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Experimental and Modeling Study of Forest Fire Effect on Soil Thermal Conductivity

Kathleen M. SMITS[1,*], Elizabeth KIRBY[1], William J. MASSMAN[2] and Larry Scott BAGGETT[2]

[1] *Center for the Experimental Study of Subsurface Environmental Processes, Department of Civil and Environmental Engineering, Colorado School of Mines, Golden CO 80401 (USA)*
[2] *USDA Forest Service, Rocky Mountain Research Station, Fort Collins CO 80256 (USA)*

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ABSTRACT

An understanding of soil thermal conductivity after a wildfire or controlled burn is important to land management and post-fire recovery efforts. Although soil thermal conductivity has been well studied for non-fire heated soils, comprehensive data that evaluate the long-term effect of extreme heating from a fire on the soil thermal conductivity are limited. The purpose of this study was to evaluate the long-term impact of fire on the effective thermal conductivity of soils by directly comparing fire-heated and no-fire control soils through a series of laboratory studies. The thermal conductivity was measured for ten soil samples from two sites within the Manitou Experimental Forest, Colorado, USA, for a range of water contents from saturation to the residual degree of saturation. The thermal conductivity measured was compared with independent estimates made using three empirical models from literature, including the Campbell *et al.* (1994), Côté and Konrad (2005), and Massman *et al.* (2008) models. Results demonstrate that for the test soils studied, the thermal conductivity of the fire-heated soils was slightly lower than that of the control soils for all observed water contents. Modeling results show that the Campbell *et al.* (1994) model gave the best agreement over the full range of water contents when proper fitting parameters were employed. Further studies are needed to evaluate the significance of including the influence of fire burn on the thermal properties of soils in modeling studies.

Key Words: controlled burn, degree of saturation, empirical model, water content, wildfire

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Fires uniquely alter a soil's inherent physical, biological, and chemical properties, which affect the nature of several surface and subsurface processes such as water runoff and infiltration. One such change that has not been widely investigated is the change in the soil's thermal properties over time, specifically the soil's effective thermal conductivity. Because soil that is partially wet is considered a composite mixture of water, air, and soil grains (often quartz dominant), the effective thermal conductivity of partially wet soil is a function of the water and air contents. Understanding the changes in thermal conductivity as a result of fire heating is important to a wide variety of engineering and scientific applications as it ultimately affects the daily, seasonal, and annual heating and cooling cycles in the subsurface (Massman *et al.*, 2008), thus affecting soil moisture transfer (Ebel, 2012), evapotranspiration (Klock and Helvey, 1976; Tiedemann *et al.*, 1979; Moore and Keeley, 2000; Yoshikawa *et al.*, 2002) and plant growth (Abu-Hamdeh, 2000). Understanding the implications of changes in the properties of soils as a result of fire heating informs and improves agricultural development (DeBano, 1990), ecosystem recovery from wildfires (Massman *et al.*, 2008), and modeling efforts in a variety of soil science research fields (Yi *et al.*, 2009).

Field and laboratory determinations of the thermal properties of soils over the complete range of water content for non-fire-heated soils have been well studied. Past studies on non-fire-heated soil show that the effective thermal conductivity of soil varies as a function of degree of saturation, grain size, porosity, mineral content, and organic content (Yadav and Saxena, 1973; Brigaud and Vasseur, 1989; Abu-Hamdeh, 2003). For example, as the degree of saturation decreases, the effective thermal conductivity also decreases, but to varying degrees (*e.g.*, Smith, 1939; Kaune *et al.*, 1993; Bristow, 1998; Ochsner *et al.*, 2001). This is because the effective thermal conductivity of a partially saturated soil is a function of the water and air contents of the soil. The effective thermal conductivity of the soil components varies across two orders of magnitude: the

*Corresponding author. E-mail: ksmits@mines.edu.

effective thermal conductivity of mineral quartz, water, and dry air are typically 6.15–11.3, 0.58 (at 20 °C), and 0.024 W m^{-1} K^{-1} (at 20 °C), respectively (Clauser and Huenges 1995, Bristow, 1998). The effective thermal conductivity also decreases with decreasing grain size (Al Nakshabandi and Kohnke, 1965; Midttømme and Roaldset, 1998); the decrease in effective thermal conductivity is more significant in fine grain than coarse grain materials (Midttømme and Roaldset, 1998). As explained by Smits *et al.* (2010), for finer grained soils, the reduction in heat flow is due to the increased number of grain contacts in fine-grained materials, which results in more thermal resistance to the heat flow than the actual soil grains themselves. Porosity also affects effective thermal conductivity; effective thermal conductivity increases with a decrease in porosity due to a greater fraction of soil material (Usowicz *et al*, 1996; Abu-Hamdeh, 2000, 2003; Abu-Hamdeh and Reeder, 2000) as the soil grains themselves have a higher thermal conductivity than air or water. Mineral content has a variable effect on the thermal properties of soil because of the unique nature and wide variability in mineral composition and volume among soils. Finally, previous studies show that effective thermal conductivity decreases with an increase in organic matter content (Abu-Hamdeh and Reeder, 2000; Bachmann *et al.*, 2001; González-Pérez *et al.*, 2004). In many soils, organic matter content increases a soil's hydrophobicity (Jaramillo *et al.*, 2000) which in effect changes the water distribution within the soil and hence the effective thermal conductivity.

Although the thermal properties of non-fire-heated soils have been well studied, there are few studies that report the long-term impact of fire on soil thermal properties (Massman *et al.*, 2008, 2010; Nobles *et al.*, 2010; Rubio *et al.*, 2012; Rubio, 2014; Jiang *et al.*, 2015). To our knowledge, no laboratory studies of fire-heated soils across the full range of water contents have been previously reported. Massman *et al.* (2010) and Nobles *et al.* (2010) suggested that fire may cause convective airflow through the shallow subsurface, transporting combustion products and coating soil grains with organic and possible inorganic (mineral) vapors. An "organic coating" can seal soil pores, potentially inducing hydrophobicity and thus decreasing the effective thermal conductivity (Morin and Benyamini, 1977; Neary *et al.*, 1999; DeBano, 2000; González-Pérez *et al.*, 2004; Massman *et al.*, 2010; Dlapa *et al.*, 2015). Rubio *et al.* (2012, 2014) showed that effective thermal conductivity decreases after a soil is burned with the extent of change dependent on the volume and type of ash. A metallic or mineral coating, on the other hand, may enhance the soil's thermal conductivity (Nobles *et al.*, 2010). In addition to the coating of soil grains altering the thermal properties of soil, fires may alter the soil structure, depending on the fire's temperature and duration, also altering the soil's thermal properties (DeBano, 1990; González-Pérez *et al.*, 2004; Certini, 2005). For example, fires can shift a soil classification more towards coarse grains due to the heat-induced formation of stable aggregates (gravels and sands) from clays and silts (Ulery and Graham, 1993; Ketterings *et al.*, 2000). In addition, at fire temperatures between 100–200 °C, organic material begins to volatilize, changing the contact surfaces between soil grains and resulting in a decrease in soil effective thermal conductivity (Kang and Sajjapongse, 1980; Giovannini and Lucchesi, 1997; Certini, 2005; Boerner *et al.*, 2009). These fire-induced physical changes may increase the effective thermal conductivity of the soil and lead to decreases in permeability and infiltration rates (Fuller *et al.*, 1955; Scott and Burgy, 1956).

A wide range of empirical and semi-empirical models have been developed to describe the effective thermal conductivity of soil under varying soil moisture conditions (*e.g.*, de Vries, 1963; Johansen, 1975; McCumber and Pielke, 1981; Campbell, 1985; Côté and Konrad, 2005, 2009; Massman *et al.*, 2008). These models are used to investigate the contribution of individual soil properties (*i.e.*, porosity, grain size, soil texture, and organic content) to soil effective thermal conductivity, but do not explicitly account for the physical and chemical changes that result from heating by fire. In this study, fire-heated and (no-fire) control soils over the full range of water contents were directly compared to evaluate the long-term impact of fire on the effective thermal conductivity of soils. The effective thermal conductivity and water content were continuously measured for soil samples obtained from two field sites of the Manitou Experimental Forest, a wildfire site and a slash pile burn site, for the degree of saturation varying from 0 to 1. Corresponding nearby, non-fire-heated soil control samples were also tested, recorded, and compared with the fire-heated soils. Thermal properties measured were used for comparing the performance of the empirical models of Campbell *et al.* (1994), Côte and Konrad (2005), and Massman *et al* (2008).

MATERIALS AND METHODS

Soils used

Soil samples were collected in May 2011 from the

Manitou Experimental Forest (MEF, 39°04′ N and 105°04′ W), located in the central Rocky Mountains approximately 45 km west of Colorado Springs, Colorado, USA (Massman *et al.*, 2008). The soil samples were taken from two different burn sites within the MEF: a slash pile burn conducted in April 2004 (Massman *et al.*, 2008), and a human-caused (catastrophic) forest fire, known as the Hayman wildfire, which occurred in June–July 2002. At each site, multiple fire-heated and control soil samples were collected within the first 5.0 cm of topsoil. Each sample was approximately 1 200 cm^3 in volume. At the 2004 slash pile burn site, fire-heated soil samples were collected within the slash pile burn area and control soil samples were collected at locations adjacent to the slash pile. Details of the 2004 slash pile burn can be found in Massman *et al.* (2008). At the 2002 Hayman wildfire site, the fire-heated soil samples were collected towards the edge of the fire, and the control soil samples were collected outside of the burn area, next to the wildfire site. The sampling locations were approximately 15 m apart. A total of five sets (two heated and two controls for each set) of soil samples were analyzed: three sets (Sets 1–3) from the 2004 slash pile burn site and two sets (Sets 1 and 2) from the 2002 Hayman wildfire site.

All soil samples used in this study are sandy loams, comprised of approximately 66% sand, 21% silt, 13% clay, and 2% organic matter by volume (Massman *et al.*, 2008). Like most typical field soils, the samples naturally included rocks, charcoal, and ash (if burned) which were removed prior to experimentation. Removing large aggregates allows for the duplication of field porosities in the laboratory (Dane and Hopmans, 2002) and uniform conditions (*e.g.*, porosity) across soil samples, thus allowing for accurate comparisons. In addition, this preparatory process ensures that the sensors are in good contact with the soil grains and prevents sensor damage.

Experimental procedure

Field soils were carefully wet-packed into the experimental apparatus with deionized water. Soils were poured into the cell at 0.50-cm increments. Uniform densities were achieved by rapidly tapping the plexiglass sidewalls of the cell using the method outlined in Smits *et al.* (2010). Each sample was packed to the same porosity (0.356–0.367) (Table I) to isolate the influence of fire heating on the soil samples from porosity effects. Once packed, the cell was sealed with a plastic lid and placed in an incubator (120 V, 7.7 A, 50–60 Hz) (Model Number 650D, Fisher Scientific, Dubuque, USA). The temperature within the saturated soil sample was allowed to equilibrate for about 8 h to 55 °C prior to the start of each measurement. Once the soil matrix reached isothermal conditions, the lid of the cell was removed to allow evaporation to occur. During experimentation, the degree of saturation and the effective thermal conductivity were measured at 1- and 15-min intervals, respectively. The effective thermal conductivity was measured at 15-min intervals to allow thermal gradients to dissipate in accordance with the specification of the sensor manufacturer (Decagon

TABLE I

Selected properties of soils of three different sets (Sets 1–3) of soil samples (fire-heated and control) from the 2004 slash pile burn site and those of two different sets (1 and 2) from the 2002 Hayman wildfire site

Site	Soil sample set	Porosity	Effective thermal conductivity	
			Saturated soil	Dry soil
			W m^{-1} K^{-1}	
2002 Hayman	Set 1			
wildfire site	Fire-heated	0.367	1.408 ± 0.148[a)]	0.315 ± 0.028
	Control	0.367	1.595 ± 0.134	0.346 ± 0.017
	Set 2			
	Fire-heated	0.367	1.249	0.295
	Control	0.367	1.530	0.420
2004 slash	Set 1			
pile burn	Fire-heated	0.365	1.434 ± 0.112	0.264 ± 0.056
site	Control	0.365	1.898 ± 0.045	0.316 ± 0.012
	Set 2			
	Fire-heated	0.365	1.222	0.350
	Control	0.365	1.340	0.327
	Set 3			
	Fire-heated	0.365	1.397	0.268
	Control	0.365	1.563	0.419

[a)] Means ± standard deviations ($n = 3$).

Devices, Inc., 2012). Each measurement was conducted for approximately 7 d. For two sets (Set 1 of the Hayman wildfire and slash pile burn sites) of soil samples (fire-heated and control), the measurements were triplicated to ensure repeatability.

Measurements with apparatus developed

The elevated temperature of the soil sample (*i.e.*, 55 °C) enhanced soil drying, thus decreasing experimental times and allowing for the establishment of the soil moisture-thermal property relationship over the entire range of saturation. Measurement were conducted at room temperature (22 °C) and compared to those at elevated temperature; no difference in the soil thermal properties was seen due to the elevated temperature. This was also demonstrated by Smits *et al.* (2013), who showed that soil thermal properties were not affected by temperatures at or below 55 °C.

Measurements with apparatus developed

A small plexiglass cell apparatus (outer diameter = 7.6 cm, wall thickness = 1.2 cm, height = 9.0 cm) was developed in this study. Soil moisture and thermal sensors were installed horizontally through the walls of the cell (Fig. 1). Soil moisture was continuously monitored with a dielectric soil moisture sensor (ECH_2O EC-5, prong length = 5.5 cm, measurement frequency = 70 MHz, Decagon Devices, Inc., Pullman, USA) interfaced with a data logger (Em50, Decagon Devices, Inc., Pullman, USA). The soil moisture sensor was calibrated in accordance with the method developed by Sakaki *et al.* (2008) prior to installation.

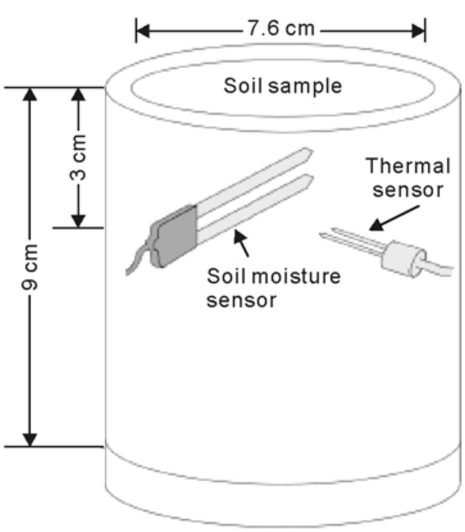

Fig. 1 Schematic of experimental apparatus used (not drawn to scale). The inside volume of the container, excluding the sensors, is 400 cm^3.

Soil thermal conductivity was monitored with a thermal property analyzer (KD-2 Pro, Decagon Devices, Inc., Pullman, USA). The KD-2 Pro thermal property analyzer's 30 mm dual-needle heat pulse sensor (SH-1, ± 10% accuracy for effective thermal conductivity from 0.2 to 2 W m^{-1} K^{-1}, ± 0.001 °C for temperature) was customized by the manufacturer to fit directly into the cell as seen in Fig. 1. The dual-needle heat pulse sensor consists of a probe with a resistive heater and thermistor inside each needle, respectively. A current passes through the heater in one of the needles for a prescribed period of time; a thermistor in the other needle 6 mm away from the heater is used to measure the change in temperature. Temperature measurements are taken during periods of heating and cooling. The KD-2 Pro then uses the full analytical solution to the heat conduction equation to determine effective thermal conductivity based on the line heat source analysis introduced by Carslaw and Jaeger (1959) and Kluitenberg *et al.* (1993) and a non-linear least squared procedure outlined in Decagon Devices, Inc. (2012). The KD-2 Pro performance was verified prior to installation in accordance with Decagon Devices, Inc. (2012).

Models used to calculate thermal conductivity

In this study, we investigated whether existing models were able to capture the behavior of effective thermal conductivity as a function of degree of saturation for the fire-heated and control soils. Three different models were considered for this study: those developed by Campbell *et al.* (1994), Côté and Konrad (2005), and Massman *et al.* (2008). The model proposed by Campbell *et al.* (1994) is an extension of the de Vries (1963) model and accounts for changes in both degree of saturation and temperature. It is based on the assumption that the effective thermal conductivity of a soil, air, and water mixture can be expressed as the weighted sum of the effective thermal conductivity of the mixture's components. Smits *et al.* (2013) demonstrated that this model could accurately predict soil effective thermal conductivity for various soils and soil temperatures and was therefore selected for the present study. The Côté and Konrad (2005) model is an extension of a model originally proposed by Johansen (1975). The Côté and Konrad (2005) model generalizes the relationship for the normalized effective thermal conductivity, often referred to as the Kersten number (Johansen, 1975). This model has been shown to predict effective thermal conductivity of a wide range of soils reasonably well across the entire range of soil moistures (Farouki, 1982; Peters-Lidard *et al.*, 1998). More recently, Massman *et al.* (2008) proposed a linear model to identify the long-term impact of prescribed burns on soil effective thermal conductivity and the concomitant soil thermal environment. This model was developed specifically for an *in-situ* field experiment intended to investigate the same 2004 slash pile burn site soils used in this study and has been shown to provide a reasonable representation of the relationship between the effective thermal conductivity and degree of saturation for relatively dry soils (degrees of saturation in the range from 0 to 0.25) in the MEF (Massman and Frank, 2004).

The Campbell *et al.* (1994) model assumes that the effective thermal conductivity of any soil comprised of water, air and mineral can be calculated based on the volume-weighted sum of the thermal conductivities of the components of the mixture (de Vries, 1963; Campbell *et al.*, 1994):

$$\lambda_{\text{Campbell}} = \frac{k_{\text{w}}x_{\text{w}}\lambda_{\text{w}} + k_{\text{a}}x_{\text{a}}\lambda_{\text{a}} + k_{\text{m}}x_{\text{m}}\lambda_{\text{m}}}{k_{\text{w}}x_{\text{w}} + k_{\text{a}}x_{\text{a}} + k_{\text{m}}x_{\text{m}}} \tag{1}$$

where $\lambda_{\text{Campbell}}$ is the effective thermal conductivity of a soil calculated using the Campbell *et al.* (1994) model, λ_{w}, λ_{a}, and λ_{m} are the effective thermal conductivity of the components water, air and mineral, k_{w}, k_{a}, and k_{m} are empirically determined weighting factors of the components water, air and mineral, and λ_{w}, x_{a}, and λ_{m} are the volume fractions of the components water, air and mineral of the soil, respectively. Also, λ_{a} is the sum of the conduction through air and the latent heat across the soil pores. The primary factor responsible for the variation of the effective thermal conductivity with temperature is the latent heat variation across the soil pores, accounted for by λ_{a}. The method proposed by Campbell *et al.* (1994) requires four parameters which can be fitted to experimental data or ideally, predicted based on the physical properties of the soil. Fitting parameters include the effective thermal conductivity of the mineral fraction (λ_{m}), the cutoff for water content recirculation (x_{wo}), the power for the recirculation function (q_{o}), and a shape factor (g_{a}). The transition between wet and dry soils is controlled by x_{wo}, which ideally can be predicted based on the geometric mean particle diameter (d_{g}):

$$x_{\text{wo}} = 0.267 d_{\text{g}}^{-0.2} \tag{2}$$

The effective thermal conductivity of dry soils is controlled by g_{a} which can ideally be determined based on the shape of the soil grains (de Vries, 1963). The recirculation function, q_{o}, does not have a physical basis. Campbell *et al.* (1994) note that values of g_{a} and q_{o} vary from soil to soil without a repeatable pattern between soil types. For detailed information on model parameters, readers are referred to Campbell *et al.* (1994).

Côté and Konrad (2005) modified the method proposed by Johansen (1975). The Johansen (1975) model interpolates between the effective thermal conductivity of dry and saturated soils, to calculate the effective thermal conductivity for a desired degree of saturation:

$$\lambda(S)_{\text{Côté and Konrad}} = K_{\text{e}}(S)(\lambda_{\text{sat}} - \lambda_{\text{dry}}) + \lambda_{\text{dry}} \tag{3}$$

where $\lambda(S)_{\text{Côté and Konrad}}$ is the effective thermal conductivity for a desired degree of saturation of a soil calculated using the Côté and Konrad (2005) model, $K_{\text{e}}(S)$ is the normalized effective thermal conductivity for a desired degree of saturation, often referred to as the Kersten number. The Kersten number, which is a function of the degree of saturation, is weighted according to soil texture (Côté and Konrad, 2005). Côté and Konrad (2005) improved Johansen's method and proposed a generalized relationship between the Kersten number and degree of saturation that is valid for all soils:

$$K_{\text{e}}(S) = \frac{\kappa S}{1 + (\kappa - 1)S} \tag{4}$$

where κ is a dimensionless empirical fitting parameter and is associated with the distribution of grain size, pore size, and pore water and S is the degree of saturation of soil. The parameter $\kappa = 3.55$ for unfrozen sand, 1.9 for silt, and 0.6 for clay (Côté and Konrad, 2005).

Once fully saturated, the soil matrix is modeled as a two-phase (soil grain and water) medium. Johansen (1975) uses a geometric mean to estimate the effective thermal conductivity at the full degree of saturation (λ_{sat}):

$$\lambda_{\text{sat}} = \lambda_{\text{s}}^{1-\eta}\lambda_{\text{w}}^{\eta} \tag{5}$$

where $\lambda_{\text{w}} = 0.647$ W m^{-1} K^{-1} at 55 °C, η is the porosity of the soil, and λ_{s} is the effective thermal conductivity of solid soils, which is also calculated using a geometric mean:

$$\lambda_{\text{s}} = \lambda_{\text{q}}^{q}\lambda_{\text{o}}^{1-q} \tag{6}$$

where q is the fraction of quartz in the soil or the percentage sand from the soil classification values, λ_{q} is the effective thermal conductivity of quartz and is in the range of 6.15–11.3 W m^{-1} K^{-1} (Clauser and Huenges, 1995), and λ_{o} is the effective thermal conductivity of other minerals in the soil, which is in the range of 0.4–5.0 W m^{-1} K^{-1} (Clauser and Huenges, 1995).

Similarly, under dry conditions, the soil matrix is a two-phase system of air and soil grains. Johansen (1975) estimates the effective thermal conductivity of dry soils (λ_{dry}) with the following semi-empirical relationship:

$$\lambda_{\mathrm{dry}} = \frac{0.135\rho_{\mathrm{b}} + 64.7}{\rho_{\mathrm{s}} - 0.947\rho_{\mathrm{b}}} \tag{7}$$

where ρ_{b} is the dry bulk density soil (kg m^{-3}) and ρ_{s} is the density of the soil solids (kg m^{-3}). Johansen (1975) defines ρ_{b} to be 2 700 kg m^{-3} (accuracy: $\pm$ 5%). Johansen (1975) stated that the accuracy of Eq. 7 is $\pm$ 20%. In this study, the laboratory measured value of 2 650 kg m^{-3} was used. The Johansen (1975) model has successfully been used to estimate the effective thermal conductivity of field soils, and lab sands under varying degrees of saturation (Farouki, 1982; Peters-Lidard *et al.*, 1998; Smits *et al.*, 2010).

Massman *et al.* (2008) developed a linear regression model using bulk density and volumetric water content to estimate *in-situ* effective thermal conductivity for soils from the MEF. This model is an empirical model specifically developed to identify the long-term impact of prescribed burns on shallow (0.025–0.20 m) subsurface soils. Given the water content and bulk density, effective thermal conductivity of a soil from the MEF is estimated as follows:

$$\lambda_{\mathrm{Massman}} = A\rho_{\mathrm{b}} + B\theta_{\mathrm{v}} \tag{8}$$

where $\lambda_{\mathrm{Massman}}$ is the *in-situ* effective thermal conductivity estimated using the Massman *et al.* (2008) model, A and B are the parameters empirically determined using the least squares method and θ_{v} is the volumetric water content. From the *in-situ* study of Massman *et al.* (2008), $A = 0.123$ and $B = 8.21$ for the control soils, while $A = 0.486$ and $B = 2.70$ for the fire-heated site soils. The Massman *et al.* (2008) model is valid for θ_{v} of 0.01–0.40 m^3 m^{-3} and ρ_{b} of 1.05–1.75 Mg m^{-3}.

Statistical analysis

To investigate the statistical significance of the behavior of effective thermal conductivity with respect to measured covariates, two analyses were performed. For the first analysis, we investigated the difference in effective thermal conductivity data between the fire-heated and control soils and between the Hayman and slash pile burn site data. For the second analysis, we investigated the difference between the fire-heated and control soils under dry (degree of saturation = 0) and saturated (degree of saturation = 1) conditions.

For the analyses, data collected at 15-min intervals were aggregated to 12-h intervals by computing the mean value of effective thermal conductivity for each interval. This mean was then used as the response for a generalized linear mixed model (GLMM) (a linear mixed model that considers both the random and usual fixed effects). The purpose of data aggregation was to mitigate the strong effect of temporal autocorrelation that would bias the standard error of the estimates obtained in the fitted model. The effective thermal conductivity data were fit assuming a lognormal distribution to treatment (fire-heated or control), degree of saturation and site (Hayman wildfire or slash pile burn). A lognormal distribution was used because of the continuous non-negative and right-skewed characteristic of the response. For degree of saturation, the continuous percent levels were binned to the intervals [0, 25], [25, 50], [50, 75], and [75, 100]. The binned degree of saturation was used because of the nonlinear relationship between effective thermal conductivity and saturation. Also included in the model were all pairwise interactions. Variations of replicates within test soils were included as a residual random effect. A sandwich estimator, also known as the robust covariance matrix estimator, was used to mitigate any misspecification of the standard errors due to any remaining autocorrelation (MacKinnon and White, 1985). The sandwich or robust covariance matrix estimator has been shown to have favorable properties even in the presence of model or distributional misspecification (Liang and Zeger, 1986; Diggle *et al.*, 1994).

RESULTS AND DISCUSSION

Experimental results

The relationships between the effective thermal conductivity and degree of saturation for the fire-heated and control soil samples are shown in Figs. 2 and 3. Measured data show that the effective thermal conductivity decreased with a decrease in degree of saturation, to varying degrees. In general, there was initially a near constant effective thermal conductivity maintained near full saturation. The continuous water phase at full saturation allows heat to transmit through both the grain and water phases, resulting in higher effective thermal conductivity values than at lower saturation degrees. The value of effective thermal conductivity then decreased gradually with a decrease in saturation until about mid-saturation degrees at

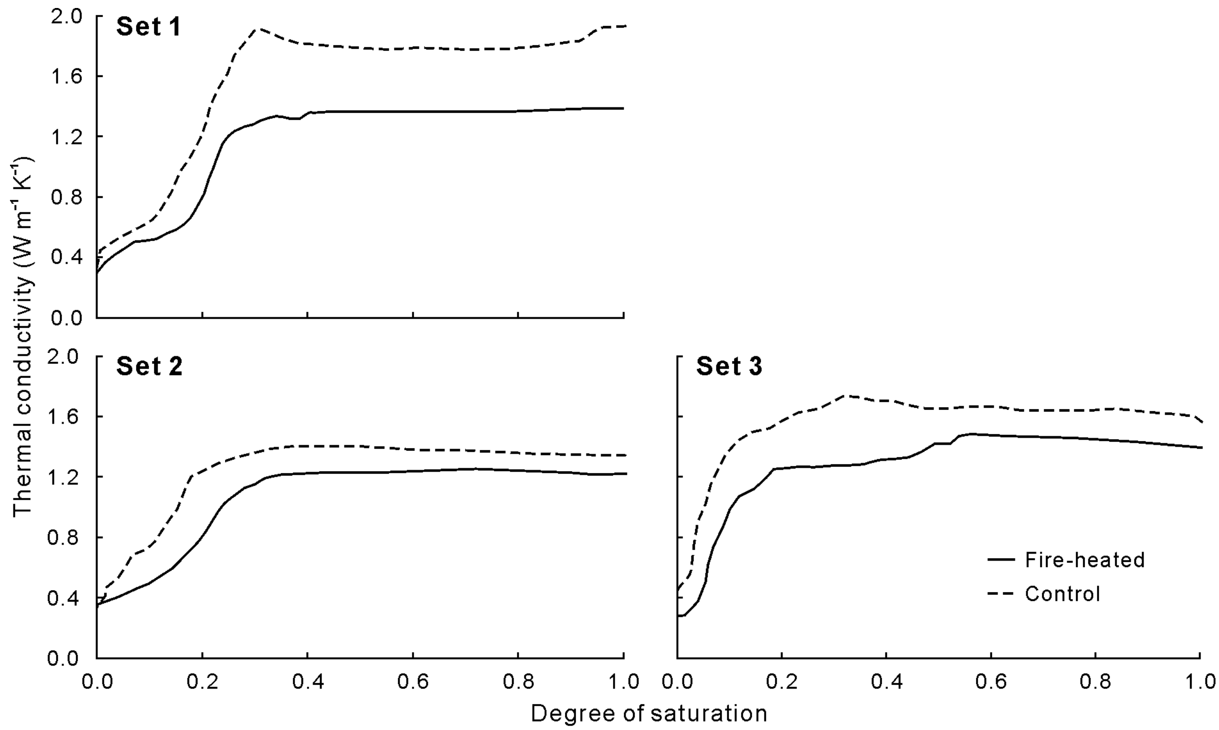

Fig. 2 Effective thermal conductivity as a function of degree of saturation for three different sets (Sets 1–3) of soil samples (fire-heated and control) from the 2004 slash pile burn site. The accuracy for the effective thermal conductivity is ± 10%. The porosity is 0.365 for all test cases.

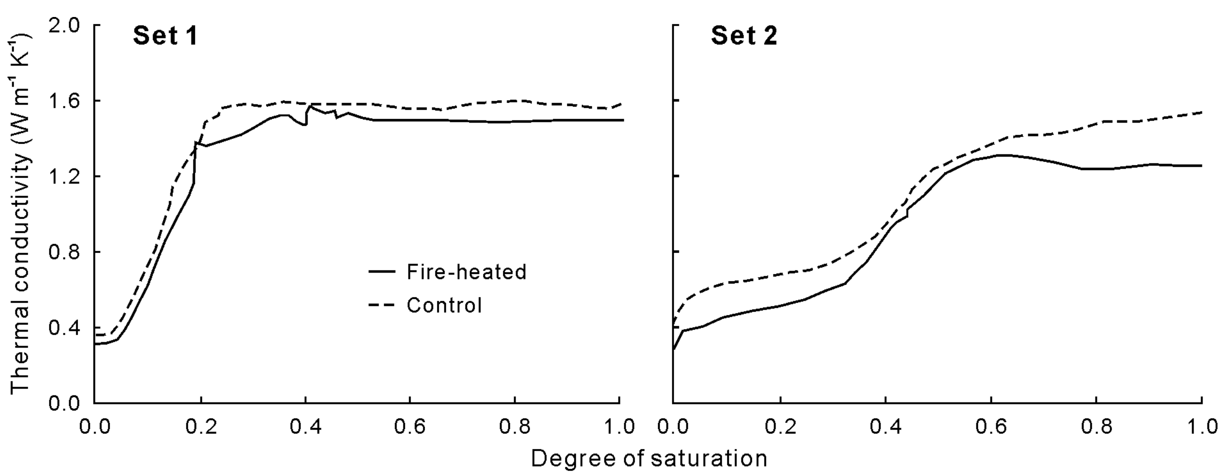

Fig. 3 Effective thermal conductivity as a function of degree of saturation for two different sets (Sets 1 and 2) of soil samples (fire-heated and control) from the 2002 Hayman wildfire site. The porosity is 0.365 for all test cases.

which time the rate of decrease increased. Consistent with previous findings (*e.g.*, de Vries, 1963; Yadav and Saxena, 1977; Horton and Wierenga, 1984; Ghuman and Lal, 1985; Hopmans and Dane, 1986; Bristow, 1998; Ochsner *et al.*, 2001; Lu *et al.*, 2007), as saturation approaches residual, the value of effective thermal conductivity decreased abruptly. This abrupt decrease occurred at or below the residual saturation and the state where the grain-water paths started to disconnect. These imply that changes in thermal conductivity were relatively small until evaporation reduced the degree of saturation to approximately the residual saturation.

Data from both the slash pile burn site (Fig. 2) and Hayman wildfire site (Fig. 3) suggest that the effective thermal conductivity of the fire-heated soil was slightly lower than the control soil for the entire range of saturation. The difference may be due to changes in the physical and chemical properties of the soil due to fire heating, such as a change in soil mineralogy or induced hydrophobicity. This difference is unlikely due to the conversion and destruction of organic matter as a result of soil heating; the organic matter in the present soils was extremely low (less than 2% by volume). The difference between the effective thermal conductivity of control and fire-heated soils was less evident at the wildfire site than the slash pile burn site as seen in the root-mean-square deviation (RMSD) for each sample pair (Table II). The smaller difference may be due to the variability of the soil samples and/or some natural recovery process of the soil over time. In Figs. 2 and 3, only one set of the measurements is shown for each of the ten soil samples. Although not shown, two sets of measurements, one from the Hayman wildfire site and one from the slash pile burn site, were triplicated, yielding similar results (see Table 1 for the mean and standard deviation values for the triplicated samples under dry and saturated conditions).

TABLE II

Root-mean-square deviation (RMSD) for comparison of effective thermal conductivity between the fire-heated and control soil samples in each of three different sets (Sets 1–3) of soil samples from the 2004 slash pile burn site and those of two different sets (1 and 2) from the 2002 Hayman wildfire site

Site	Soil sample set	RMSD
2002 Hayman wildfire site	Set 1	0.065
	Set 2	0.157
2004 slash pile burn site	Set 1	0.304
	Set 2	0.179
	Set 3	0.246

To investigate if the behavior of effective thermal conductivity is statistically significant with respect to covariates, we performed a series of statistical analyses. A statistically significant difference was observed based on the soil treatment (fire-heated and control) across all degrees of saturation for both test sites; the effective thermal conductivity of the control sample was larger than that of the fire-heated sample by a mean estimate of 0.159 54 (± 0.050 15) W m^{-1} K^{-1} ($P = 0.0258$). A statistically significant treatment difference was again observed when comparing the effective thermal conductivity values between dry (degree of saturation = 0) and saturated (degree of saturation = 1) conditions for both the Hayman wildfire and slash pile burn sites; effective thermal conductivity of the control sample was larger than that of the fire-heated sample by a mean estimate of 0.128 14 (± 0.032 564) W m^{-1} K^{-1} ($P = 0.0027$). This suggests that the effective thermal conductivity behavior seen in Figs. 2 and 3 was statistically significant for the soils studied.

When comparing the effective thermal conductivity of the soils between the slash pile burn site and the Hayman wildfire site, the only significant difference was observed at a degree of saturation of 0 to 0.25 ($P = 0.0513$), with the effective thermal conductivity being greater for the Hayman wildfire site than the slash pile burn site by a mean estimate of 0.151 10 (± 0.053 05) W m^{-1} K^{-1}. Significant differences in soil effective thermal conductivity between the slash pile burn and Hayman wildfire sites were again observed when the saturation degree = 0 (dry soil), with the effective thermal conductivity being greater for the Hayman wildfire site than the slash pile burn site by a mean estimate of 0.172 3 (± 0.043 745) W m^{-1} K^{-1} ($P = 0.0064$).

Comparison of the experimental data with those calculated with the Campbell and Côté and Konrad models

The present experimental data of effective thermal conductivity as a function of degree of saturation were compared to those calculated using the models developed by Campbell *et al.* (1994) and Côté and Konrad (2005) as shown in Figs. 4 and 5, with fitting parameters listed in Tables III and IV, respectively. The RMSD value for each set of measurements was calculated using data for all degrees of saturation (typically 800–900 data points). The RMSD values for the experimental and fitted data using the Campbell *et al.* (1994) model for the 2004 slash pile burn site (Fig. 4) were roughly 0.000–0.049, suggesting that the estimated effective thermal conductivity values using the Campbell *et al.* (1994) model were generally in good agreement with the independently measured values.

The four parameters needed for the Campbell *et al.* (1994) model are given in Table III. The effective thermal conductivity of the mineral fraction, λ_{m}, varied between the fire-heated and control soil samples from 0.46 to 1.72 W m^{-1} K^{-1}, within the range of those found in Campbell *et al.* (1994) for similar soils. The variations in λ_{m} may be due to the change in the soil physical properties due to fire heating. The shape factor g_{a} also varied between the fire-heated and control samples, suggesting a change in the texture of the soil particles during heating (*e.g.*, Ulery and Graham, 1993). The cutoff for water content recirculation function, x_{wo}, which controls the transition between saturated and unsaturated regions, did not require variation between the fire-heated and control samples. This is because the shapes of the fire-heated and control soil curves were similar (Fig. 4). Although not shown, the

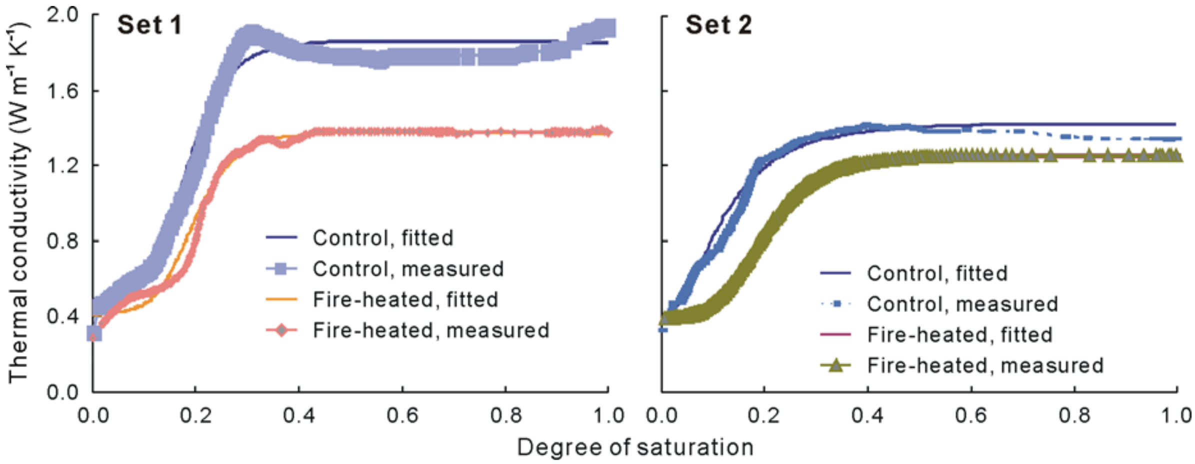

Fig. 4 Comparison of the effective thermal conductivity between the experimental data and those calculated using the Campbell *et al.* (1994) model for two different sets (Sets 1 and 2) of soil samples (fire-heated and control) from the 2004 slash pile burn site. Fitting parameters are listed in Table III.

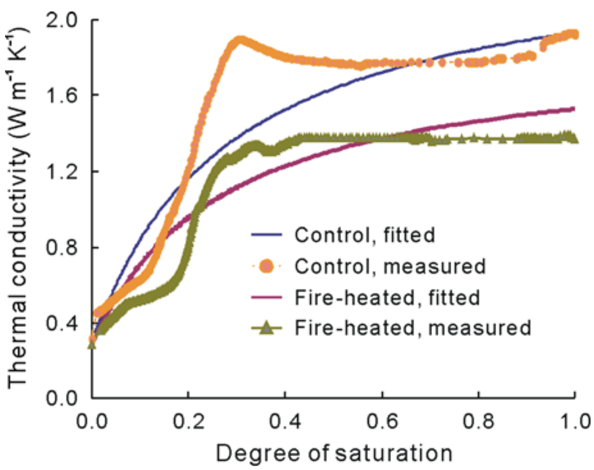

Fig. 5 Comparison of the effective thermal conductivity between the experimental data and those calculated using the Côté and Konrad (2008) method for one set (Set 1) of soil samples (fire-heated and control) from the 2004 slash pile burn site. Fitting parameters are listed in Table IV.

TABLE III

Fitting parameters[a)] of the Campbell *et al.* (1994) model for two different sets (Sets 1 and 2) of soil samples (fire-heated and control) from the 2004 slash pile burn site

Soil sample set	λ_m	g_a	q_o	x_{wo}	RMSD
Set 1					
Fire-heated	0.650	0.031	4.46	0.09	0.043
Control	1.720	0.045	4.46	0.09	0.049
Set 2					
Fire-heated	0.460	0.025	1.97	0.08	0.034
Control	0.770	0.036	1.97	0.08	0.000

a) λ_m is the thermal conductivity of the mineral fraction, g_a is the shape factor, q_o is the power for the recirculation function, x_{wo} is the cutoff for water content recirculation, and RMSD is the root-mean-square deviation.

TABLE IV

Fitting parameters[a)] of the Côté and Konrad (2005) model for one set (Set 1) of soil samples (fire-heated and control) from the 2004 slash pile burn site

Soil sample	κ	q	RMSD
Fire-heated	4.712	0.190	0.121
Control	4.600	0.500	0.165

a) κ is the dimensionless empirical fitting parameter and is associated with the distribution of grain size, pore size and pore water, q is the quartz content of the soil, and RMSD is the root-mean-square deviation.

only exception to this was for the 2002 Hayman wildfire fire-heated and control sample Set 1. The transition between the saturated and unsaturated regions did not coincide for this soil sample set; therefore, the cutoff for water content recirculation function varied for this case only. The power recirculation function, q_o, did not vary between the fire-heated and control samples; as mentioned previously, this value does not have a physical meaning.

The effective thermal conductivity calculated using the Côté and Konrad (2005) model with Eqs. 3 and 4 together with the end values with Eqs. 5–7 for dry and saturated soils, respectively, are plotted in Fig. 5 and compared to measured values for the fire-heated and control soil samples of Set 1 from the slash pile burn site. Although not shown, Sets 2 and 3 from the slash pile burn site and the Hayman wildfire site showed similar results. The Côté and Konrad (2005) model yielded poor fits when compared to the measured values (RMSD = 0.121–0.165). In general, for high and low degrees of saturation, the Côté and Konrad (2005) model overestimated the effective thermal conductivity. For the intermediate degrees of saturation, the model underestimated the effective thermal conductivity. The κ values for the soils that best described the measured data of the effective thermal conductivity as a function of degree of saturation as well as the RMSD values are summarized in Table IV. The parameter κ and the quartz content (q) were required to fit each of the fire-heated and control soil samples (Table IV). Côté and Konrad (2005) suggested $\kappa = 1.9$ (for unfrozen silt), which underestimates the effective thermal conductivity values at intermediate water contents and, hence, much larger κ values were required for these soil samples. The optimized q for the Côté and Konrad (2005) model does not reflect the physical characteristics of the soil. All of the soils used in this study were classified as a sandy loam consisting of 66% sand, 21% silt, 13% clay, and less than 2% organic matter by volume.

Comparison of the experimental data with the in-situ data estimated with the Massman et al. (2008) model

The effective thermal conductivity measurements obtained with the present laboratory methods was compared with the *in-situ* data estimated using the Massman *et al.* (2008) model for the degree of saturation < 0.25 as shown in Fig. 6. The Massman *et al.* (2008) model is a linear regression model that describes the behavior of the effective thermal conductivity of a site and therefore did not reproduce the data well across the full range of saturation. Consistent with the experimental measurements in this study, Massman *et al.* (2008) found that for wetter soils (*i.e.*, degree of saturation > 0.25), the effective thermal conductivity of the fire-heated soils was lower than that of the control soils. However, they found that in dry soils (*i.e.*, degree of saturation < 0.25), the effective thermal conductivity of the fire-heated soils was slightly greater than that of the control soils. Possible explanations for the difference in the dry soil values included the accuracy of the sensors ($\pm$ 10%) for the effective thermal conductivity from 0.2 to 2 W m^{-1} K^{-1}, physical changes of the soils (*i.e.*, formation of thin films) during fire heating (Nobles *et al.*, 2010), and/or the gradual loss of these thin films over time. The soil samples used in the present study were collected 8–10 years after the fire heating events while the samples in Massman *et al.* (2008) were collected 1–4 years after the slash pile burn.

CONCLUSIONS

This study presents a comparison of the long-term effect of forest fire on the effective thermal conductivity of soil under a wide range of moisture conditions. The effective thermal conductivity of the fire-heated soils was lower than those of the control soils for the entire range of soil moisture conditions ($P = 0.026$). The di-

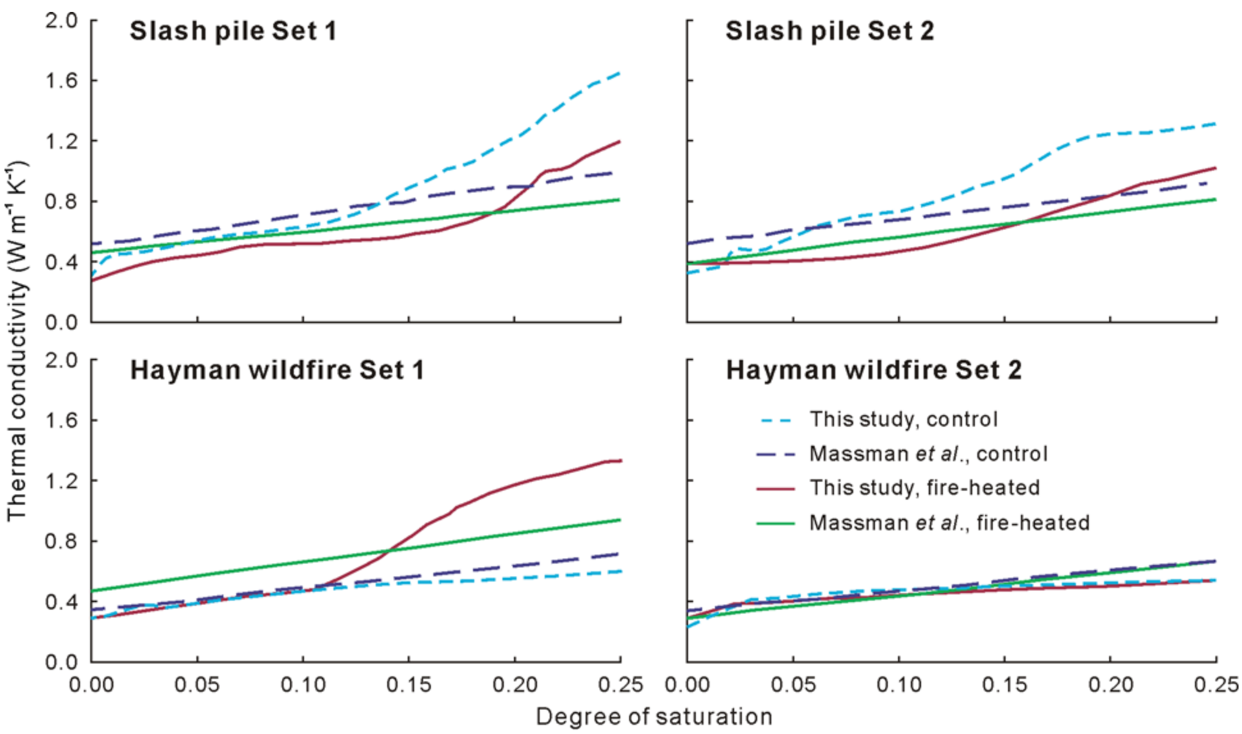

Fig. 6 Comparison of the effective thermal conductivity between the experimental data in the present laboratory data and the *in-situ* data estimated with the Massman *et al.* (2008) model for two different sets (Sets 1 and 2) of soil samples (fire-heated and control) (degree of saturation < 0.25) from the 2004 slash pile burn site and the 2002 Hayman wildfire site. The porosity is 0.365 for all test cases.

fference may be due to changes in the physical and chemical properties of the soil due to fire heating, such as a change in soil mineralogy or induced hydrophobicity. The semi-analytical Campbell *et al.* (1994) model was able to accurately estimate the behavior of effective thermal conductivity as a function of degree of saturation for fire-heated and control soils through variation of the mineral fraction and shape factor of the soils. This model can readily be incorporated into numerical codes for simulating heat and moisture transfer in fire-heated soils; however, the model requires calibration for each soil type. Further studies focusing on the evaluation of the significance of changes in the soil thermal properties as a result of forest fire, as well as the effect of these changes on modeling, are still needed.

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