Information on Soil Heating from In-situ Burning

James Reardon, Rocky Mountain Research Station Fire Science Laboratory
James Myers, Chevron Energy Technology
and
Alexis Steen, ExxonMobil Research and Engineering

Abstract
The use of in-situ burning (ISB) in response to inland or onshore spills has often been limited or disregarded because of concerns that heat from burning spilled oil might damage soils. However, there has been negligible information on soil heating from combustion of spilled oil on soils. Although heat transfer to soils during wildfires has been the focus of much research, soil heating from ISBs has received little attention. Wildland fires tend to burn off aboveground biomass while having minimal impact to soil, seeds, plant and microbes, because most of the heat flux (>95%) goes into the air and not into the soil. This paper summarizes results from a three-year laboratory study on effects of heat from in-situ burning (ISB) on soil cores by the US Forestry Service[1] as part of the ISB research program of the American Petroleum Institute (API).

Wide-diameter soil cores (15.2 and 25.4 cm) were used for testing a range of oils, soils, and degrees of oiling versus water saturation to measure soil heating at various depths in the cores with time. This is the first dataset of soil heating from ISB. ISB soil core heat flux is similar to on-water ISB heat flux: >95% of heat dissipates upward into the air. Although soil surface microlayera (at 0 cm depth) can receive a lot of heat from burns, the heat flux did not raise soil temperatures to damaging soil structure, plants, seeds or microbes. Investigation showed the Campbell soil heating model for wild fire behavior can reasonably predict soil heating for inland ISB. Further, post-burn measurements of soil CO_2 respirometry showed no decline, but rather a slight increase. The CO_2 increase is an indication that the microbial populations are not only active after exposure to an ISB but are benefiting from a fertilizer or substrate effect as the fire increased the availability of nutrients. Many ecosystems are adapted to fire. ISB is a good cleanup option for many inland spills.

Introduction
Visual observations of intense energy released by flaming combustion of woody and petroleum fuels suggest exposure of vegetation and soils to severe heating. Are such suggestions reflective of actual burn exposures? Data indicate they are not. While wildland fire and prescribed fire research results have shown surface fire intensity is a good predictor of aboveground effects on vegetation across a wide range of ecosystems (Duchesne and Hawkes, 2000), results have shown little relationship between surface fire intensity and soil heating (Neary et al., 2005). The fire environment associated with burning of forest fuels and petroleum hydrocarbons (fire fuels) is driven by fuel properties and the amount of fuel. Heat flux through soil surface layers is a function of heat energy at the soil surface and soil thermal properties including heat capacity, thermal conductivity and diffusivity. These properties are sensitive to soil moisture (Campbell et al., 1994). The transfer of heat under saturated soil conditions is dominated by thermal properties of water. In contrast, heat transfer on a dry soil surface is primarily dependent on soil properties.

Wildland fire temperature effects on plants, soils and microbes have been widely studied. The immediate effects of soil heating are characterized by temperature thresholds which reflect increasing levels of the biological and chemical sensitivity to heating (**Figure 1**).

- The biological soil components such plant roots, seeds and soil organisms are the most temperature sensitive. Soil temperatures >60^{o}C are commonly considered lethal in wildfire and prescribed burning literature. Although at these low temperatures the duration of the heating is also an important consideration.

[1] Rocky Mountain Research Station, Fire Science Laboratory in Missoula, MT

- More moderately sensitive components, such as soil organic matter (SOM), contribute to important soil properties. Changes in SOM begin as low as 100°C; nitrogen and other nutrient volatilization begins between 200 to 400°C, and the loss of SOM is > 400°C.
- Mineral soil nutrients, such as Ca and K, are the least temperature sensitive, and are lost by volatilization above 450°C.

In addition to immediate effects, soil heating can influence a soil's ability to supply water and nutrients in support of the above ground vegetative community (Neary et al., 1999).

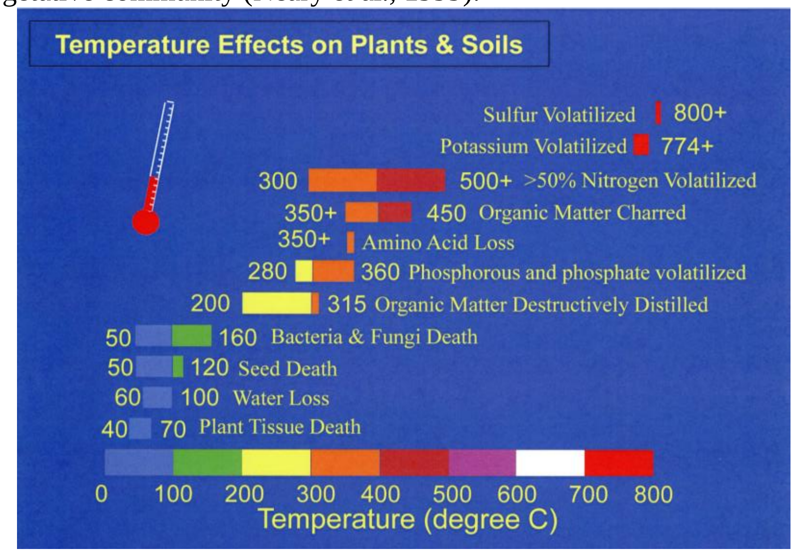

Figure 1. Temperature Effects Thresholds for Plants and Soils (Reardon et al., 2014).

In wildland fires and prescribed burns, a fire can be "hot" characterized by high temperatures and intensities yet its duration can be short, so heating of soils would not be great. Most heat flux during flaming combustion (>95%) goes into the air while little (<5%) goes into soil. Further, fire intensity tends to be patchy, and this enables microbes, seeds and plant roots in cooler spots to recolonize nearby hotter spots.

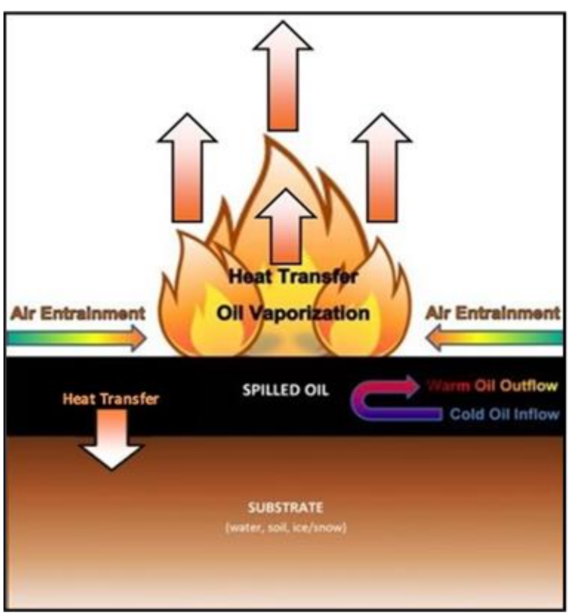

Figure 2. Schematic of the movement of air and transfer of heat from an in-situ burn (modified from Fritt-Rasmussen, 2010).

ISB is a valuable response option on inland or on-shore spill sites where accessibility is constrained, where significant damage from mechanical recovery equipment is undesirable, or to lessen oil exposure to plant roots and wildlife. Previously, our limited understanding and inability to predict soil heating contributed to the limited consideration of ISB as an on-land oil spill response option, and its execution. Similar to wildfires or prescribed burns, most of the heat from an ISB dissipates into the air (**Figure 2**) by radiation. Air is less dense than water and heat follows the course of least resistance. The water serves as infinite heat sink and the surface water temperature only rises a few degrees as heat passes from the fuel layer into the water by conduction. The cooling water replaces the ISB-warmed water through conduction and convection.

ISB effects on the plant community and on spill site recovery are important decision-making considerations. Chemical stress from exposure to spilled oil plus the heat from burning are two factors which influence recovery of aboveground vegetation (Lin et al., 2002). There is a need to better understand the potential for soil heating from ISB, and this paper summarizes results of laboratory experiments from Reardon and O'Donnell (2013), and Reardon and O'Donnell (2014), plus the latest data from this API project. Results were used to evaluate the effectiveness of the Campbell soil heating model in simulating heating effects from ISB on land.

ISB Soil Heating Research

Several studies investigated the influence of ISB and soil heating on the vegetation response in wetland vegetation communities and documented conditions under which the effects of soil heating were minimized (Lin et al., 2002; Lin et al., 2005). Prediction of temperature changes within a soil depth profile during burning is a function of initial conditions: the energy content and amount of fuel, soil moisture and soil properties.

- The amount of heat energy is a function of the heat content and the amount of fuel available.
- The amount of woody fuels present is dependent on site productivity, past disturbances (e.g., fire and windstorms) and land management activities such as logging or thinning.
- In contrast, the amount of energy available for an ISB is a function of the heat content and amount of oil which is the product of the density, the thickness of the oil layer and surface area on a burn site.

The objectives of this API research are: 1) generate soil heating data from realistic burn tests of oiled soils, 2) determine predictive ability of First Order Fire Effects Model[2] (FOFEM) for soil heating from ISBs, and 3) create hydrocarbon fuel values for a FOFEM module suitable for ISB planning.

Phase 1 Testing

One component of FOFEM is the Campbell soil heating model (Campbell et al., 1995). This model was developed for high surface temperatures expected during prescribed burning and wildfires, and includes the simultaneous solution of heat and water transfer equations (Albini et al., 1996). However, it is dependent on the heat energy received at the soil surface and soil properties, and not dependent on properties of woody fuels. Phase 1 testing was designed to determine if soil heating from ISB followed similar heat transfer principles. Testing was conducted using triplicate burns of two oils on a sandy soil with three soil moisture levels and three fuel thicknesses (**Table 1**). Core samples which failed to show a consistent burning response and samples with technical failures from either the thermocouple or data recording equipment were excluded from analysis.

Table 1. Experimental Design Matrix.

Fuel Thickness		**Fuels Tested at Three Soil Moisture Levels**	
Core Depth	**Air Dry**	**Saturated Soil**	**Standing Water**
2 mm	Kerosene/Diesel	Kerosene/Diesel	Kerosene/Diesel
5 mm	Kerosene/Diesel	Kerosene/Diesel	Kerosene/Diesel
7 mm	Kerosene/Diesel	Kerosene/**	Kerosene/Diesel

(** Data missing due to soil moisture boil over)

Kerosene and diesel fuel, common refined products, were selected as heat inputs. To simplify interpretation, the quantity of fuel for each treatment level was expressed as a thickness. Three oil thickness depths (2, 5 and 7 mm) were selected to supply a range of heat inputs. The 2 mm thickness represents the lower thickness threshold expected to support sustained combustion. Three soil moisture levels were selected to reflect a range of conditions expected to have distinctive influences on soil heating: saturated soil with water at the soil surface, saturated soil with 2.54 cm (1 inch) of standing water, and air dry soil.

[2] Developed by the US Forestry Service, FOFEM is a software application used to predict effects of prescribed burning. It is commonly used in pre-burn planning to predict consumption of vegetative fuels, smoke emissions, tree mortality and soil heating.

Burns. Laboratory burning was conducted using a 15.2 cm diameter x 30.5 cm deep cylindrical container of lightly packed sand (**Figure 3**). Prepared soil columns were used to reduce variation in soil properties and moisture content, and facilitate accurate thermocouple placement. Each column was instrumented with K type thermocouples (1.5 mm diameter, bare bead) were placed at four depths: soil surface, 2, 4, and 6 cm.

Figure 3. One of the Soil Core Test Burns.

Campbell Model heat simulations. Soil heating model simulations were done for each fuel type, fuel thickness and soil moisture treatment (N=17). Soil property values for particle and bulk density, and thermal conductivity inputs were default values for a sand soil. Soil moisture content of dry soil treatments was <3% and of saturated and standing water treatments was 40 %.

A simple measure of heat transfer efficiency was calculated as the ratio of energy input to the soil surface and the total energy available (Garo et al., 1999). This value reflects the highly directional energy distribution during combustion, soil thermal properties, moisture content and the fuel depth. Rather than assume a steady state heating rate, the heat input into soil was modeled using a Gaussian heat distribution (Steward et al. 1990, Campbell, 1994). Similar to the spike exposures expected for water column organisms from dispersant use, soil heating has a spike profile (**Figure 4**).

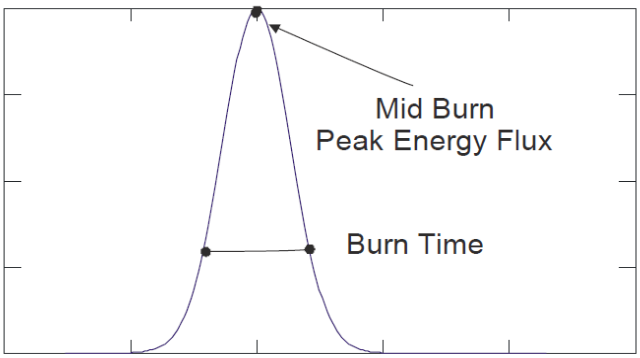

Figure 4. Spike Profile of Typical Soil Surface Heating from Burns.

Phase 1 Results. The influence of soil moisture on soil heating is a balance between temperature and depth of heating.

- The durations of the laboratory burns show the influence of soil moisture and oil thickness or amount. Dry soils show higher temperatures but less depth of heating while wet soils show lower temperatures but a greater depth of heating.
- The effect of the moisture treatments on burn times was clear; the dry burn duration of both fuel types was longer than the wet burn duration. In addition, the wet soil moisture burn times increased with fuel thickness while the dry soil moisture burn times showed little sensitivity to fuel thickness.
- The overall mean heat efficiency for all Phase 1 burns was 2.18 %.

The observed soil surface temperatures from dry burns were consistently higher than either saturated soil or standing water treatments for all oil thicknesses and both fuels. Trends for kerosene dry soil burns showed increasing maximum surface temperatures with increasing oil thickness. Diesel burns showed less sensitivity.

- Dry moisture treatment maximum temperatures decreased with depth within soil profiles. Diesel mean temperature range for all fuel thickness levels was 113 to 126^{o}C at 2 cm soil depths, and decreased to a range of 69 to 83^{o}C at 6 cm.

- Maximum dry soil temperatures for kerosene were slightly more variable, and marginally lower than for diesel. The maximum temperature range at 2 cm depths was 68 to 109°C while at 6 cm depths it was markedly lower with a range of 56 to 72°C, and comparable to diesel soil temperatures at this depth (**Figure 5**).

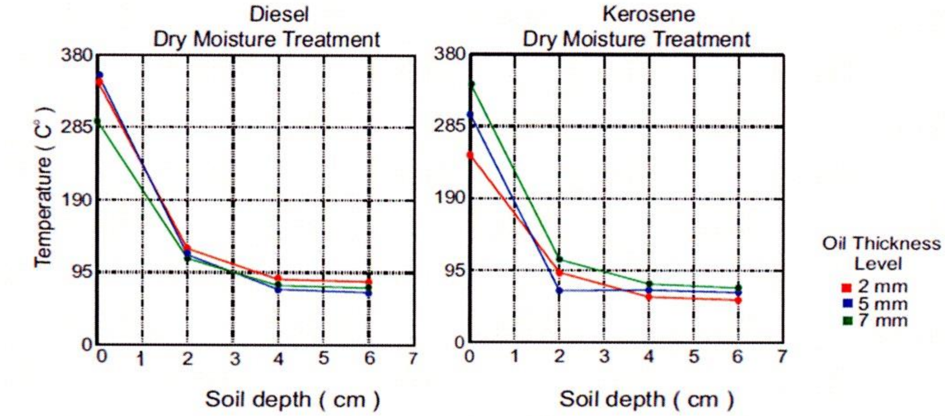

Figure 5. Diesel and Kerosene Burn Maximum Soil Temperatures of the Dry Soils.

Peak Soil Flux. The estimated peak surface heat fluxes showed the influences of fuel type, fuel depth and fuel thickness factors. The largest fluxes for both fuel types were 44.5 and 37.6 kW/m^2 for diesel and kerosene, respectively, from burns of the standing water and the 7 mm oil thickness treatment. In contrast, the lowest peak fluxes were associated with the 2mm thickness of both fuel types across all moisture treatments (**Table 2**).

Table 2. Calculated Peak Flux values for Diesel and Kerosene Burns.

Oil Depth in Core (mm)	Peak Flux (kW/m^2)					
	Dry Soil		Saturated Soil		Standing Water	
	Diesel	Kerosene	Diesel	Kerosene	Diesel	Kerosene
2	12.1	12.6	6.4	8.9	13.2	18.0
5	27.0	22.2	17.3	18.3	22.2	32.2
7	27.9	22.5	**	23.5	44.5	37.6

Phase 2 Testing

Soil heating experiments continued with a similar experimental design. In Phase 2, diesel and Bakken crude oil were tested. Rather than only sand in Phase 1 burns, Phase 2 tested burns on soil cores well-drained sand, a silt, and slow draining clay soils conducted with unaltered soil cores collected from the Missoula, Montana area. The soil core moisture treatments were:

- 2.54 cm of water above the soil surface,
- water at soil surface, and
- water level 2 cm below soil surface with 2 cm of oil-saturated soil.

Two oil thicknesses were tested: diesel at 1.0 cm, and Bakken at 0.5 cm. The average soil heating temperatures are in **Table 3**.

Table 3. Mean Soil Temperatures from Diesel Fuel and Bakken Crude Oil burns.

Oil Depth in Core (mm)	Standing Water Treatment (°C)		Water Saturated Treatment (°C)		Oil Saturated Treatment (°C)	
	Diesel	Bakken	Diesel	Bakken	Diesel	Bakken
Soil Surface	73.5	79.2	191.5	191.8	592.6	447.8
2 cm	26.4	29.3	40.1	35.7	74.5	39.1

4 cm	29.0	31.3	27.6	29.5	31.3	26.1
6 cm	26.1	28.5	24.6	28.7	32.6	24.1

The Bakken and diesel burn results show similar trends: there appears to be no significant differences in soil heating attributable to fuel type between either standing water or just saturated water. The temperatures for treatment 3 are consistently lower for Bakken but there was only half as much oil.

Respirometry. Carbon dioxide (CO_2) is an indirect measure of biological (microbes and plants) activity. Aerobic bacteria and plants respire CO_2. Measurements show a slight increase in CO_2 respiration in post-ISB soil when compared to control soil (no ISB) (**Figure 6**). The increase may be the result of a fertilizer or substrate effect attributable to increased nutrient availability from the products of combustion and soil heating. The individual contribution of microbes and plants to the CO_2 increase was not determined. The results indicate ISB did not harm the soil and actually stimulated biological activity. This is not surprising because many ecosystems are adapted to fire. In those ecosystems, fires are an important factor in controlling plant succession and cycling of nutrients.

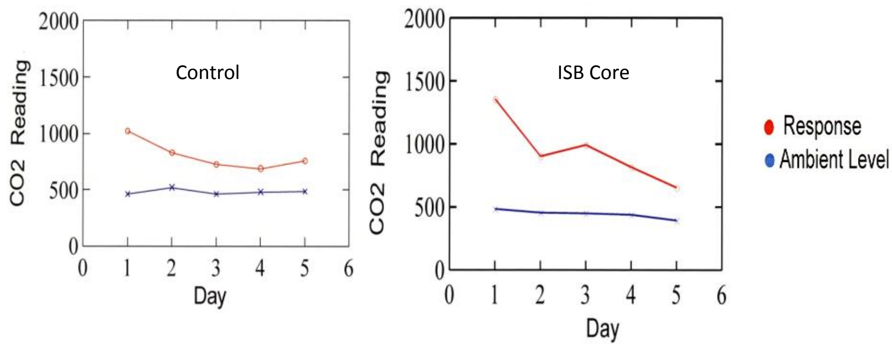

Figure 6. Fire stimulates biological activity in Nature and ISB soil cores.

Discussion of Results

The influence of soil moisture on soil heating can be thought of as a balance between temperature and depth of heating.

- Dry soils show higher temperatures but less depth of heating while wet soils show lower temperatures but a greater depth of heating.
- The insulating effects of soil moisture are most apparent in the flux values for the dry and high moisture content samples.

The temperatures observed in laboratory burns showed the distinct influence of soil moisture. The surface temperatures of dry soil burn were greater than 250^{o}C with maximum temperatures within the soil profile between 56 and 126^{o}C. These temperatures are in the range expected to adversely affect soil biological activity if the duration of the heating is long. The soil temperatures of wet burns were markedly lower. Although surface temperatures were in the 57 to 110^{o}C range, temperatures in the soil profile at 2 to 6 cm depths were 57^{o}C or lower. Consequently, these temperatures are expected to have little or no immediate effect on soil biological activity. Also, water saturation, even just to soil surface provided insulation against heat from burns.

The mean heat efficiency estimated from test burns was <3% and is consistent with values reported by Garo (1999). The estimated heat transfer into test soils from saturated and standing water moisture burns were comparable to expected heat transfer from burning of an oil slick on water (e.g., Figure 2).

The maximum soil temperatures predicted by the Campbell model were in good agreement with observed temperatures during Phase 1 for saturated soil and standing water treatments (**Figure 7 and Figure 8**). The results showed:

- Some over prediction of maximum soil temperatures for kerosene at the 7 mm oil thickness treatment. These burns showed temperatures exceeding 100°C at the soil surface which occurs as a result of water loss at the soil surface.[3]
- Some under prediction of maximum soil temperatures of the dry treatments for both diesel and kerosene burns. Model inputs of energy transferred to soil surfaces were derived from observed soil surface temperatures, and accuracy was dependent on good thermal contact between a thermocouple and soil.[4]

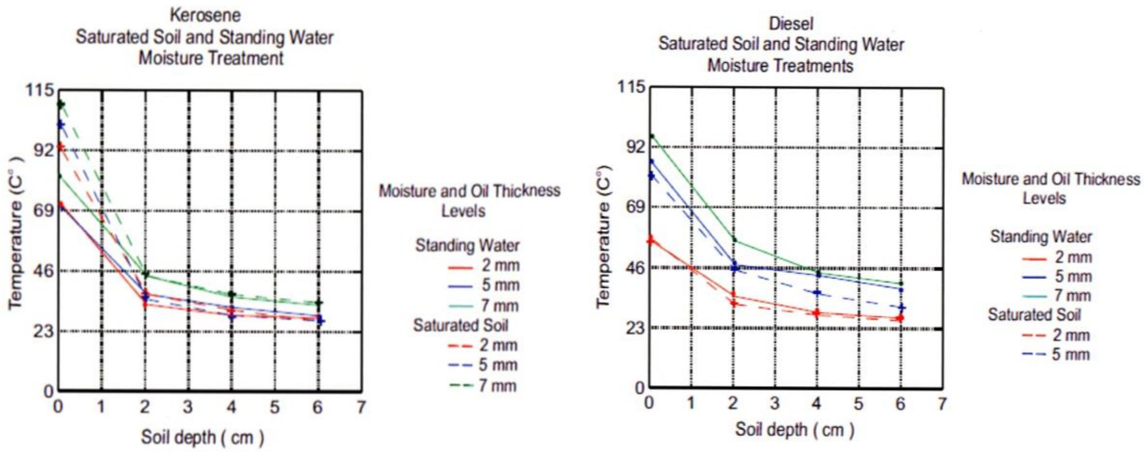

Figure 7. Kerosene and Diesel Maximum Soil Temperatures in Saturated Soils.

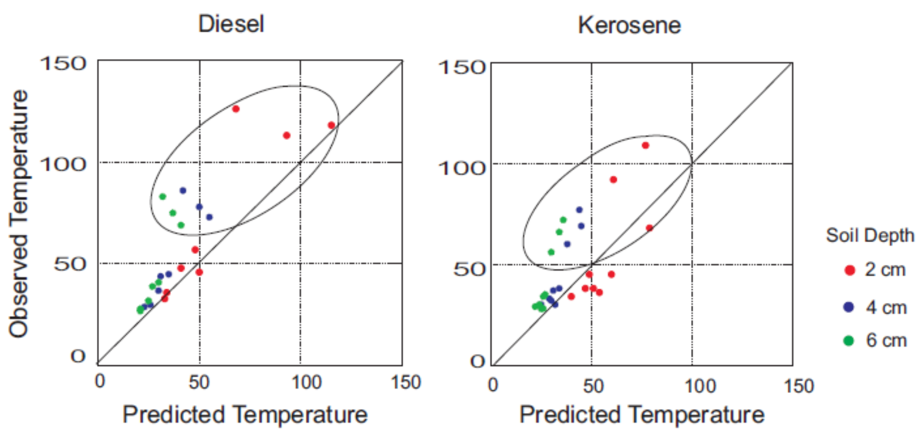

Figure 8. Comparison of diesel and kerosense burns' observed and predicted tempertures. The dry soil treatment temperatures are within the ellipsoids.

Conclusion

This paper presents the first soil heating tests data to improve our understanding of factors which influence heat transfer to and within soils resulting from in-situ burning. Phase 1 soil heating test results showed the Campbell model (FOFEM) captures the dominant soil heat transfer processes for ISB. The soil temperature observations

[3] NOTE: changes in moisture content of the upper soil level at thermocouple interface would affect heat energy estimates and the prediction of subsequent heat transfer. This was also a significant problem limiting the use of the data from the saturated soil moisture diesel burns with the 7 mm oil thickness treatment. These results suggest improvement in measuring heat energy input at the soil surface would improve model predictions.

[4] NOTE: under prediction could have been from surface thermocouple temperature measurements that were not representative of surface temperatures. If a thermocouple was not in good contact with soil or exposed to air above the soil surface, then the thermocouple bead could heat or cool more rapidly than surrounding soil.

and estimates of total heat energy and heat flux were comparable with results from other ISBs, and the model was able to reasonably predict temperature distributions in soil during Phase 1 burns with kerosene and diesel fuel. Phase 2 results were similar to Phase 1 in that saturated soil conditions during burning limited soil heating. The moisture content of saturated soils (standing water and 2 cm of standing water) was sufficient to insulate soils from burning of crude and diesel oil. The results suggest that the post burn increase in soil CO_2 respiration is likely to due to the fertilizer effect induced by fire increasing the availability of nutrients.

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