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

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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

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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