EFFECTS OF *IN-SITU* OIL BURNING ON COASTAL WETLANDS: SOIL TEMPERATURES AND REGROWTH OF MARSH PLANT SPECIES

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ABSTRACT: *Twenty-one full-scale in-situ burn experiments examined soil temperatures which marsh plants experience during in-situ burning. Two hundred sixty four plant sods, including Spartina alterniflora, Spartina patens, Distichlis spicata, and Sagittaria lancifolia plants, were exposed in a 6 m diameter tank to burning diesel fuel or crude oil for intervals ranging from 400 s to 1400 s. Individual sods were instrumented with thermocouples to track soil temperatures throughout each burn. After the burns, the sods were returned to the greenhouse where plant recovery was monitored for up to a year. The water depth over the soil surface during in-situ burning was a key factor controlling plant recovery. For either 400 s or 1400 s burn exposures, soil temperatures did not exceed 50 °C and 70 °C for 10 cm and 2 centimeters of water overlying the soil surface, respectively. Ten and 2 centimeters of water overlying the soil surface were sufficient to protect all 3 types of marsh plants from burning impacts. In contrast, 2 cm of soil exposure to the fire during the burn resulted in high soil temperatures, with 80 °C to 100 °C at 0 cm to 0.5 cm below the soil surface. The effect of thermal stress on plant survival differed with species as 2 cm of soil exposure during 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. For plants positioned 10 cm above the water level, peak surface soil temperatures ranged from 350 °C to 800 °C for 400 s and 1400 s burns, respectively. Thermal stress almost completely inhibited the post-burn recovery of S. alterniflora in this water level treatment.*

Introduction

Oil spills of crude or refined hydrocarbons in environments such as salt marshes can represent difficult challenges for oil spill response teams. *In-situ* burning or intentional burning of spilled oil in wetlands offers the oil spill remediation teams with an alternative that may avoid much of the damage caused by mechanical reclamation while still removing most of the oil from the marshland and preventing the further spread of oil to environmentally sensitive areas. However, *in-situ* burning imposes a fire or thermal stress to the wetland plants that have already been exposed to the chemical toxicity of the oil. The extent to which the thermal energy has penetrated the soil and the impact of elevated soil temperatures on plant regrowth and recovery needs to be fully understood by the response team in order that the team be able to determine whether or not *in-situ* burning is an appropriate spill clean-up tool for a specific spill.

How deep does the thermal energy penetrate into the soil? Water levels in the marsh could provide significant protection against the thermal stress of an *in-situ* burn, but it not clear how thick the water layer needs to be to protect the roots from thermal damage. The overall goal of this study is to measure the soil temperatures that result from an *in-situ* burn and to understand the relationship between the soil temperatures and the recovery of the plants.

Experimental

Within the 6 m diameter round tank facility at Louisiana State University (LSU), each plant sod was positioned on a plant support stand that allowed the elevation of the specimen to be adjusted to either -10 cm, -2 cm, 0 cm, +2 cm, and +10 cm relative to the surface of the water. After being transported from the LSU greenhouses to the burn tank, plant specimens were arranged in concentric circles in order to provide uniform exposure. 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. More detailed descriptions of the experimental apparatus were included in Bryner *et al.* (2000 and 2001) and Mendelssohn *et al.* (2002).

In-situ burning of a wetlands oil spill 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. An initial charge of fuel (either diesel fuel or crude oil) was floated on the surface of the water and ignited. 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.

Three hundred thirty-two marsh specimens were collected for two series of burn experiments. In the first series of burns, 100 sods, 80 specimens to burn and 20 specimens for controls, were collected from a *Spartina alterniflora* dominated 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 L (five gallon) container. Each plant specimen was assigned a unique number and randomly assigned to different elevations and specific burns. 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.

Specimens were instrumented with the arrays consisting of either four or eight thermocouples arrays in order to track the temperature gradients within the soil. 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. The array was arranged so that the tips of the thermocouples were positioned vertically near the centerline of the bucket.

After the burns, the mesocosms were returned to the greenhouse where plant regrowth was assessed by measuring plant or sod survival. 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 or 5 sods) times 100 %.

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 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).

Soil temperatures. Each thermocouple array 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 °C 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 °C 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 °C isotherm. The estimated depth of the 60 °C isotherm are plotted as a function of plant sod elevation (-10 cm, -2 cm, 0 cm, +2 cm and +10 cm) for 400 s, 770 s, and 1400 s burn exposures in Figures 1 to 5.

The soil temperature profile data demonstrate 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 °C with the 60 °C 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 °C and exceeded 100 °C in several sods. Without water overlying the soil, the 60 °C 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 °C and 800 EC were observed during the 400 s and 1000 s burn exposures, respectively.

Post-burn regrowth and recovery of marsh plants. For the first series of 10 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. The 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, Figure 1 and 1400 s, Figure 2). 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. No experimental units survived after a 1400 s burn with 10 cm of soil exposure. There was no significant difference in sod survival between burn durations, 400 s versus 1400 s at the -10 cm, -2 cm, or 0 cm sod elevations.

For the second set of 11 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 (Figures 3, 4 and 5). Values were averaged over oil application 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*.

Uncertainty analysis. There are different components of uncertainty in the temperatures, plant elevation, 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 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%. After estimating uncertainties by either Type A or B analysis, the uncertainties are combined in quadrature to yield the combined standard uncertainty.
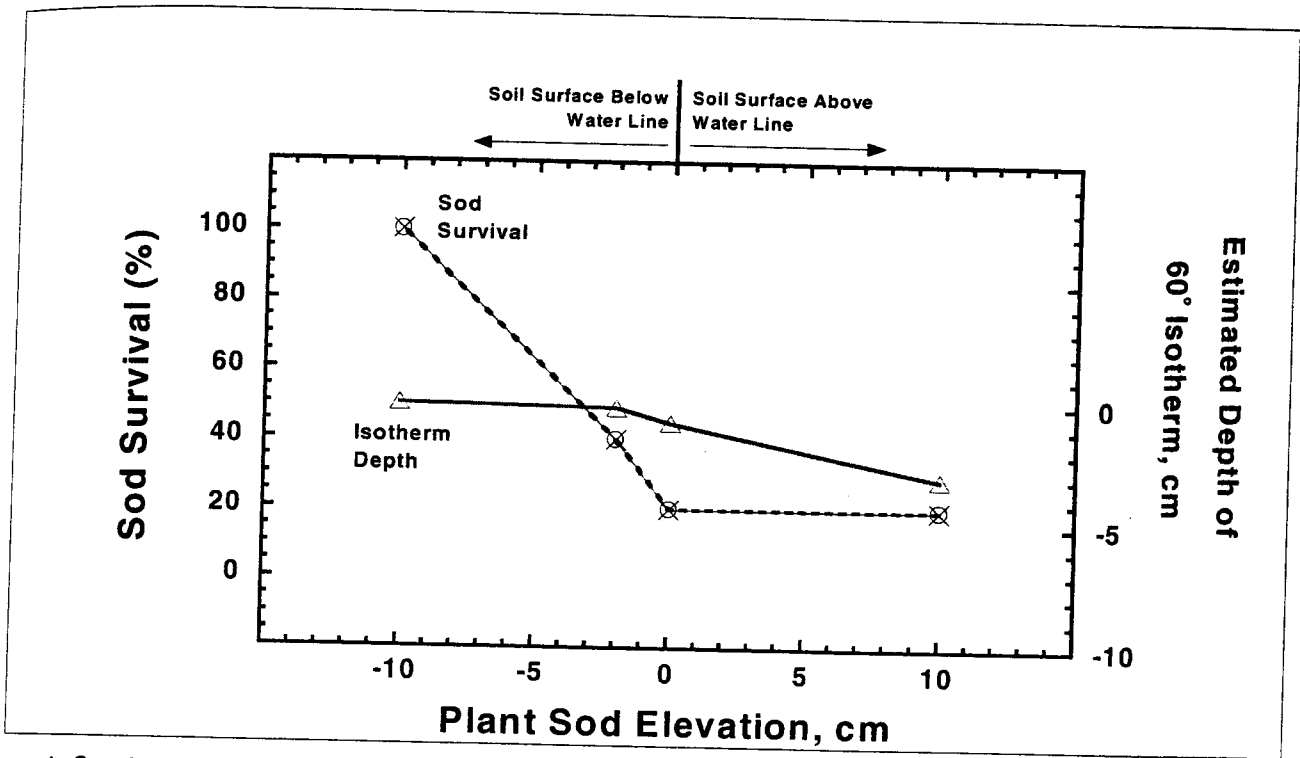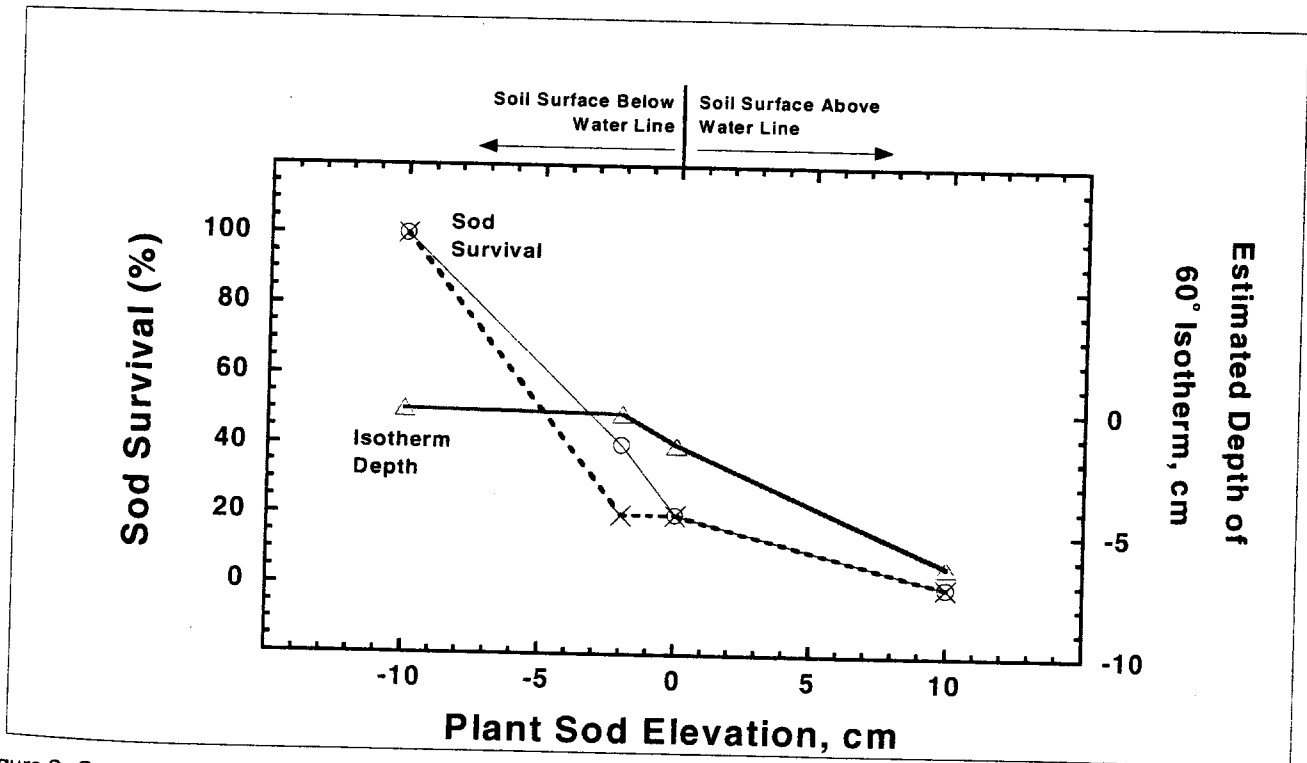
Figure 1. *Spartina Alterniflora* sod survival percentage and estimated depth of 60 °C isotherm versus plant elevation for 400 s burn exposure. (△) symbols with solid line are estimated depth of 60 °C isotherm for diesel fuel burns. (o) symbols with thin solid line are sod survival at 7 months. (x) symbols with dashed line are sod survival at 1 month.

Figure 2. *Spartina Alterniflora* sod survival percentage and estimated depth of 60 °C isotherm versus plant elevation for 1400 s burn exposure. (△) symbols with solid line are estimated depth of 60 °C isotherm for diesel fuel burns. (o) symbols with thin solid line are sod survival at 7 months. (x) symbols with dashed line are sod survival at 1 month.
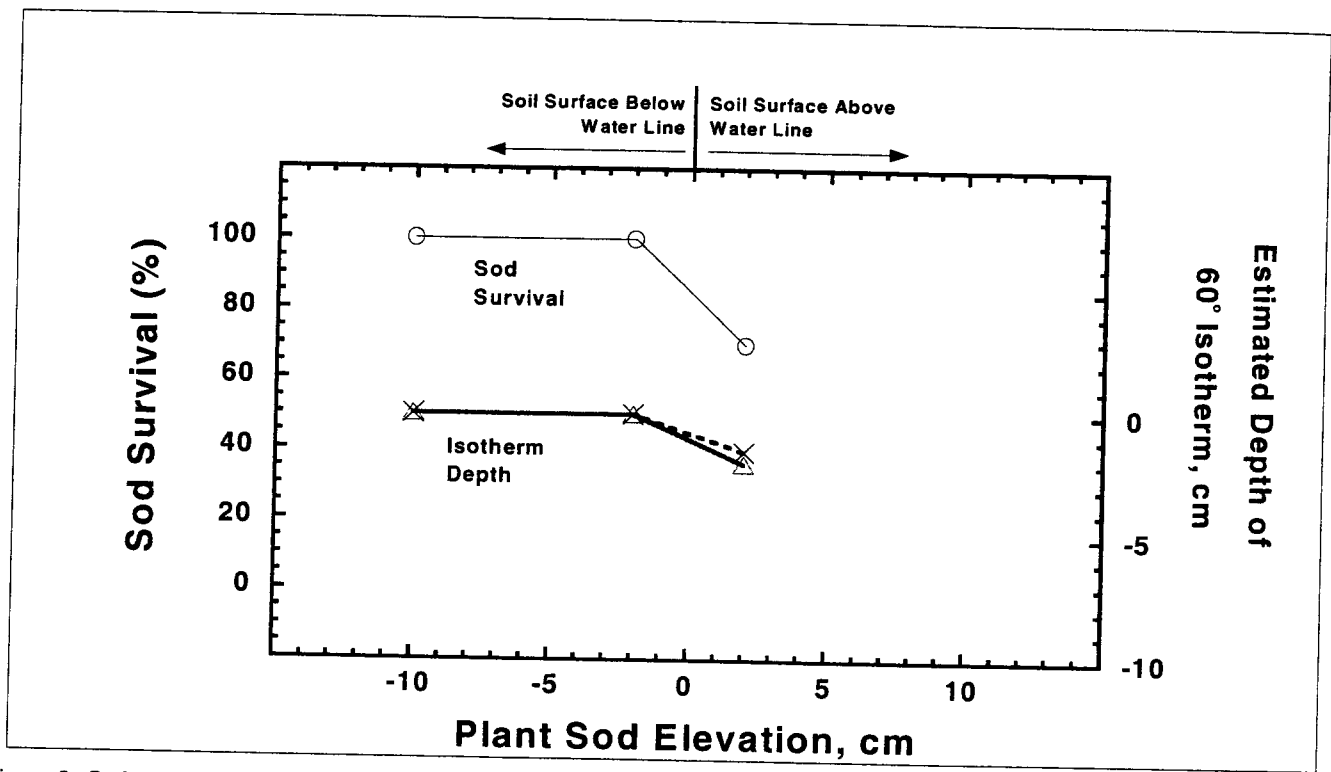
Figure 3. *S. Alterniflora* sod survival percentage and estimated depth of 60 °C isotherm versus plant elevation for 700 s burn exposure. (△) symbols with solid line are estimated depth of 60 °C isotherm for diesel fuel burns. (x) symbols with dashed line are estimated depth of 60 °C isotherm for crude oil burns. (o) symbols with thin solid line are sod survival at 12 months.
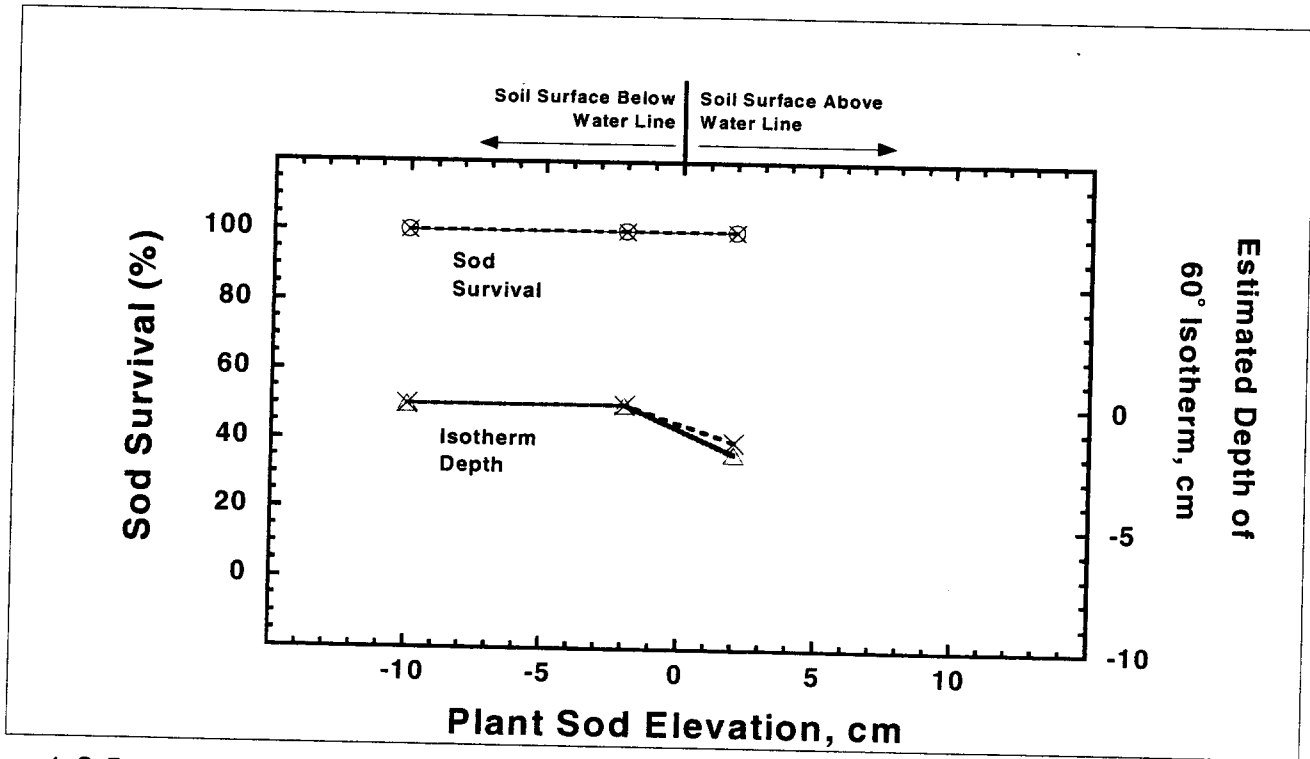

Figure 4. *S. Patens and D. Spicata* sod survival percentage and estimated depth of 60 °c isotherm versus plant elevation for 700 s burn exposure. (△) symbols with solid line are estimated depth of 60 °c isotherm for diesel fuel burns. (x) symbols with dashed line are estimated depth of 60 °c isotherm for crude oil burns. (o) symbols with dashed line are *S. Patens* sod survival at 12 months. (x) symbols with thin solid line are *D. Spicata* sod survival at 12 months.
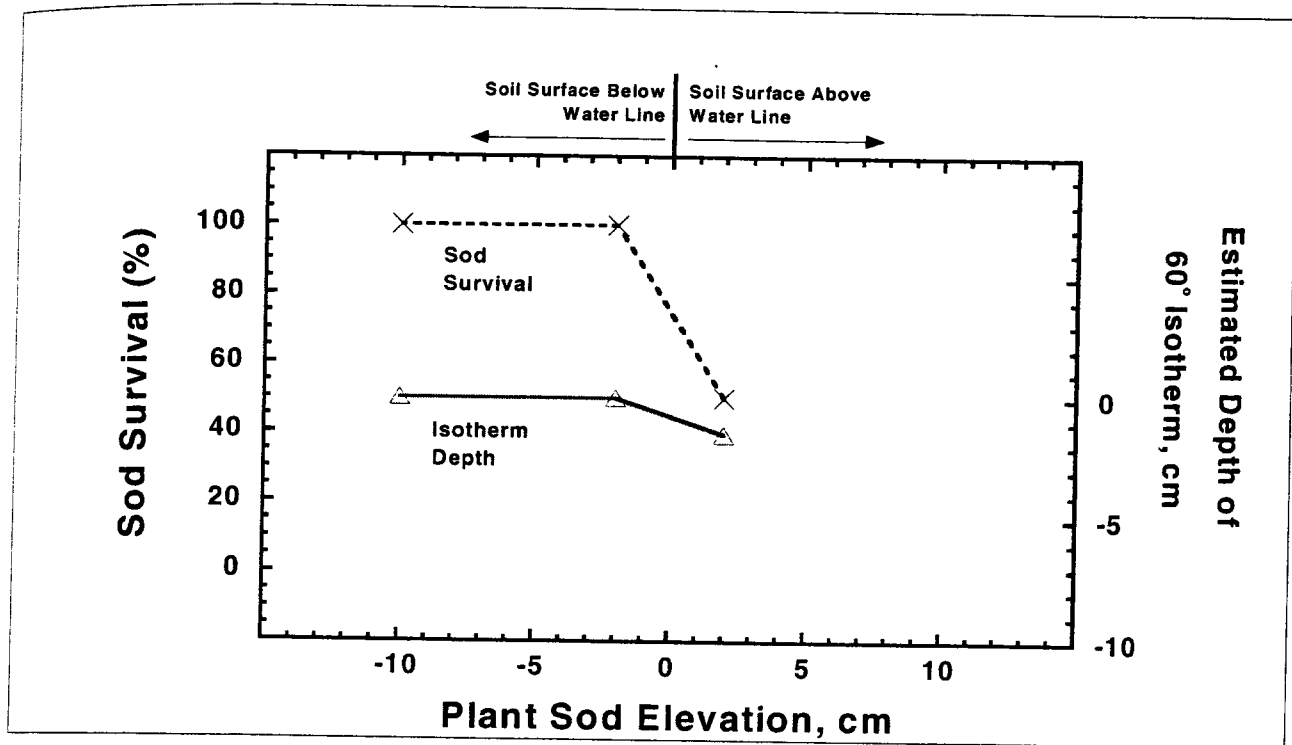
Figure 5. *S. lancifolia* sod survival percentage and estimated depth of 60 °C isotherm versus plant elevation for 700 s burn exposure. (△) symbols with solid line are estimated depth of 60 °C isotherm for diesel fuel burns. (x) symbols with dashed line are *S. lancifolia* sod survival at 12 months.

Table 1. 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%		
Percentage Sod Survival			
Repeatability	±5%	±6%	±12%
Random	±3%		
Plant Elevation			
Repeatability	±2%	±3%	±6%
Random	±2%		

Note: Random and repeatability evaluated as Type A, other components as Type B.

Multiplying the combined standard uncertainty by a coverage factor of two results in the expanded uncertainty which corresponds to a 95 percent confidence interval (2σ).

Components of uncertainty are tabulated in Table 1. Some of these components, such as the zero and calibration elements, are derived from instrument specifications, while other components, such as determining dominant species include past experience. The combined standard uncertainty for soil temperature includes 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 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 percentage sod survival was estimated at ±12%.

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. Increased water depth over the marsh surface provided increased protection to the marsh vegetation during the *in-situ* burn, resulting in lower soil temperature and higher survival rates. However, the impact of *in-situ* burning on marsh-plants was species-specific.

Ten centimeters of water over the soil surface was sufficient to protect the 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 (Figures 1, 2, 3, 4, and 5).

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.

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 cm 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 diesel oil (described below) that impacted the recovery of those plants. But, excluding the plants that suffered from the chemical stress of oil 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.

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* (Figure 5), with a 50 % decrease in survival rate. In addition, the effect of burning on *S. alterniflora* (Figure 3) was also significant, with a 30 % decrease in survival rate. 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* (Figure 4). 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*. 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.

Ten centimeters of soil exposure during *in-situ* burning impeded the post-burn recovery of *S. alterniflora* (Figures 1 and 2). 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. Thermal stress on the plants appeared to be the main factor, which resulted in little recovery of *S. alterniflora* at the +10 cm elevation.

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 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.

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.

Conclusions

Water depth over the soil surface during *in-situ* burning is a key factor controlling recovery of coastal marsh-plants. 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 the three types of marsh vegetation examined in this study, oil spill response teams should expect that 2 cm of overlying water will be sufficient to protect the marsh plants from the thermal stresses of *in-situ* burning of oil spills. However, an oil spill response team should understand that significant thermal damage is likely to occur to the marsh vegetation during an *in-situ* burn when the water table is below the soil surface, such as a +2 cm soil exposure.

References

1. Ahlgren, I.F., "The Effect of Fire on Soil Organisms," in *Fire and Ecosystems*, eds. T.T. Kozlowski and C.E. Ahlgren, Academic Press, New York, NY, Chap. 3, p. 47, 1974.

2. Bryner, N.P., W.D.Walton, L.A. DeLauter, W.H. Twilley, I.A. Mendelssohn, Q. Lin, and J.V. Mullin, "*In-Situ* Burning in the Marshland Environment- Soil Temperatures," in *Proceedings of the Twenty-Third Arctic and Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, Ontario, pp. 823-846, 2000.

3. Bryner, N.P., W.D.Walton, L.A. DeLauter, W.H. Twilley, I.A. Mendelssohn, Q. Lin, and J.V. Mullin, "*In-Situ* Oil Burning in the Marshland Environment - Soil Temperatures Resulting from Crude Oil and Diesel Fuel Burns," in *Proceedings of the Twenty-Fourth Arctic and Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, Ontario, pp. 729-753, 2001.

4. Byram, G.M., "Vegetation Temperature and Fire Damage in the Southern Pines," Fire Control Notes, Vol. 9, No. 4, pp. 34-37, 1948.

5. Levitt, J., *Response of Plants to Environmental Stresses: Volume I, Chilling, Freezing and High Temperature Stresses*, Academic Press, New York, NY, 479 p., 1980.

6. Lin, Q. and Mendelssohn, I.A., "A Comparative Investigation of the Effects of Louisiana Crude Oil on the Vegetation of Fresh, Brackish, and Salt Marsh," *Marine Pollution Bulletin*, Vol. 32, No.2, pp.202-209, 1996.

7. Lin, Q., Mendelssohn, I.A., Carney, K., Bryner, N.P., and Walton, W.D., "Salt Marsh Recovery and Oil Spill Remediation after *In-Situ* Burning: Effects of Water Depth and Burn Duration," *Environmental Science & Technology*, Vol. 36, No. 4, pp.576-581, 2002a.

8. Lin, Q., Mendelssohn, I.A., Carney, K., Bryner, N.P., and Walton, W.D., "Interactive Effects of Surface Water, Oil and Marsh Types on Vegetation Recovery and Oil Remediation After *In-Situ* Burning," to be submitted to *Environmental Science & Technology*, 2002b.

9. Mendelssohn, I.A., Q. Lin, N.P. Bryner, W.D.Walton, L.A. DeLauter, and J.V. Mullin, "*In-Situ* Oil Burning in the Marshland Environment - Recovery and Regrowth of *Spartina alterniflora, Spartina patens*, and *Sagittaria lancifolia* Plants," in *Proceedings of the Twenty-Fifth Arctic and Marine Oilspill Program Technical Seminar*, Environment Canada, Ottawa, Ontario, pp. 785-808, 2002.

10. Mendelssohn, I.A., M.W. Hester, and J.W. Pahl, "Environmental Effects and Effectiveness of *In-Situ* Burning in Wetlands: Considerations for Oil-Spill Cleanup," *Louisiana Applied Oil Spill Research and Development Program*, Louisiana Oil Spill Coordinator's Office/Office of the Governor Baton Rouge, Louisiana, 57 p., 1995.

11. Taylor, B. N. and C. E. Kuyatt, *Guidelines For Evaluating and Expressing the Uncertainty of NIST Measurement Results*. National Institute of Standards and Technology (U.S.) NIST-TN 1297; September, 20 p. 1994.