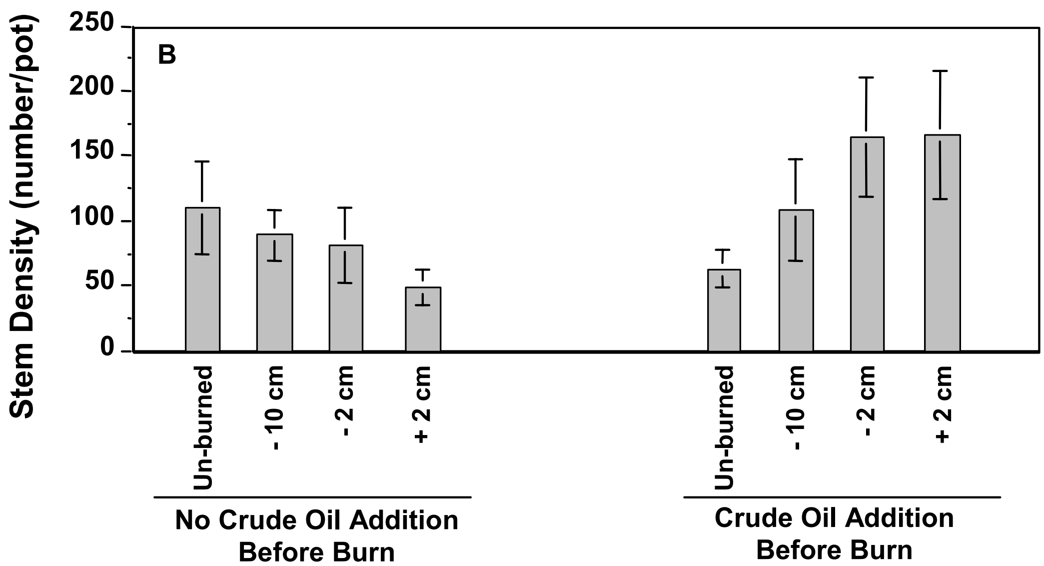


Figure 13. Effects of Soil Elevation and Pre-Oiling on Stem Density of *S. lancifolia* (A) and *Eleochlis spp.* (B) One Year After the Crude Oil Burns. Error Bars are Standard Errors (n=4).

Ten centimeters of water over the soil surface was sufficient to protect the marsh vegetation of all 3 types of marshes from burning impacts. Soil surface temperature 10 cm below the water did not exceed 50 °C. Thermal stress on plants was absent. The plant survival and growth responses to the water level treatments support the temperature data.

Two centimeters of water over the soil surface also protected the marsh sods from thermal stress during the burns. Soil temperatures for different marsh and burn types were below 50 °C even at the soil surface for most marsh sods. Plant survival and growth responses were not significantly different from the unburned control.

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

Soil temperatures during the *in-situ* burns, generally, depended upon the water depth over the soil surface during the burns. In addition, soil temperatures generated during the burns differed with soil depth. Lower temperatures were found with greater depth in the soil. However, a question that must be addressed regarding *in-situ* burning is: What soil temperature will result in plant mortality? In the second series of *in-situ* burns, all plants survived at 10 and 2 cm of water over the soil surface, with soil temperature < 40 °C and 50 °C at soil surface, respectively. In the first series of experiments, there was contamination of the sods at –2 cm elevation by "rogue diesel" (described below) that impacted the recovery of those plants. But,

Table 2. Uncertainty in Experimental Data.

	Component Standard Uncertainty	Combined Standard Uncertainty	Total Expanded Uncertainty
Soil Temperature			
Calibration	± 1 %		
Position	- 5 % to + 10 %	- 9 % to + 13 %	- 18 % to + 25 %
Repeatability	± 7 %		
Random	± 3 %		
Stem Density			
Repeatability	± 7 %		
Random	± 3 %	± 8 %	± 15 %
Percentage Survival			
Repeatability	± 5 %		
Random	± 3 %	± 6 %	± 12 %
Plant Elevation			
Repeatability	± 2 %		
Random	± 2 %	± 3 %	± 6 %
Note: Random and repeatability evaluated as Type A, other components as Type B.			

excluding the plants that suffered from the chemical stress of "rogue" contamination, a 50 °C surface soil temperature during the burn with 2 cm of standing water over the soil surface was safe for most plants. Lethal temperatures for most vascular plants have been cited in the range of 60 °C to 65 °C (Byram 1948; Ahlgren 1974; and Levitt 1980).

However, 2 cm of soil exposure during *in-situ* burning resulted in wide range of soil temperatures (100 °C at 0 cm of soil depth to <40 °C at 5 cm of soil depth) and differentially affected the survival of marsh-plant species to *in-situ* burning. The effect of burning on plant species was greatest for *S. lancifolia*, with a 50% decrease in survival rate and a significantly lower stem density. In addition, the effect of burning on *S. alterniflora* was also significant, with a 30% decrease in survival rate and a significantly lower stem density. However, 2 cm of soil exposure during *in-situ* burning did not detrimentally affect the post-burn recovery of the brackish marsh grasses, *S. patens* and *D. spicata*. Therefore, it is apparent that the thermal effect during *in-situ* burning is plant species-specific. The causes for the species-specific effect of *in-situ* burning appear to be due to the location of reproductive organs in the soil profile. All these species are perennial, and reproduce new plants mainly from belowground rhizomes. Rhizomes of *S. lancifolia* are large, and shallowly located. It is not rare that parts of the *S. lancifolia*'*s* rhizome are located at the soil surface or even extrude above the soil surface. Thus, 80 °C to 100 °C temperatures at 0 cm to 0.5 cm of soil depth could greatly affect the survival of the rhizomes of *S. lancifolia*. For *S. alterniflora*, as indicated by Lin *et al.* (2002), surface soil temperatures (0 cm and 0.5 cm below the soil surface) may not be appropriate to predict thermal effects on this plant species since they were in the range of 80 °C to 100 °C. At 2 cm soil depth, a mean temperature of 55 °C with a significant uncertainty (- 18 % to + 25 %) suggests that temperature of some experimental units were > 60 °C, and that may affect the survival of reproductive organs of *S. alterniflora*. Lethal temperatures for most vascular plants have been cited in the range of 60 °C to 65 °C (Byram 1948; Ahlgren 1974; and Levitt 1980). However, 2 cm of soil exposure during *in-situ* burning did not detrimentally affect the post-burn recovery of the brackish marsh grasses, *S. patens* and *D. spicata*. These two species have very dense stems, and some rhizomes may be located at deeper soil depths. In addition, they generally reproduce rapidly from rhizomes. Thus, the biomass of new plants grown from surviving rhizomes could reach the level of the unburned control rapidly. Mendelssohn *et al.* (1995) and Pahl *et al.* (1999) indicated that response to burning impact differed with marsh-plant species after an *in-situ* burn of a hydrocarbon product spill at the Rockefeller Wildlife Refuge on Louisiana's southwest coast. Initial revegetation within the oiled and burned marsh was dominated by *Schoenoplectus robutus*. However, the frequency of *S. robutus* within the burned marsh decreased during the growing season, while the frequency of the graminoid species, such *as D. spicata* and *S. patens*, increased. After 3 years (Pahl and Mendelssohn, 1999), *D. spicata and S. patens* co-dominated the site and *S. robutus* was only a minor constituent.

Ten centimeters 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 hydrocarbons was low at this soil elevation, 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.

In the first series of *in-situ* burns which exposed *S. alterniflora* to diesel fuel, 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 cm and -2 cm soil elevations at a 2 cm soil depth were 42 °C and 48 °C, respectively, which was probably not high enough to severely stress the plants. The contamination of sods with the diesel used to create the burn exposure referred to as "rogue diesel fuel" since this diesel was not intended to pre-oil the sods. It 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. The experimental procedure was modified before the second series of 11 burns to minimize "rogue oil" contamination (Bryner *et al.* 2001).

In the first 10 burns for *S. alterniflora* sods which were positioned at -10 cm, pre-oiling with diesel fuel at a rate of 1.5 l/m^2 (first series) did greatly reduce survival of plants. The poor recovery in the treatments with 10 cm of overlying water and diesel fuel added to the soil was due to the stress of the added petroleum hydrocarbons prior to the burn. In the second series of burns for all plant elevations, pre-oiling with diesel fuel or crude oil at a rate 0.5 l/m^2 (second series) prior to the burn resulted in oil concentrations that were not high enough to detrimentally affect plant survival.

Diesel is more toxic to plants than crude oil. In general, petroleum hydrocarbon toxicity increases from alkanes to aromatics; and within each series of hydrocarbons, the small molecular weight hydrocarbons are more toxic than the large ones (Baker, 1970). Alexander and Webb (1985) demonstrated that 1.5 l/m^2 of *No*. 2 fuel oil significantly reduced live aboveground biomass of *S. alterniflora*, while 2 l/m^2 of crude oil did not. The composition and toxicity of No. 2 fuel oil and diesel oil are similar. Furthermore, Lin and Mendelssohn (1996) reported that even 4 l/m^2 of Louisiana crude oil did not significantly reduce live aboveground biomass of *S. alterniflora* 4 and 9 months after oiling, supporting the contention that No. 2 fuel oil and diesel have a greater toxicity on plants than crude oil.

In-situ burning of crude or refined hydrocarbons can be used by oil spill remediation teams in order to minimize the impact of spilled oil within a wetland environment. However, *in-situ* burning of the oil will impose an additional thermal stress on the same plants that have already been exposed to the chemical stress of the oil toxicity. If the oil toxicity has already killed the plants within the spill boundary, then exposing the plants to the thermal stress of *in-situ* burning is a moot point from the perspective of plant survivability. Even if all or most of the plants have succumbed to the chemical stress, *in-situ* burning may still play an important role in removing the oil from the marsh. If the plants have not succumbed to the chemical stress, 2 cm of water over the soil surface provided sufficient protection to the marsh-plants from the thermal stress of an *in-situ* burn. For marshlands with water over the soil surface, *in-situ* burning offers a less intrusive and less stressful technique than mechanical oil recovery to remove the oil from the wetlands.

5.0 Conclusions

Water depth over the soil surface during *in-situ* burning is a key factor controlling recovery of coastal marsh-plants. Ten centimeters of water overlying the soil surface was sufficient to protect marsh vegetation of all 3 types of marshes from burning impacts. Soil surface temperature 10 cm below the water did not exceed 50 °C. The plant survival rate was 100%, and growth responses after the burn with 10 cm of water over the soil surface was not significantly different from the unburned control. Two centimeters of water overlying the soil surface provided similar protection to marsh vegetation of all 3 types of marshes from burning impacts as 10 cm of water, with < 50 °C soil surface temperature 2 cm below the water, 100% plant survival rate, and similar plant growth responses as the unburned control. In contrast, a water table 2 cm below the soil surface (2 cm of soil exposure to the fire) resulted in high soil temperatures, with 80-100 °C at 0 cm to 0.5 cm below the soil surface. Thermal stress generated with a water table 2 cm below the soil surface differed with plant species. Two centimeters of soil exposure during *in-situ* burning impeded the post-burn recovery of the salt marsh grass, *S. alterniflora*, and fresh marsh species, *S. lancifolia*. However, 2 cm of soil exposure during *in-situ* burning did not detrimentally affect the post-burn recovery of the brackish marsh grasses, *S. patens* and *D. spicata.*

Our results show that some standing water over the marsh surface is important during *in-situ* burning for post-burn recovery of marsh vegetation. For most marshes, 10 cm of overlying water is certainly sufficient. Lower water levels, such as 2 cm of overlying water also appears to be adequate. However, a water table below the soil surface, such as a 2 cm soil exposure during *in-situ* burning in this experiment, should be avoided for most marshes.

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