In Situ Soil Temperature and Heat Flux Measurements During Controlled Surface Burns at a Southern Colorado Forest Site

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Abstract—*This study presents in situ soil temperature measurements at 5-6 depths and heat flux measurements at 2-5 depths obtained during the fall/winter of 2001/2002 at seven controlled (surface) fires within a ponderosa pine forest site at the Manitou Experimental Forest in central Colorado. Six of these burns included three different (low, medium, and high) fuel loadings under both a closed-canopy forested site and an open forest with a grassy meadow understory. The fuel loading for the seventh burn was a conical pile of slash about 6 m in height and 9 m in diameter and was intended to duplicate the structure and loading of a slash pile resulting from mechanical harvesting activities. One basic purpose of this initial experiment was to assess how well some commercially available soil heat flux plates would perform at high temperatures. The data presented here include soil temperatures, heat fluxes, and depth and duration of the thermal energy penetration into the soils. The maximum surface heat fluxes were estimated to be about 2400 Watts/meter^2 [Wm^{-2}] at the slash pile burn site, 2300 Wm^{-2} at the high fuel meadow site, and 3000 Wm^{-2} at the high fuel forested site. Extrapolated surface temperatures are about 436 C at the slash burn site, 359 C at the high fuel meadow site, and 95 C at the high fuel forested site. Recovery of a normal daily temperature cycle depended on fire duration and fuel loading. The recovery times were between 16 and 20 hours at the high fuel sites, about half this time at the medium fuel sites, and less that 2 hours at the low fuel sites. However, the recovery time at the slash pile site was about 2 weeks. Although further tests and refinements are planned, the present results suggest not only that soil heat flux can be reliably measured during controlled burns, but that soil temperatures and heat flux can differ significantly with different fuel loadings.*

Introduction

Both natural and prescribed fires play important roles in managing and maintaining most ecosystems in the western United States. In many ecosystems, fire is the major cause of disturbance and change. One of the less visually obvious changes caused by fire, even a relatively small fire, is the heat pulse and associated high temperatures that penetrate the soil. High soil temperatures influence forests and their ability to regenerate after a fire by altering soil properties; killing soil microbes, plant roots, and seeds; destroying soil organic matter; and altering soil nutrient and water status and soil nutrient cycling (Frandsen and Ryan 1986; Hungerford et al. 1991; Campbell et al. 1995; DeBano et al 1998). Some consequences of fire can be subtle and long term (Sackett and Haase 1992; DeBano et al 1998), while others, such as increasing soil erosion and the concomitant effects on water quality and the hydrological cycle, are more immediate and obvious. Because fire is frequently used by land managers to reduce surface fuels, it is important to know how

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soil properties and fuel conditions interact to determine the nature and extent of the soil heat pulse. Ideally, quantifying this coupling between surface fuels and the soil heat pulse requires both observational and modeling studies (e.g., Steward et al 1990), for which both soil temperature and soil heat flux data are necessary for understanding the physical processes governing heat propagation through soils and for verifying model performance. Ultimately, such a combined approach should help managers to maximize the ecosystem benefits of a prescribed fire while minimizing the potential for harm.

This report presents and discusses the initial results of a larger experiment to evaluate how different amounts and geometrical arrangements of fuel loadings influence forest regeneration after fires. Here we specifically detail in situ measurements of soil temperature and heat flux taken during seven controlled burns in Manitou Experimental Forest in central Colorado. The primary motivation for these initial burn experiments was to assess the ability of two commercially available soil flux heat plates to operate at the high temperatures encountered during surface fires. This is achieved in this report by examining the data for internal consistency and by developing a simple method of extrapolating the measured soil temperature and heat flux data to surface values during the fires.

Experimental Design

Site Location and Description

Manitou Experimental Forest is located in Teller County, central Colorado. The site latitude and longitude are 39 ° 04' North and 105 ° 04' West with an elevation of about 2400 m. Vegetation at the burn areas is predominantly ponderosa pine with an understory of bunchgrasses with numerous grassy openings throughout the area. Soils at the burn areas were either Boyett-Frenchcreek-Pendant associated with 15 to 40 percent slopes with a typical bulk density of 1.20-1.35 gm cm^{-3} and an air permeability of about 12 ± 6 (10^{-12}) m^2 or Pendant cobbly loam also occuring on 15 to 40 percent slopes with a bulk density of 1.30-1.70 gm cm^{-3} and air permeability of about 4 ± 2 (10^{-11}) m^2 (USDA and other agencies 1986). Except for the few soils that are derived from red arkosic sandstone, all soils in the area are derived from biotite granite and associated igneous rocks of the Pikes Peak batholith. Annual precipitation on the forest is about 400 mm and the annual mean ambient temperature is about 5 C.

Fuel Loadings and Sensor Deployment

Three sites were instrumented and then amended by adding slash of various densities. The first two sites, consisting of three plots each, were instrumented on March 22, 2001, on the Boyett-Frenchcreek-Pendant type soil. Three plots with low, medium, and high fuel loadings were under a closed-canopy forest (forest site) and the other three plots were within a grassy meadow associated with a more open forest (meadow site), created as a result of a timber harvest two years prior. The forest site was about 130 m west of the meadow site and the plots within each site were adjacent to one another and averaged about 70 m^2. These 6 sites were amended on April 5, 2001, and the controlled burn occured November 9, 2001. The third or slash burn site consisted of one plot and was instrumented on October 12, 2001, amended on October 18, 2001, and burned on January 11, 2002. It was about 200 m east of the meadow site. The slash pile was conical in shape and approximately 9 m in diameter and 6 m in height. The soil type at this burn site was Pendant cobbly loam and it was located within a very large grassy meadow that had been forested two years prior. The forest and meadow burn sites were on south facing slopes of small 2-3 m deep draws. The fires were initiated (as much as possible) at the bottom of the slope. The instruments were inserted horizontally and buried in the soils at relatively more horizontal areas near the top of the slope. The slash pile site was on a gentle west facing slope. Table 1 gives the details on the fuel loadings at each site for pre- and post-burn conditions.

Table 1—Fuel loadings for controlled burns at Manitou Experimental Forest. The first number in each entry is the preburn data and the second is postburn data. NA = Not Available.

Site (loading)	Fuel depth (cm)	Duff depth (cm)	Litter depth (cm)	Total loading (tonsM/hectare)
Meadow (low)	5.0/0.0	1.4/0.0	5.0/0.0	8.80/0.0
Meadow (med)	19.5/2.5	0.63/0.25	5.0/2.5	23.1/7.60
Meadow (high)	30.5/0.85	0.38/0.00	9.3/0.85	68.6/7.94
Forest (low)	5.0/3.4	0.51/0.08	5.0/2.5	1.44/0.78
Forest (med)	22.0/3.4	0.25/0.08	3.4/2.5	15.0/7.11
Forest (high)	21.2/2.5	0.25/0.00	3.4/2.5	31.8/14.4
Slash pile	600[a]/0	NA[b]/NA	NA[b]/NA	560[a]/0

[a] Estimate.
[b] Expected to be similar to average of meadow sites above.

All data were logged on Campbell Scientific CR23X's (Campbell Scientific Inc., Logan, UT). All wires connecting the sensors to the data logger were laid in a trench which was then backfilled (as much as possible) with the original soil. The data loggers were located 10 to 30 m from the sensors. All data loggers were enclosed in a metal fire resistance box. However, at the slash burn site the data logger box was also buried to ensure additional protection from the fire. Data sampling rates before and well after the fires was 1 Hz with average data recorded every half hour. Between 2 and 4 hours before, during, and for about 4 days after the fire, data were sampled at 4 Hz and recorded every 15 s. Table 2 gives the type, number, and depth of the temperature and heat flux sensors. To minimize interference between the sensors, the soil heat flux plates and soil temperature probes were separated laterally by a few centimeters.

On the morning of the fires the moisture content of the litter layers, duff layers, and the uppermost few centimeters of soil were measured at the six forest and grassy meadow sites. The litter layers were 15 percent by weight (meadow) and 23 percent by weight (forest). The duff layer was 33 percent by weight at the meadow sites and 14 percent by weight at the forest sites. Finally, the soil moisture content was about 3 percent by weight at the meadow site and about 2 percent by weight at the forest site. No fuel or soil moisture data were obtained at the slash burn site.

Potential Concerns

Before presenting the observed data it is important to bear in mind the context and the intent of this experiment. All burn sites are representative of slash left after harvesting in the area. Therefore, we would expect the present data are quite typical of many prescribed surface fires within the Manitou

Table 2—Placement and type of soil temperature and heat flux sensors for controlled burns at Manitou Experimental Forest. Here T means a temperature sensor and G_R and G_T are soil heat flux plates. Note: all thermocouple junctions were coated with epoxy (Omegabond 101) for electrical isolation.

	3 closed canopy sites and 3 grassy meadow sites		Large slash pile	
Depth (m)	**Sensor type**		**Sensor type**	
0.02	T^a	G_R^d	T^a	
0.05	T^b		T^a	G_T^f
0.10	T^c	G_R^d	T^b	G_T^f
0.15	T^c			
0.30	T^c	$G_R^{d,e}$	T^c	G_T^f
0.50			T^c	G_R^d
1.365			T^c	G_R^d

[a] Omega Engineering, Stamford, CT: model no. HH-K-24, rated 704 C.
[b] Omega Engineering, Stamford, CT: model no. TT-J-24, rated 260 C.
[c] Omega Engineering, Stamford, CT: model no. TT-T-24, rated 200 C.
[d] Radiation Energy Balance Systems, Seattle, WA: model no. HFT 3.1.
[e] Not included at the low fuel loading sites.
[f] Thermonetics Corporation, La Jolla, CA: glazed ceramic design, rated to 775 C, nominal sensor sensitivity 1250 to 1750 $Wm^{-2}mV^{-1}$, cromel extension wire to data logger: Omega Engineering TFCH-020, temperature rated to 260 C. Note: post-burn examination of extension wire did not reveal any high temperature damage.

Experimental Forest and surrounding areas. However, fuel loadings for wildfires could be quite different and could vary considerably depending primarily on recent fire history and amount of slash from previous logging activities.

Other considerations and concerns involve the measurement of soil heat flux and possible alterations or disruptions of the soil. For example, reliable estimates of soil heat flux require good contact between the soil and the heat flux plate. Any moisture present in the soil will also help maintain this contact. However, when soil temperatures reach about 100 C, soil moisture will be vaporized and the contact between the plate and the soil may degrade, resulting in poor data quality. Furthermore, performance of some of the soil heat flux plates at high temperatures is questionable because they were not specifically designed for these conditions. Finally, there is the possibility that the soil may have been disturbed when amending the plots. For these reasons, therefore, we removed all the soil temperature and heat flux plates several months after the fires and checked the vertical placement of all the sensors and the heat flux plate calibrations.

Results

Observed Soil Temperatures and Heat Fluxes

Soil temperatures and heat fluxes are presented as a pair of graphs for each burn site. The figure denoted with an 'a' is temperature and 'b' refers to soil heat flux. The first 3 figures are the meadow sites (high, medium, and low amended). The next 3 are for the forest sites (high, medium, and low amended). Figure 7 shows data from the slash burn site. As denoted on figure 7b two different soil heat flux plates were used for this site. None of the data shown in these figures have had any dropouts removed. Here data dropouts are defined as physically unrealistic negative values, such as those shown in Figs. 1a and 3a. These dropouts are associated with checking or resetting the data logger. Figs. 1a and 4a also show some spikes, which are thought to be related to spurious data logger errors. Each of these figures includes one or two days before the burn and two or more days after the burn to emphasize the dramatic change in the daily soil thermal regime caused by the fire and to give some indication of the time required at each site to recover a new daily temperature cycle.

In general, the duration and intensity of the fires were determined primarily by the amount and type of the fuel loading and secondarily by fuel moisture content and rate of spread. These secondary factors are discussed in the next section. Here we examine the primary factors, the amount and type of the fuel loading.

The data show that higher temperatures and greater magnitudes for the soil heat flux are associated with higher fuel loading. For example, the loading at the medium and high meadow sites is about double the medium and high forest sites. Correspondingly, the maximum 2 cm soil temperatures are much higher at the meadow sites for the medium (222 C) and high loadings (260 C) than at the medium (36 C) and high (69 C) forest sites. A preponderance of dry grass in the meadow site versus pine needles in the shaded forest site probably accounts for the more intense, hotter fires at the meadow site than occured at the forest sites. Even more dramatic are the differences in fuel loadings and temperatures between the slash pile site, where the temperature at 2 cm reached about 407 C, and the forest or meadow site. Similarly, soil heat flux is greater (negative indicating heat flow into the soil) with increasing fuel loading, such that the magnitudes at 2 cm reached to about 1500 Wm^{-2} at the high density forest and meadow sites and more than 1700 Wm^{-2} at 5 cm at the slash burn site.

Likewise, the depth of thermal energy penetration and the duration of the heat pulse increased with fire duration and intensity and, ultimately, fuel loading. The duration of the heat pulse can be estimated from the time required for the transient heat pulse associated with the fire to dissipate, re-establishing a daily thermal cycle after the burn. Although these recovery times do vary with depth, in general the data suggest that they were between 16 and 20 hours at the high fuel sites, about half this time at the medium fuel sites, and less that 2 hours at the low fuel forest site. In contrast, the recovery time at the slash pile site was about 2 weeks. The deepest measured penetration of thermal energy occurs at the slash pile site where the temperature and heat flux at 1.365 m began increasing several days after the fire.

The only exception to this general association between the soil thermal response and fuel loading appears to be the low fuel meadow site. At this site it appears that the fire dynamics and the micro structure of the fuel loading prevented the fire from having any measurable influence on the soil. This occured in spite of the fact that the fuel loading was about 6 times the fuel loading of the low fuel forest site. The fire was intense at this site but extremely brief. It flashed over the burial location of the sensors in just a few seconds and had mostly burned itself out in less than a minute or two. Therefore, it appears that the fire duration was too short to have had much effect on the soil (at least at 2 cm and below).

Another possible anomaly occurs with the 30 cm soil heat flux during the slash pile fire. The data are noticeably noisier and for a time are directed upward (away from the soil), rather than into the deeper soil levels. The noisy

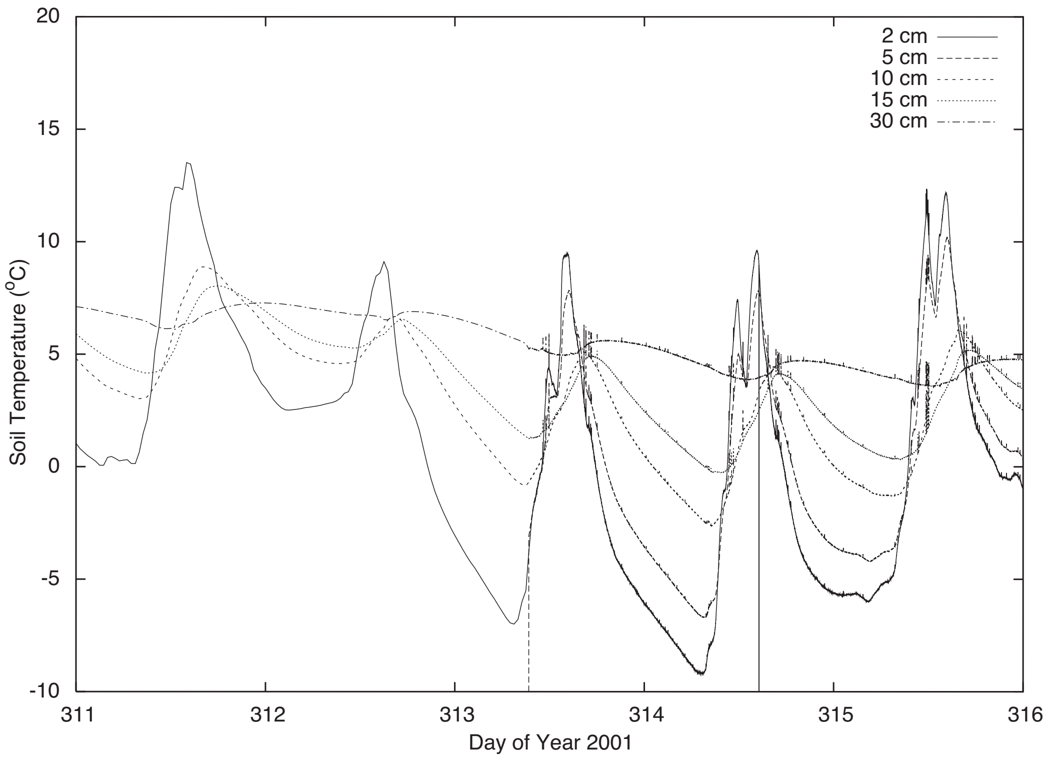
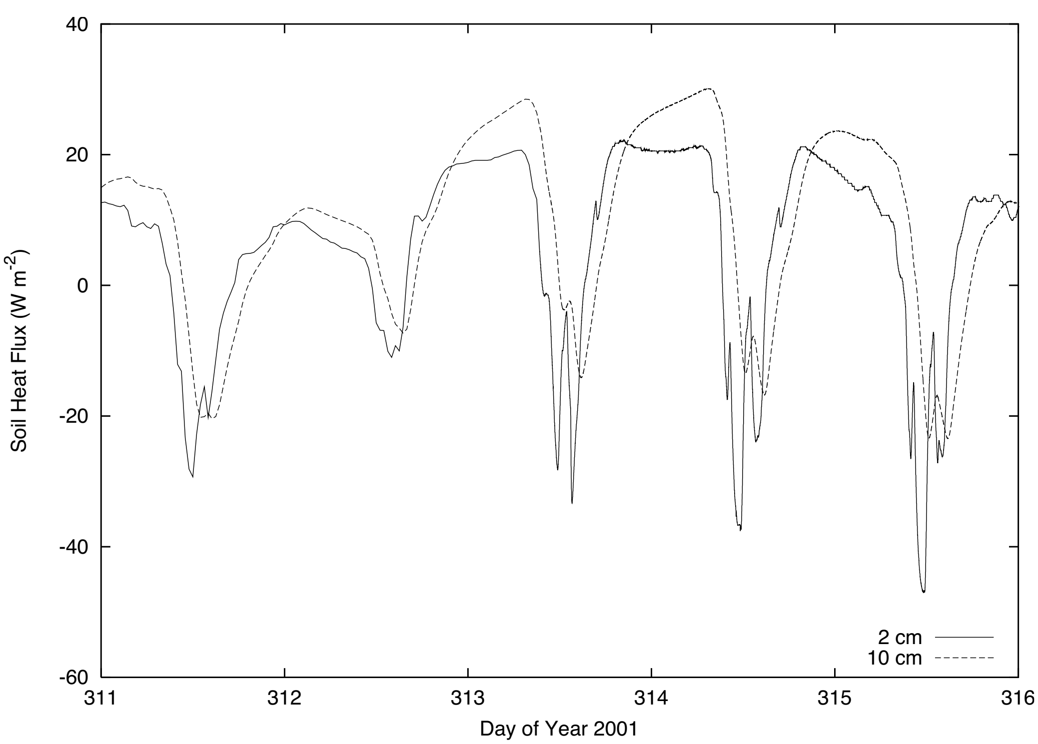
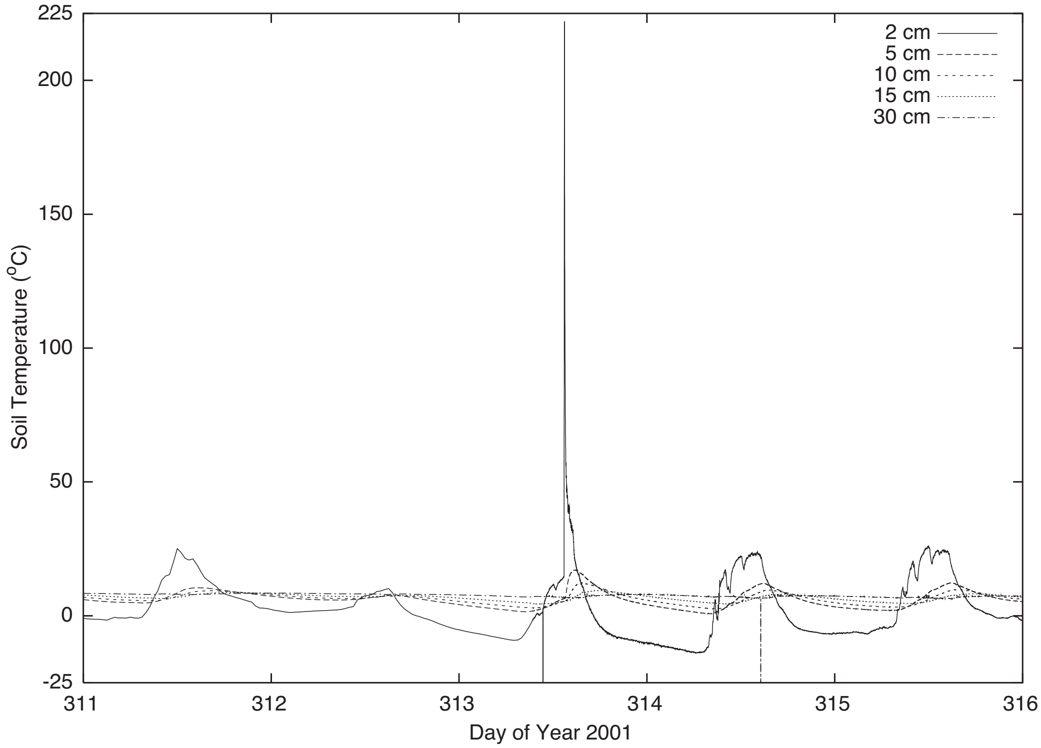


Figure 1—Five days of recorded soil temperatures (a) and heat fluxes (b) at the low fuel meadow site. Time series include two days before the fire and include two days after the fire. The fire was initiated about 1:20 PM MST on day 313 of 2001 and was over by about 1:25 PM. The soil heat flux was measured using Radiation Energy Balance Systems heat flux plates.





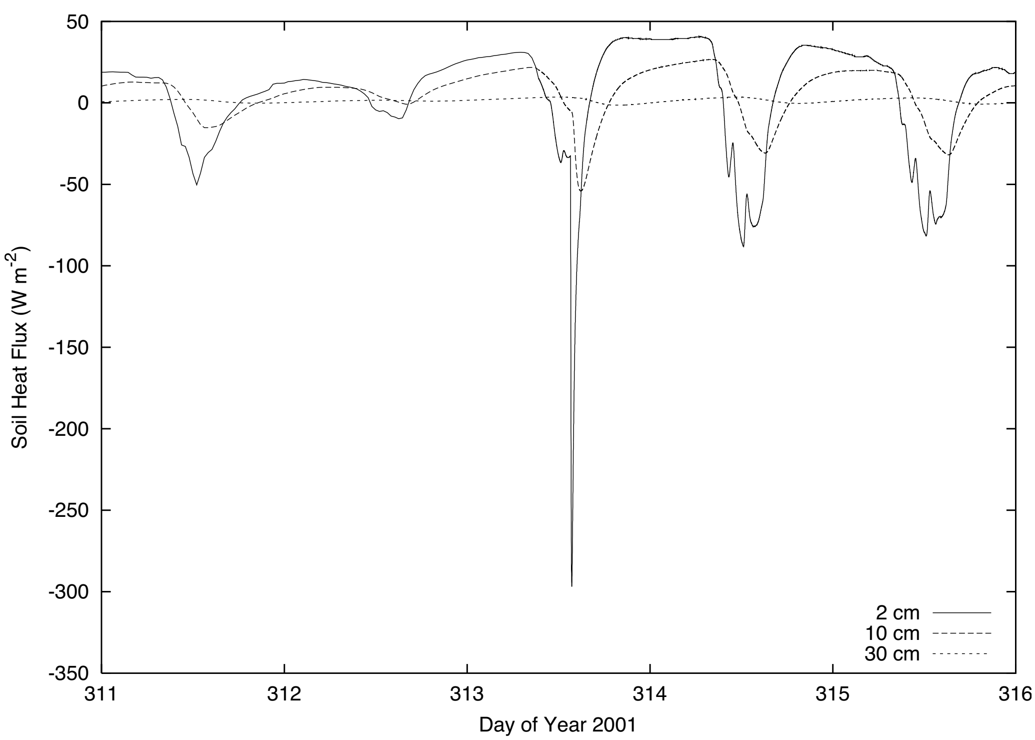


Figure 2—Five days of recorded soil temperatures (a) and heat fluxes (b) at the medium fuel meadow site. Time series include two days before the fire and include two days after the fire. The fire was initiated about 1:30 PM MST on day 313 of 2001 and was over by about 1:40 PM. The soil heat flux was measured using Radiation Energy Balance Systems heat flux plates.

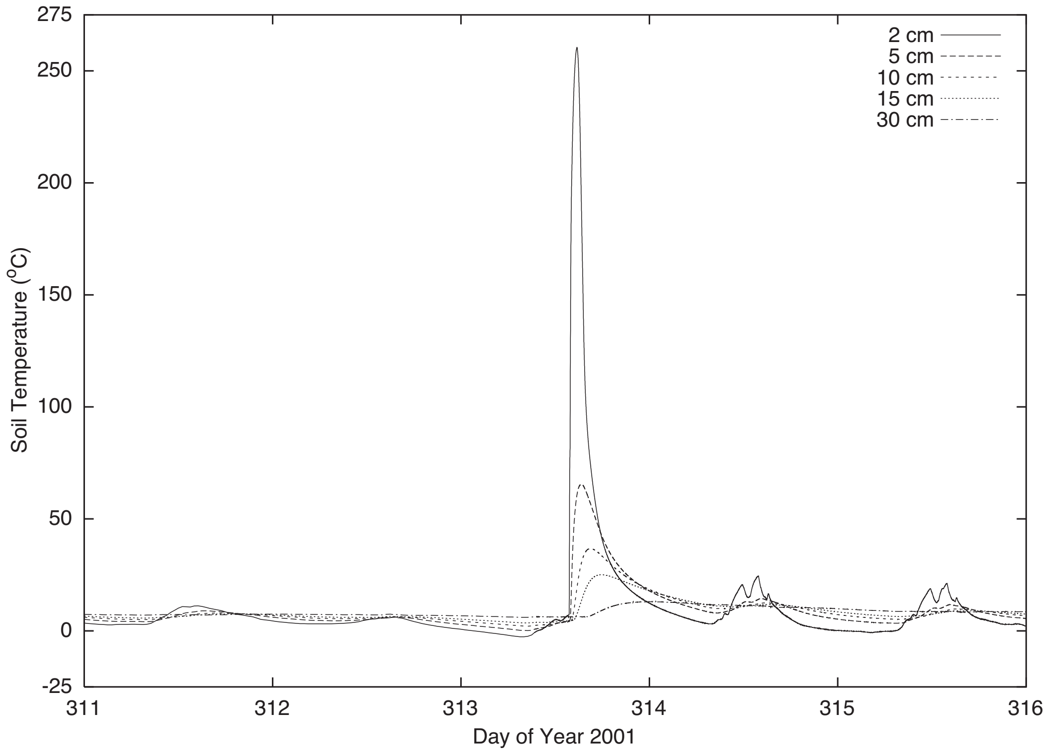
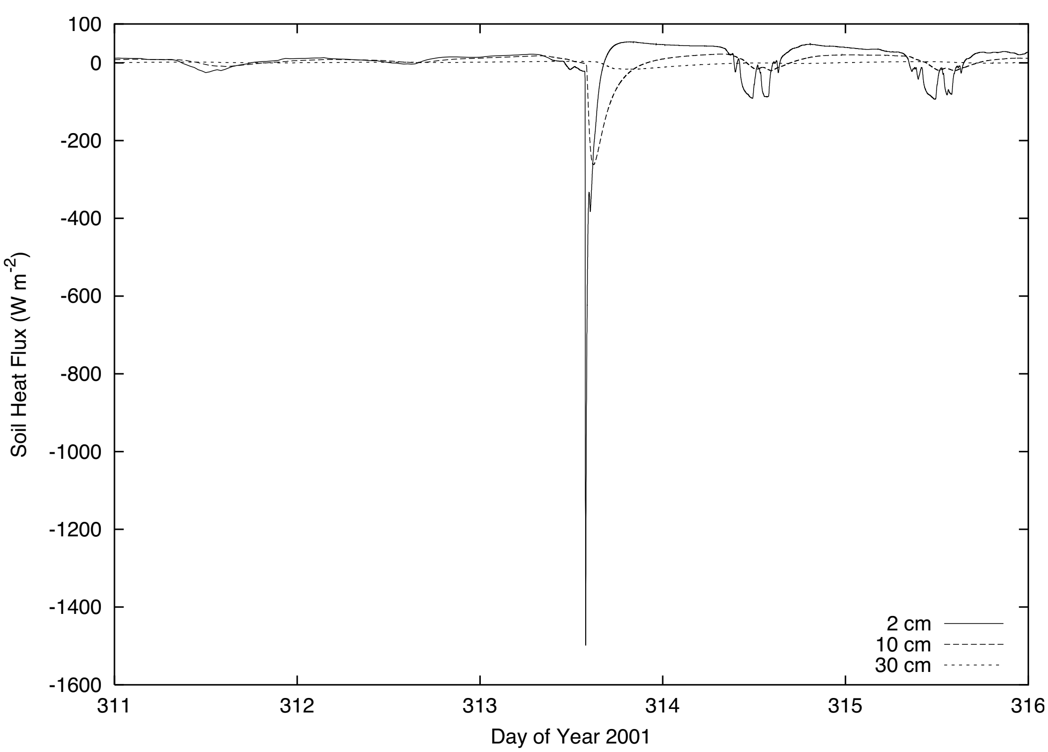
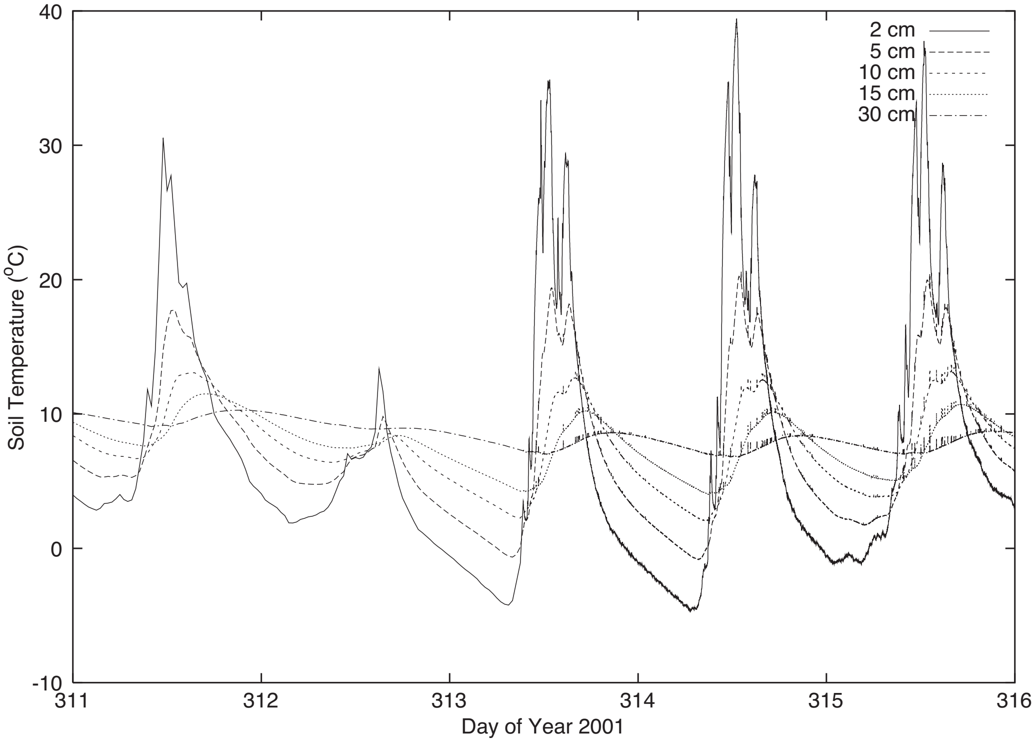


Figure 3—Five days of recorded soil temperatures (a) and heat fluxes (b) at the high fuel meadow site. Time series include two days before the fire and include two days after the fire. The fire was initiated about 1:48 PM MST on day 313 of 2001 and was mostly over by about 2:20 PM. The soil heat flux was measured using Radiation Energy Balance Systems heat flux plates.





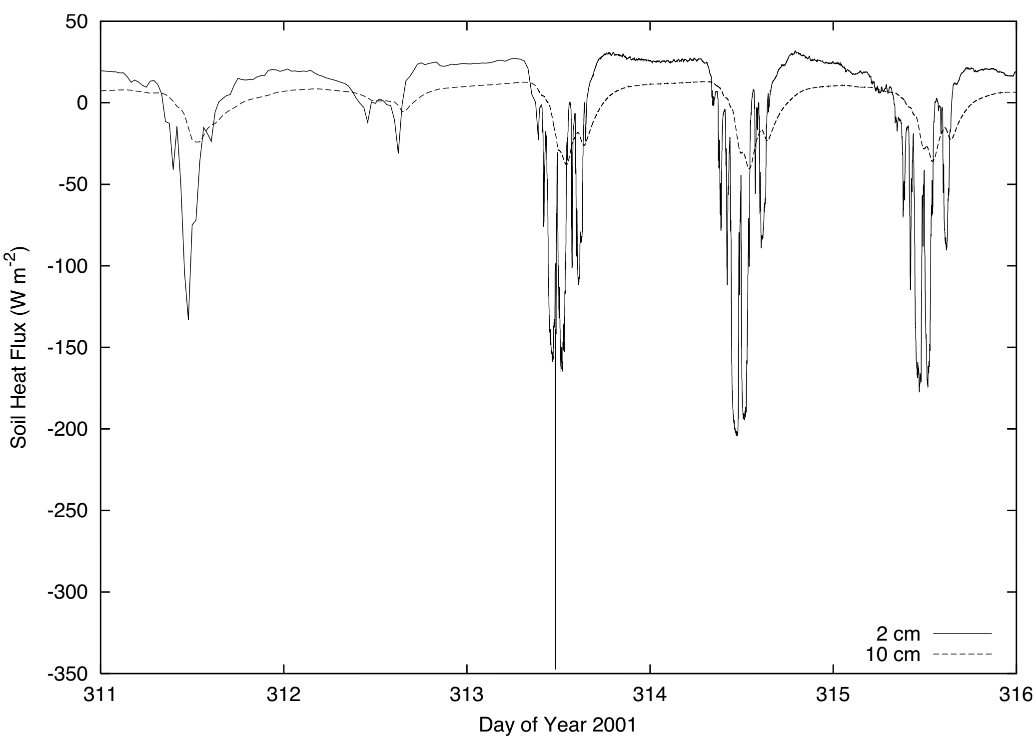
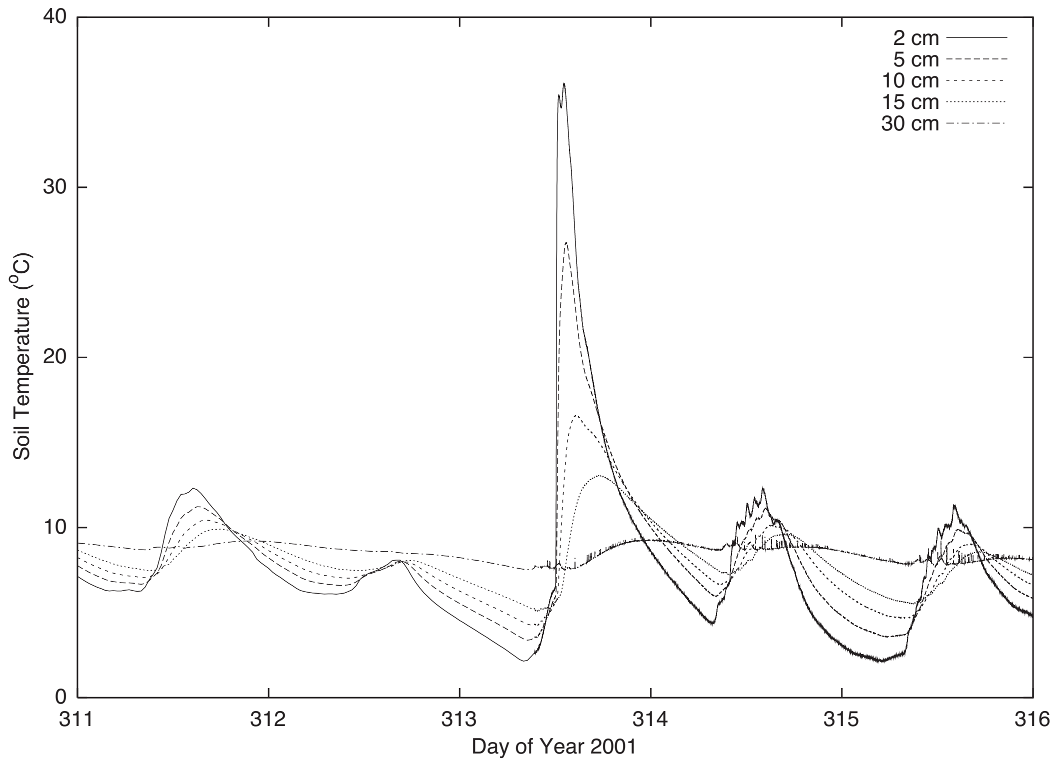


Figure 4—Five days of recorded soil temperatures (a) and heat fluxes (b) at the low fuel forest site. Time series include two days before the fire and include two days after the fire. The fire was initiated about 11:15 AM MST on day 313 of 2001 and was over by about 11:40 AM. The soil heat flux was measured using Radiation Energy Balance Systems heat flux plates.



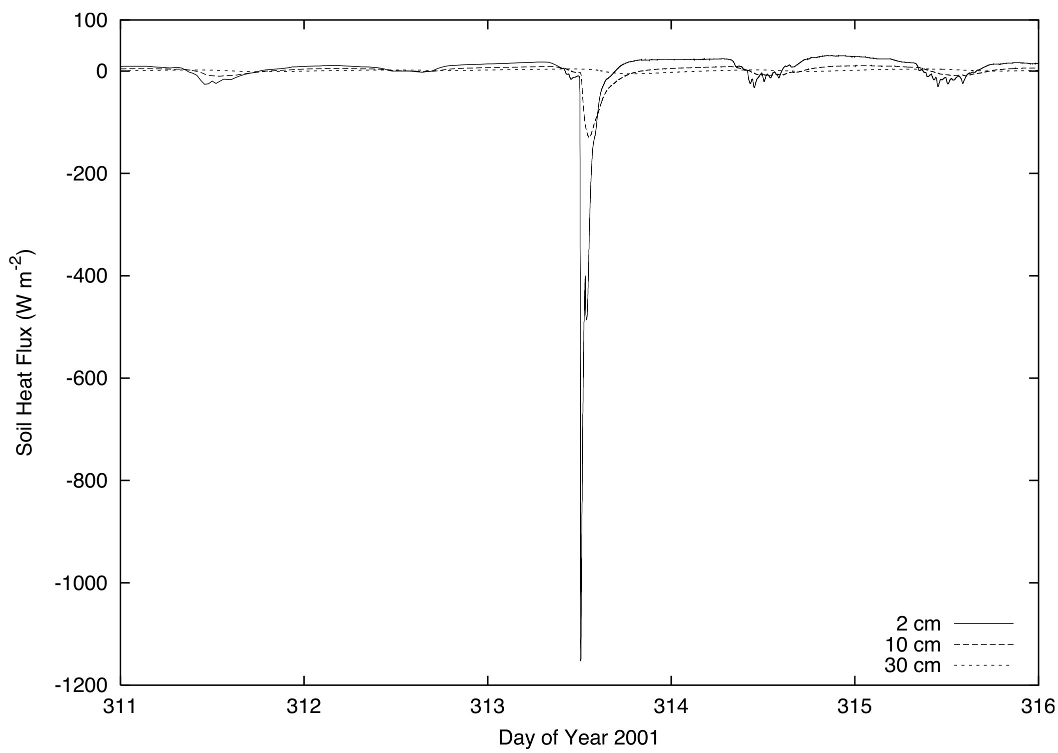
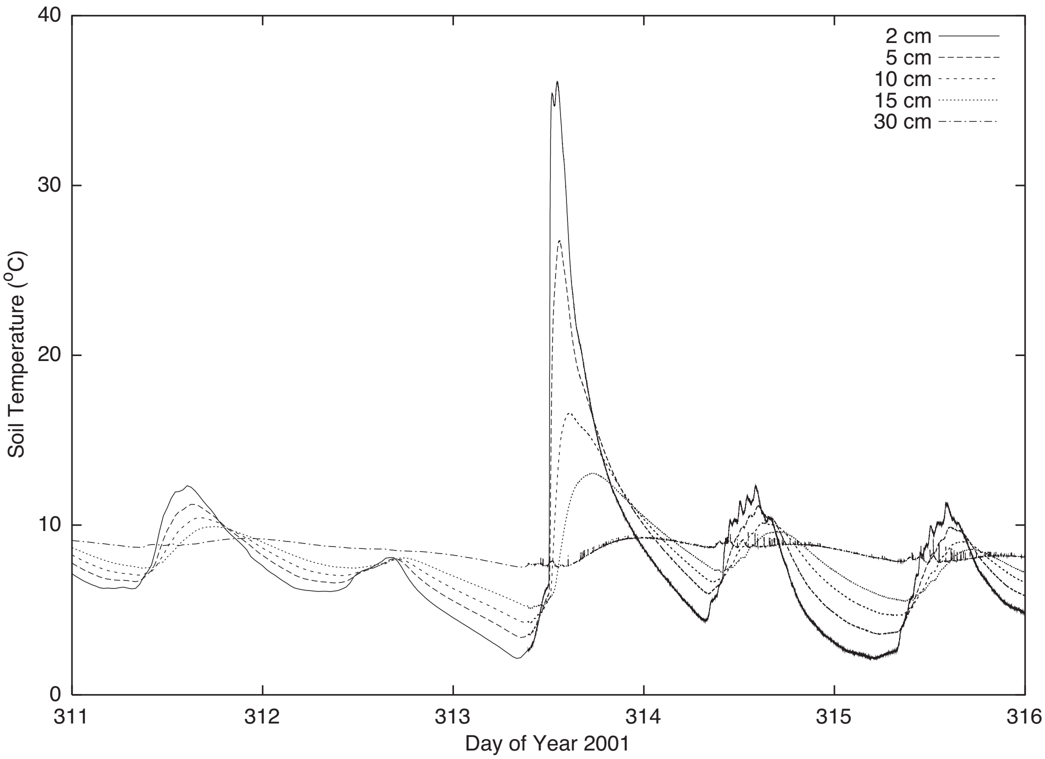


Figure 5—Five days of recorded soil temperatures (a) and heat fluxes (b) at the medium fuel forest site. Time series include two days before the fire and include two days after the fire. The fire was initiated about 11:41 AM MST on day 313 of 2001 and was over by about 12:10 PM. The soil heat flux was measured using Radiation Energy Balance Systems heat flux plates.



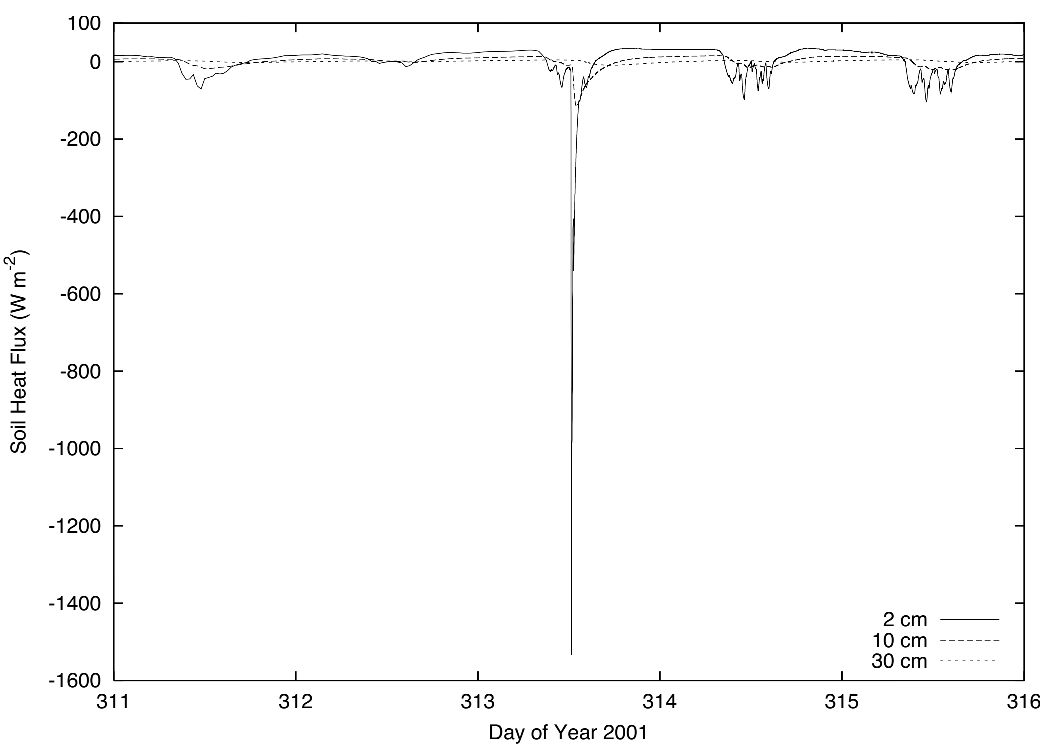


Figure 6—Five days of recorded soil temperatures (a) and heat fluxes (b) at the high fuel forest site. Time series include two days before the fire and include two days after the fire. The fire was initiated about 12:11 PM MST on day 313 of 2001 and was over by about 12:40 PM. The soil heat flux was measured using Radiation Energy Balance Systems heat flux plates.

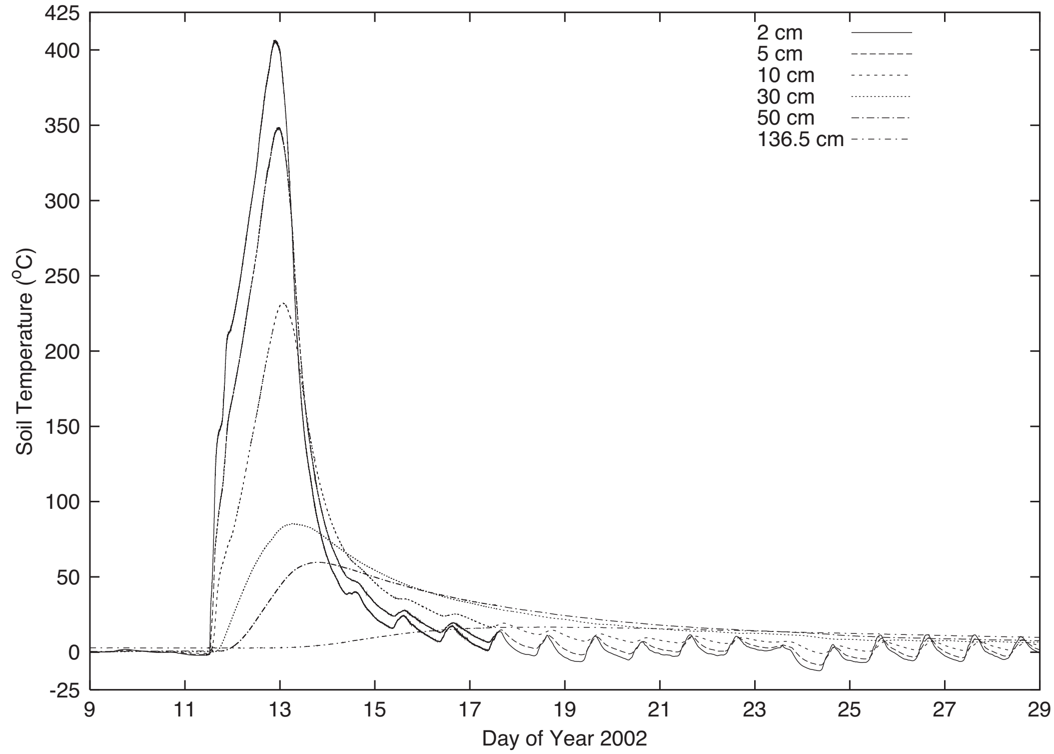
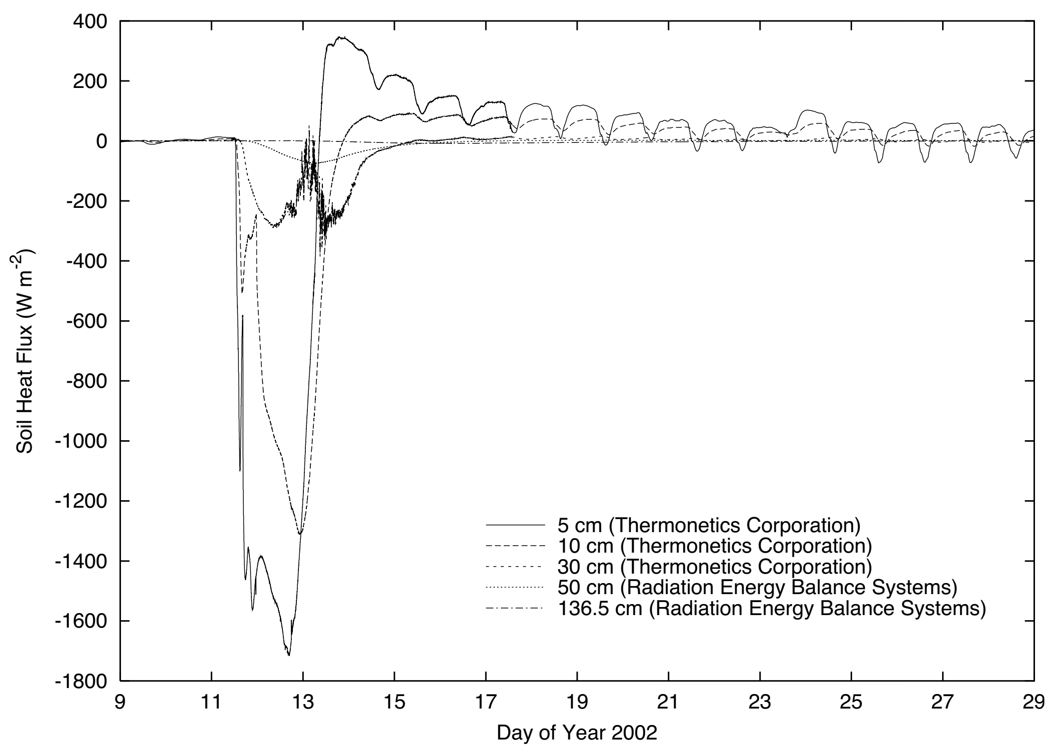


Figure 7—Twenty days of recorded soil temperatures (a) and heat fluxes (b) at the slash pile site. Time series include two days before the fire and include 18 days after the fire. The fire was initiated about 12:20 PM MST on day 11 of 2002 and burned for several hours. The manufacturers of the soil heat flux plates used during this experiment are given in the figure legend.



signal may be caused by seepage of soil moisture or water vapor through cracks or flaws in the glass glaze that seals the heat conductor from moisture. The directional change may also be related to the abrupt change from cooling to warming associated with the collapse of the burn pile about 35 minutes after initiating the fire. Both the 5 and 10 cm heat flux traces show two heat pulses separated by a brief period during which the magnitude of the flux is diminished. Furthermore, the temperature traces also show corresponding periods during which the rate of temperature increase slows considerably. When combined with the heat flux data these temperature data implicate, not only the fire and pile structure dynamics, but also that some of the thermal energy may be vaporizing any remaining soil moisture as the heat pulse propagates through the soil. The final phase of this experiment, discussed in the next section, included retrieving the sensors, rechecking their placement in the soil and the calibration factors of the heat flux plates, and in general examining them for possible defects or damage that may have occured during the periods of installation, the fire, or the site amendment.

Analysis

By using a simple mathematical description of the soil thermal pulse it is possible to estimate (or extrapolate to) the maximum temperatures and heat fluxes that occured at the soil surface during the fire. This information is probably the best way to standardize comparisons between the fires, but it may not be directly measurable. It is also useful for inferring something about the initial soil moisture content and its influence on the soil thermal properties as well as highlighting potential problems with the sensors. To accomplish this we assume a model that (at least approximately) partitions the thermal input to the soil into a dominant fire component and a secondary component representing all other thermal inputs to the soil. The simplest model we can assume relates the vertical profile of the measured amplitude (or maximum) of the heat pulse to soil depth as follows:

$$T_{max}(z) = T_0 + \Delta T\, e^{-z/D} \quad (1)$$

and

$$G_{max}(z) = G_0 + \Delta G\, e^{-z/D} \quad (2)$$

where $T_{max}(z)$ is the maximum observed value of the soil temperature as a function of depth, T_0 is a constant temperature, ΔT is the temperature amplitude associated with of the thermal pulse of the fire, and D is the soil thermal attenuation depth, which is related to the thermal properties of the soil. The symbols $G_{max}(z)$, G_0, and ΔG, used for soil heat flux, have a similar interpretation. By using the model expressed by equations (1) and (2) we follow an approach similar to Raison et al. (1986) who also suggested that the maximum fire related soil temperature decreased exponentially with soil depth. However, the present analysis differs from their study because they did have soil heat flux data nor did they calculate a thermal attenuation depth.

Because we assume that the fire dominates all other forms of thermal input to the soil we should expect that $\Delta T >> T_0$ and $\Delta G >> G_0$ are required for the model to be valid. Therefore, as we depart from this condition the model results will become less reliable. As a consequence, we can state a priori that the larger and more intense the fire, the more useful this model will be for interpretive purposes. Under this analysis scenario, ΔT is the maximum soil surface temperature during the fire and ΔG is the maximum soil heat flux at the surface during the fire.

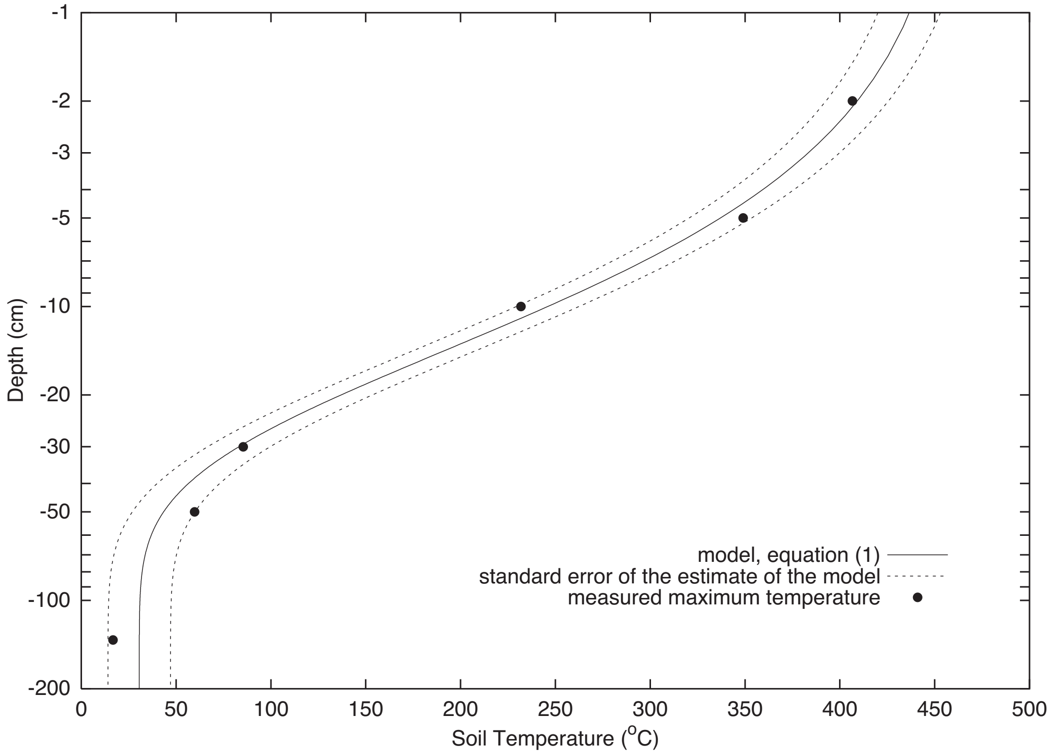
Table 3—Extrapolated surface temperatures, ΔT, and heat fluxes, ΔG, and inferred attenuation depths, D, for burns at the Manitou Experimental Forest. The standard error of the estimates are enclosed in parentheses. I = insufficient number of data points to estimate standard error of the estimate.

Site (loading)	T_0 (C)	ΔT (C)	D (cm)	G_0 (Wm^{-2})	ΔG (Wm^{-2})	D (cm)
Slash pile	31 (13)	436 (21)	14.2 (2.0)	15 (44)	-2350 (121)	16.9 (2.3)
Meadow (high)	24 (6)	734 (140)	1.8 (0.3)	-14 (I)	-2324 (I)	4.5 (I)
Meadow (med)	10 (1)	2049 (467)	0.9 (0.1)	-1 (I)	-454 (I)	4.7 (I)
Forest (high)	12 (2)	95 (7)	4.0 (0.5)	-9 (I)	-2968 (I)	3.0 (I)
Forest (med)	11 (1)	36 (4)	5.8 (1.2)	-5 (I)	-2001 (I)	3.4 (I)

The main benefit to this method of analyzing the fire data is its simplicity. However, one weakness is that it focuses only on the attenuation of the thermal pulse and does not include any aspect of the phase or time lag associated with the propagation of the thermal pulse through the soil. A phase analysis, which requires significantly more mathematical and computational effort, is beyond the intentions of the present study and is the subject of a later study. In this analysis we also treat temperature and soil heat flux independently, although theoretically at any given site the thermal attenuation depth, *D*, should be the same for both temperature and soil heat flux. The implications of similar and different values of *D* are discussed after presenting the results of the analysis.

To apply this model and these concepts to the present set of observations we simply fit equations (1) and (2) to the profile of observed maximum temperatures and heat fluxes. Table 3 gives the results of this analysis for the slash pile burn and the high and medium fuel burns at the forest and meadow sites. Note that because we are treating temperature and heat flux independently for this analysis there are two values for *D* given in table 3. The first (from left to right) is associated with temperature and the second is associated with the heat flux. The low fuel sites, which are not good candidates for this type of analysis, are not included in table 3 because it was not possible with such low intensity fires to distinguish between the thermal signals of the fires and that of the normal background. Figure 8 shows the graphs of the curve fits and observations for the slash pile burn. For this calculation the 30 cm soil heat flux data were not used because it was not possible to unambiguously identify the 30 cm peak magnitude for $G_{max}(z)$. The shaded areas of these figures correspond to the model's standard error of the estimate. Given the size and intensity of the slash pile burn, it probably provides the most reliable results. Overall, for most of these burns the thermal pulse was easily identified and the results confirm the requirement that $\Delta T >> T_0$ and $\Delta G >> G_0$. Only the temperature data at the medium fuel forest site is questionable in this regard.

Table 3 indicates that ΔT varied significantly from site to site. However, the meadow site ΔT values appear surprisingly high, suggesting there may have been temperature sensor problems. On the other hand, these high values may result from the rather high burn rate associated with the meadow sites. But, even before the burn the 2 cm temperature sensor at the medium loading meadow site seemed to be measuring anomalously high temperatures (for example compare figures 2a and 3a). The post fire inspection of the temperature sensors suggested that the nominal 2 cm temperature probes were actually much nearer the surface at both the meadow sites. The cause for this sensor misplacement is unknown, but it may have occured as a result of an



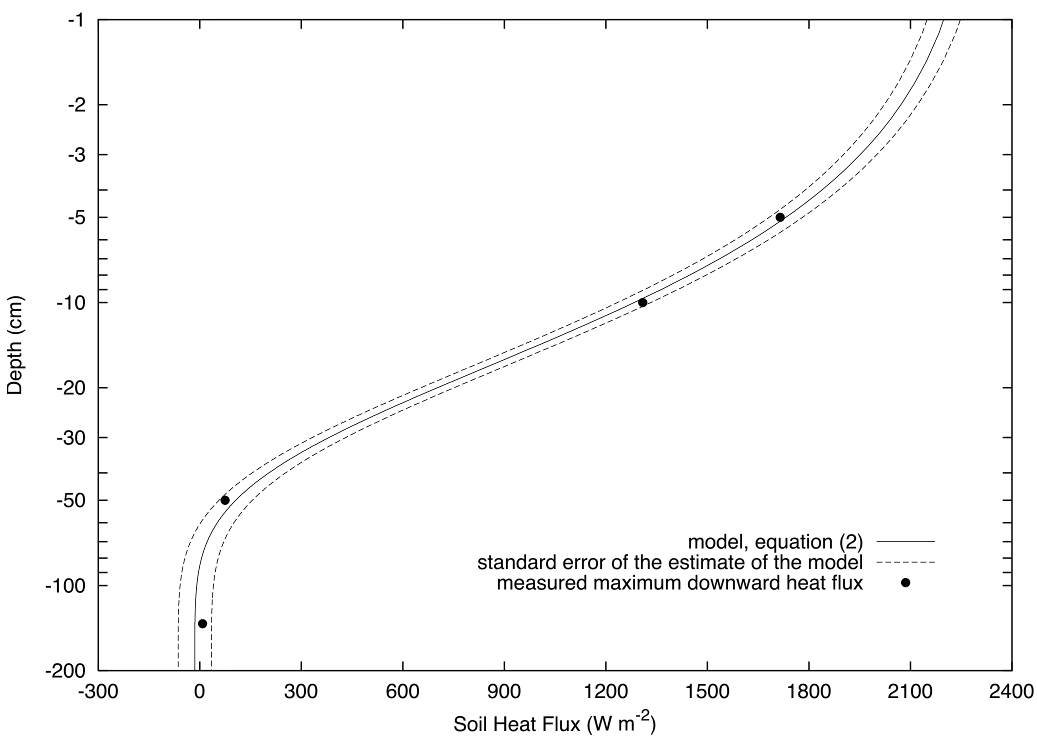


Figure 8—(a) Vertical profile of maximum measured soil temperatures (•) and the corresponding curve fit from equation (1) at the slash pile burn. (b) Vertical profile of maximum measured soil heat fluxes (•) and the corresponding curve fit from equation (2) at the slash pile burn. The shaded area in each figure encloses the model's standard error of the estimate.

Table 4—Post fire reanalysis of extrapolated surface temperatures, ΔT, and heat fluxes, ΔG, and inferred attenuation depths, D, for medium and high density fuel loadings at the meadow site burns. Sensor depth is assumed to be 1.0 cm for the high density plot and 0.25 cm for the medium density plot. The standard error of the estimates are enclosed in parentheses. I = insufficient number of data points to estimate standard error of the estimate.

Site (loading)	T_0 (C)	ΔT (C)	D (cm)	G_0 (Wm^{-2})	ΔG (Wm^{-2})	D (cm)
Meadow (high)	22 (6)	359 (25)	2.4 (0.4)	-12 (I)	-1812 (I)	5.0 (I)
Meadow (med)	10 (1)	253 (5)	1.4 (0.1)	0.2 (I)	-310 (I)	5.8 (I)

unintended disturbance during the site amendment or it may have resulted from a measurement error when the sensors were originally installed. There was no evidence of any misplacement or movement of the 2 cm soil heat flux plates at the meadow site, but the soil heat flux plates are much larger and more easily secured than the soil temperature probes. Table 4 is a recalculation of the model fits for equations (1) and (2) at the meadow site using a post fire estimate of the depth of the sensor probes. The recalculated ΔT values are still quite high at the meadow site, but they appear somewhat more reasonable. The post fire inspection also suggested that the soil sensors at the high fuel loading site were very close to a burned clump of grass, suggesting that this microscale feature of the fire may have contributed toward biasing these results somewhat high. Nevertheless, the recalculated values still indicate that there are significant site-to-site differences in soil temperatures, suggesting the need to examine why temperatures at the grass site were so much higher than the forest site.

These temperature differences likely resulted from differences in fuel type and loading, moisture content, and soil thermal properties. The differences in fuel type and loading between the meadow and forest sites (grass versus pine needles) likely contributed to a faster rate of fire spread across the meadow plots. These meadow burns lasted less than 3 minutes around the area where the sensors were buried, whereas the forest burns lasted between 10 and 12 minutes and the slash pile burn lasted several hours. Therefore, the rate of energy release was probably greatest at the meadow site. This is unquestionably true when compared with the two forest plots because of the much heavier fuel loading at the two meadow sites (table 1). Thus the thermal pulse at the meadow plots was probably confined to the upper few centimeters of soil, which is supported by the fact that the 5 cm meadow data show much less of a thermal pulse than the temperature data above 5 cm. The difference in thermal attenuation depth, D between temperature and heat flux is also greatest at the meadow site. This may be due to greater variation with depth of the soil thermal properties, which are functions of soil moisture and other soil physical parameters, than at the other sites. Finally, the total moisture content of the duff and litter layers at the meadow site was higher than at the forest site. At the meadow site the duff layer was not only deeper than the forest site (table 1), but on the day of the fire it was 33 percent water by weight, whereas the forest duff layer was 14 percent by weight. The same is also true for litter layer. However, on the day of the fire the litter layer at the forest site was slightly higher (23 percent by weight) than the litter layer at the meadow site (15 percent by weight). But, the total mass of litter at the meadow site was more than enough to compensate for the slightly lower water content. However, the moisture content of upper few centimeters of soil was about the same at both sites (between 2 percent and 3 percent by weight). Evaporating the additional moisture in the upper soil layers at the meadow site would also have tended to limit the thermal heat pulse to the upper few centimeters of the soil when compared with the forest site. On the other hand, the soil moisture content at the meadow site would have reduced soil temperatures and heat fluxes relative to what would have occured if the site had been drier (Frandsen and Ryan 1986).

Like the extrapolated surface temperature, ΔT, the extrapolated surface heat flux, ΔG, also shows significant variation. In general however, except for the medium fuel meadow site, ΔG was between 2000 and 3000 Wm^{-2} at all sites, which is in good agreement with the observations of surface soil heat flux made under a burning experimental log pile by Tunstall et al. (1976). Even allowing for the (unsupported) possibility of a meadow site soil heat flux plate positioning problem, the results of the recalculation at the meadow site (table 4) do not significantly alter this general conclusion concerning the surface heat flux, ΔG. Consequently, ΔG at the medium fuel loading meadow plot does appear anomalously low. The recalibration of the REBS soil heat flux plates (table 2) indicated that all sensors were functional and that they had maintained their calibrations in spite of the high temperatures. Possible explanations of the relatively low value for ΔG at the medium loading meadow site are poor contact between the soil and the 2 cm soil heat flux plate or the microstructure of the fire on this plot was such that the soil just above the 2 cm heat flux plate was not exposed to as much heat as the temperature sensors, which were separated laterally from the heat flux plates by 6-8 cm. Poor contact seems more likely, although we cannot completely eliminate the other possibility. The recalibration of the Thermonetics sensors also showed that they survived the fire at the slash pile site without damage, which reinforces our confidence that all other ΔG values are reasonable and that value for ΔG at the medium loading meadow site is in fact related to measurement error.

Although we did not list it in table 2, one of the REBS sensors was destroyed (melted) during the slash pile burn. We had installed this particular sensor at a depth of 10 cm before the fire to compare with the 10 cm Thermonetics sensor. However, the data obtained by this sensor before the fire were not consistent with the 10 cm Thermonetics sensor or any of the other 10 cm sensors. An examination of this sensor after the fire showed that the shrink tubing at the splice joining the sensor wires to the extension wires was not in good contact with the splice, which could have allowed moisture to short the connection and degrade the sensor signal. A similar problem was found with the heat flux plate at the 2 cm low loading meadow plot (figure 1b), which in this case may have caused an underestimation of the soil heat flux at 2 cm. (Otherwise the soil heat flux wave at 2 cm would show more attenuation at 10 cm than it does; see figure 1b.) Again, however, we cannot rule out poor contact as the cause for these two problem sensors. Nevertheless, potential measurement problems before the fire would not have caused the sensor to melt. For the benefit of future studies we note that the maximum soil temperature measured during the fire at this site was 232 C and that this REBS sensor was exposed to temperatures in excess of 150 C for over 48 hours (figure 7a). The 2 cm heat flux plates at the meadow medium and high loading plots were exposed to similar temperatures, but their exposure times were much shorter (figures. 2a and 3a).

Finally tables 3 and 4 also suggest that the attenuation depth, D, varies significantly from site to site. The large differences in the values of D between the slash burn site and the other sites suggests either significantly different soil thermal properties at the slash burn site or that the duration and intensity of the slash burn fire were sufficient to alter the soil thermal properties by evaporating the soil moisture at this site, combusting soil organic matter, and altering soil physical structure (e.g., DeBano et al. 1998). Evaporating soil moisture, at least, is quite likely if the soil contained any water in the upper 30 - 50 cm at the time of the fire. The significant variation in *D* between the temperature data and the soil heat flux data at the meadow site is probably more indicative of some of the previously discussed problems with the temperature and heat flux sensors at this site than it is indicative of any soil physical or thermal characteristics of the site.

Discussion and Conclusions

This study has demonstrated that it is possible to measure soil heat flux during a surface burn. Such data are important for modeling the soil thermal pulse during fires and to help with diagnosing possible soil moisture effects and evaporation during fires. Present results also confirm that soil temperatures and heat fluxes associated with surface fires can vary significantly with fuel loading, duration and intensity of the fire, and (at least indirectly) with the moisture content of the surface litter and duff. This study has also shown that large, long duration fires in heavy surface fuels can cause the thermal pulse to reach deeper into the soil and are more likely to affect belowground biota than shorter and more intense fires. Steward et al. 1990 reached a similar conclusion in their modeling study of surface fires. In addition, results of this study also suggest that surface temperatures of shorter more intense fires may also be high, but that the effects may be confined to shallower soil depths. It is possible, therefore, that such fires may cause greater loss of seeds lying on or embedded shallowly within the soil than larger less intense fires. This last scenario depends of course on the individual and species seeds' heat resistance and the moisture content of the near-surface soil layers, with the more moist soils associated with lower lethal temperatures (DeBano et al. 1998). Nevertheless, during this experiment soil temperatures at all but the lightest fuel loading plots reached nearly 100 C which should prove lethal to virtually all seeds (Hungerford et al. 1991, DeBano et al. 1998).

Management implications of these results for the Front Range of Colorado would indicate that burning surface fuel loadings under ponderosa pine forests and those resulting from lopping and scattering logging slash tend to produce soil heat pulses that are of relatively short duration and have a shallow depth of penetration. Burning large slash piles produce long duration, high temperature heat pulses that penetrate deep into the soil, potentially altering both physical and biotic characteristics of the soil to significant depths. Potential consequences of such large intense fires include the increased risk of erosion and a decreasing likelihood of seeding establishment and survival (DeBano et al. 1998).

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