1.8

An in situ investigation of the influence of a controlled burn on the thermophysical properties of a dry soil

W. J. Massman[1] and J. M. Frank
USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado

1 Introduction

High soil temperatures associated with fire influence forests and their ability to regenerate after a fire by altering soil properties and soil chemistry and by killing microbes, plant roots, and seeds. Because intense wild fires are an increasingly common component of the landscape (Graham 2003) and because fire is frequently used by land managers to reduce surface fuels, it is important to know if and how soil properties may change as a consequence of the fire-associated soil heat pulse. In particular, it is important to know whether the intrinsic (dry) soil thermophysical properties – volumetric specific heat capacity (C_s) and thermal conductivity (λ_s) – change as a result of soil heating. Significant changes, particularly in the intrinsic thermal conductivity of fire-affected soils, could indicate changes in the soil's structure, because soil thermal conductivity is strongly influenced by soil structure (Farouki 1986). Furthermore, such changes will lead to changes in the daily energy flow through the soil and the associated patterns and magnitudes of soil temperatures, which in turn may affect soil chemistry, soil aggregate stability, soil biota, and ultimately the nature of the soil's recovery from fire.

2 Soil Thermal Properties

More details concerning the controlled burn experiments and the soil heat flux and concurrent soil temperature measurements can be found in Massman *et al.* (2003) and Massman and Frank (2004). This section summarizes their results.

The average daily values of the soil thermophysical parameters are estimated from measurements of the daily cycle of soil temperature and heat flux for a few days before (see Figs. 1 and 2) and after the controlled burn. The basic approach used in this study exploits the nearly sinusoidal nature of the daily energy flow in and out of the soil and is quite similar to the approach Massman (1992) used at an eastern Colorado prairie site. Of course the basic presumption is that any significant changes in the soil thermal properties should be detectable from changes in the daily temperature and heat flux waves.

[1]Corresponding author address: W.J. Massman, USDA/Forest Service, 240 West prospect, Fort Colins, CO 80526; e-mail: wmassman@fs.fed.us

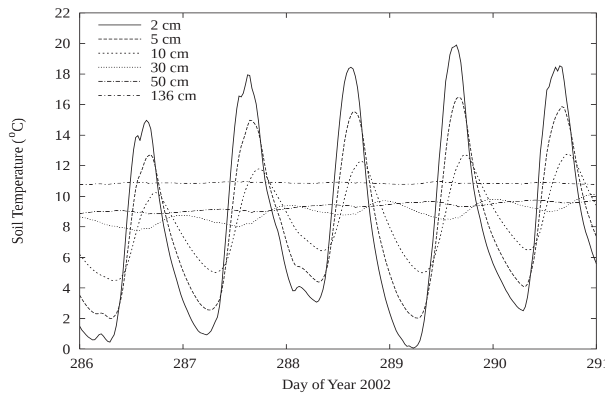

Figure 1: Pre-burn soil temperatures for October 13 - 17, 2001 at Manitou Experimental Forest (Colorado) controlled burn site.

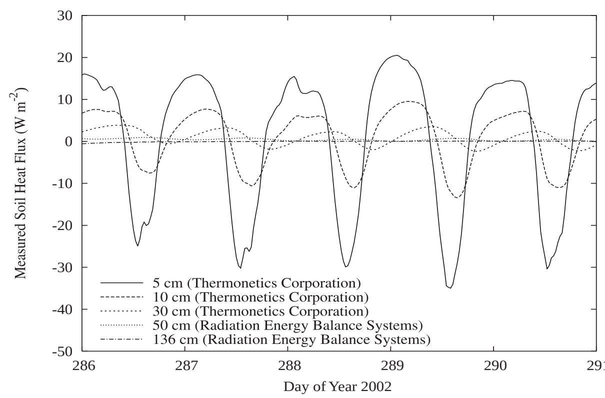

Figure 2: Pre-burn soil heat fluxes for October 13 - 17, 2001 at Manitou Experimental Forest (Colorado) controlled burn site. Negative fluxes indicate that the heat flux is into the soil.

Assuming soil thermal properties that are uniform with depth and constant with time the daily temperature and heat flux waves can expressed as Fourier series:

$$T(z,t) = T_0 + Q_0 z + \sum_{n=1}^{N} \Delta T_n e^{-z\sqrt{n}/D} e^{i(n\omega t - z\sqrt{n}/D + \phi_n)}$$

and

$$G_s(z,t) = G_0 + \sum_{n=1}^{N} \Delta G_{sn} e^{-z\sqrt{n}/D} e^{i(n\omega t - z\sqrt{n}/D + \phi_n + \pi/4)}$$

where $T(z,t)$ is the soil temperature as a function of depth z and time t; T_0 is the mean daily temperature; Q_0 is the mean daily temperature gradient; ΔT_n is the surface amplitude of the n^{th} harmonic of the daily temperature wave; $\omega = 2\pi/(24 \text{ hrs})$ is the frequency of the daily soil thermal energy wave D [m] is the soil attenuation depth, which by definition is $\sqrt{2\lambda_s/(C_s\omega)}$; G_0 is the mean daily soil heat flux; and ΔG_{sn} is the surface amplitude of the n^{th} harmonic of the daily heat flux wave. Note that $z = 0$ is the soil surface. For the purposes of this study the mean daily heat flow terms ($T_0 + Q_0 z$ and G_0) and the higher harmonics ($n > 1$) are not necessary. Consequently the following analysis focuses on the fundamental ($n = 1$) or 24-hour wave with the understanding that all results can easily be generalized to higher harmonics if necessary. We will also drop the $n = 1$ harmonic subscript for the remainder of the discussion.

The Fourier transform of these equations yields the following depth attenuation functions for the amplitudes of the fundamental temperature and heat flux waves:

$$A_T(z) = \Delta T e^{-z/D}$$

and

$$A_G(z) = \Delta G_s e^{-z/D}$$

where $A_T(z)$ and $A_G(z)$ are the amplitudes of the associated waves as functions of depth. These relationships are used along with a nonlinear least squares technique to determine the best fit values of the amplitudes and attenuation depth from the observed temperature and heat flux profile data. Next employing the general relationship between the soil temperature gradient and the soil heat flux, $G_s(z,t) = -\lambda_s \partial T(z,t)/\partial z$, yields an estimate of the soil thermal conductivity:

$$\lambda_s = \left[\frac{\Delta G_s}{\Delta T}\right] \frac{D}{\sqrt{2}}$$

However, the difference between the thermal conductivities between the heat flux transducer (HFT) and the soil (Philip 1961) must be take into account. This is achieved by combining Philip's (1961) model with the equation above, eliminating G_s, and solving the resulting quadratic for λ_s in terms of ΔT, D, the measured heat flux amplitude (ΔG_m), the thermal conductivity of the HFT (λ_p), and the HFT geometry parameters (r and β – Philip 1961). This yields:

$$\lambda_s = \frac{-(1-\beta r)\lambda_p + \sqrt{(1-\beta r)^2 \lambda_p^2 + 4\beta r \lambda_p [\frac{\Delta G_m}{\Delta T}] \frac{D}{\sqrt{2}}}}{2\beta r}$$

Once λ_s has been determined, C_s and the soil thermal diffusivity ($\kappa_s = \lambda_s/C_s$) can be found as follows:

$$C_s = \frac{2\lambda_s}{D^2\,\omega}$$

and

$$\kappa_s = \frac{D^2\,\omega}{2}$$

The foregoing analysis is based on the assumption that the soil thermal properties (C_s and λ_s) are uniform with depth, which implies that the maximum soil heat flux at a given depth should lead the maximum soil temperature at the same depth by 3 hours. However, an analysis of the phase between the measured heat fluxes and temperatures suggested that the soil heat flux leads the temperatures by between 2.5 and 2.7 hours. See Massman and Frank (2004) for the model that generalizes the above uniform-properties model of soil heat flow for a phase that is less than 3 hours. Their derivation will not be repeated here.

3 Results

The controlled burn was initiated on January 11, 2002 (Fig. 3). The pre-burn data were obtained during the 5 day period between October 13 and 17, 2001 (Figs. 1 and 2). The post-burn data were obtained during two different periods: January 25-28, 2002 and February 5-8, 2002.

Table 1 lists the estimates of the soil thermophysical parameters with the new model (Massman and Frank 2004), with the uniform-properties model, and the laboratory analysis. In general, the new model agrees more closely with the laboratory results than does the more familiar uniform-properties model. However, both models tend to underestimate the laboratory results for λ_s and C_s. This may be explained, at least in part, by the small amount of moisture present in the laboratory sample, which could cause the laboratory results to be a bit higher than the in situ estimates.

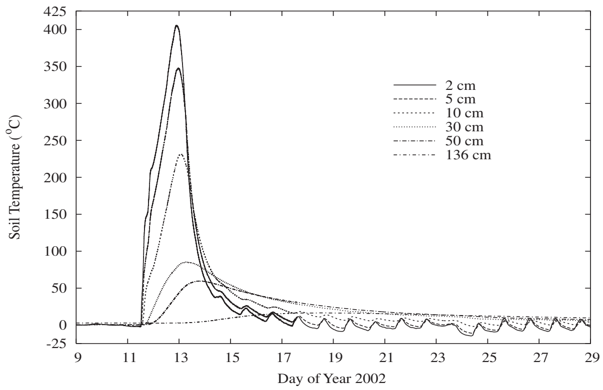

Figure 3: Soil temperatures at the controlled burn site for January 9 - 28, 2002. Time series begin two days before the fire. The fire was initiated about 12:20 PM MST on January 11 and burned for several hours.

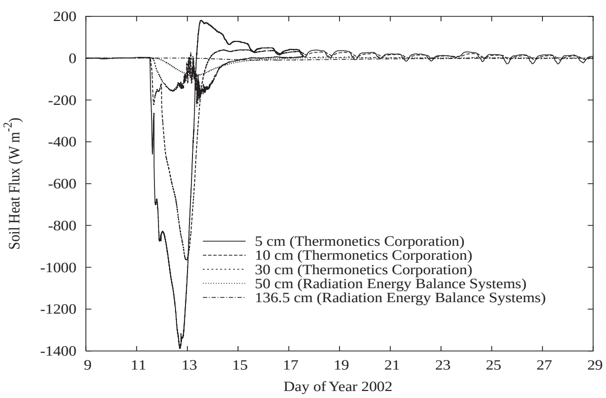

Figure 4: Corrected soil heat fluxes (Philip 1961) for January 9 - 28, 2002 (before, during, and after the controlled burn) at the Manitou Experimental Forest controlled burn site. Negative fluxes indicate that the heat flux is into the soil.

Nevertheless, none of the changes in the thermophysical parameters from before to after the controlled burn appear to be significant, because all variations in the parameters are less than the inherent variability identified previously in the day to day changes. Therefore, we conclude that this controlled burn, which heated the upper centimeters of soil to over 400 C, probably did not affect the thermophysical properties of the soil.

Given that so much of the soil was exposed to temperatures exceeding 300 C, which is the threshold of expected change in soil structure (DeBano *et al.* 1998), and the close connection between soil structure and thermal conductivity (Farouki 1986), our results may seem at odds with expectations. But there are at least two mitigating issues. First, the soils at Manitou Experiment Forest are extremely poor in organic

Table 1: Comparison of the thermophysical parameters before and after the controlled burn as determined in situ with the new model of heat flow, the uniform-soil-properties model, and the laboratory analysis from a soil sample obtained after the burn and within the burned area. The parameter values are a result of averaging over several contiguous days. λ_s values are W m^{-1} K^{-1}, C_s values are MJ m^{-3} K^{-1}, and κ_s values are 10^{-6} m^2 s^{-1}.

Parameter	10/2002	1/2003	2/2003	Lab
λ_s [new]	0.30	0.29	0.28	0.32
λ_s	0.23	0.21	0.21	
C_s [new]	0.83	0.83	0.85	0.92
C_s	0.81	0.81	0.85	
κ_s [new]	0.34	0.35	0.33	0.35
κ_s	0.29	0.26	0.25	
D_0 (m) [new]	0.10	0.10	0.10	0.10
D (m)	0.09	0.08	0.08	

material (1-2% by volume) and most is located on top of the mineral layer. Therefore, the soil aggregates, which result from the presence and action of organic material (DeBano *et al.* 1998), may not have been significantly affected by the combustion of the soil organic matter. A second consideration is that for the month or so after the fire, the period examined in this study, the soils were not perturbed. There were no wetting or drying cycles. Although the soil did undergo a freeze-thaw cycle almost nightly. But again with virtually no soil moisture, the associated cycle of soil expansion and contraction may not have been enough to have perturbed soil aggregate stability. It is possible, therefore, that the conditions and soils at Manitou Experimental Forest are sufficiently unique, particularly during the period covered by the present study, that only minimal (or undetectable) structural change was possible as a result of the burn. Of course, it is also possible that the duration of the in situ soil observations was not long enough to have permitted a perturbation to cause an observable change.

We close this section with Figure 4, which shows the true soil heat flux, G_s, during and after the fire as found from the measured heat flux, G_m, Philip's (1961) correction, and the in situ estimates of λ_s (Table 1), which have been augmented by appropriate temperature effects (Campbell *et al.* 1994). The measured soil heat fluxes also include the temperature effects on the HFTs' thermal conductivities and calibration factors. Data such as this should be helpful in future modeling studies of the soil thermal heat pulse associated with fire, because heretofore soil heat flux data have not been available for model validation.

4 Conclusions

This study explored the possibility that dry-soil thermal conductivity and volumetric specific heat capacity can be altered by fire by combining in situ observations of soil temperatures and heat fluxes with models of the daily (periodic) soil heat flow. The analysis was performed using several days of data before and after the controlled burn. Although the experimental burn achieved soil temperatures in excess of 400 C in the top 0.02 m of soil and over 300 C within most of the top 0.10 m of soil, it appears that it was not sufficiently intense to have significantly altered the thermophysical properties of the soil at the burn site at least during the month immediately following the fire.

Neverthess, the soil has undoubtedly been significantly impacted. Much of the soil's microbial population and other biota are likely to have been eliminated from the upper few centimeters of soil. Even as deep as 0.30 m the soil temperature reached about 80 C, which would have been enough to have affected most of the biota (DeBano *et al.* 1998). The long term consequences of changes in soil biota to the thermophysical properties, aggregate stability, and structure of these soils is not known. However, it is likely that the interplay and feedbacks between the soil biota and the soil physical and thermophysical properties ultimately determine the soil's recovery from fire. The present experiment is the first of several studies intended to examine how the interaction between soil microbial recovery, the soil's physical properties, and different fuel amounts, geometries, and loading densities influence soil recovery and forest regeneration after fires. Ultimately, the pragmatic goal of this study and future fire experiments is to provide tools to assist land managers in the use of prescribed fire to benefit ecosystems and to reduce the potential for harm.

References

Campbell GS, Jungbauer JD Jr, Bidlake WR, Hungerford RD (1994) Predicting the effect of temperature on soil thermal conductivity. *Soil Science* **158**, 307-313.

DeBano LF, Neary DG, Ffolliott PF (1998) *Fire's effects on ecosystems.* John Wiley & Sons, Inc., New York.

Farouki OT (1986) *Thermal properties of soils.* Trans Tech Publications, Clausthal-Zellerfeld, Germany.

Graham, RT [Technical Editor] (2003) *Hayman fire case study: Summary.* USDA Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-115, Ogden, UT.

Massman WJ (1992) Correcting errors associated with soil heat flux measurements and estimating soil thermal properties from soil temperature and heat flux plate data. *Agricultural and Forest Meteorology* **59**, 249-266.

Massman, W.J. and Frank, J.M. (2004) The effect of a controlled burn on the thermophysical properties of a dry soil using a new model of soil heat flow and a new high temperature heat flux sensor. Submitted to *International Journal of Wildland Fire.*

Massman, W.J., Frank, J.M., Shepperd, W.D., and Platten, M.J. (2003) In situ soil temperature and heat flux measurements during controlled surface burns at a southern Colorado forest site. In: (Eds. Omi, P.N. and L.A. Joyce) *Fire, fuel treatments, and ecological restoration: Conference proceedings; 2002 16-18 April; Fort Collins, CO.* USDA Forest Service Proceedings RMRS-P-29, 69-87.

Philip JR (1961) The theory of heat flux meters. *Journal of Geophysical Research* **66**, 571-579.