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Effects of controlled burns on the bulk density and thermal conductivity of soils at a southern Colorado site

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1. Introduction

Throughout the world fire plays an important role in the management and maintenance of ecosystems. However, if a fire is sufficiently intense, soil can be irreversibly altered and the ability of vegetation, particularly forests, to recover after a fire can be seriously compromised. 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.

The present study outlines an experiment to determine the effect that controlled burns can have on the bulk density (ρ_b) [g cm^{-3}] and thermal conductivity (λ_s) [Wm^{-1}K^{-1}] of soils within the Manitou Experimental Forest (MEF), which is located in the Rocky Mountains of southern Colorado. In so far as soil thermal conductivity is in part determined by soil structure (Farouki, 1986), then changes in the soil's thermal conductivity could indicate changes in soil structure. More importantly, changes in λ_s can lead to changes in the daily and seasonal energy flow through the soil and therefore, changes in the temporal patterns and magnitudes of soil temperatures. In turn this may affect soil chemistry, soil aggregate stability, soil biota, and ultimately the nature of the soil's recovery from fire.

Previous studies indicate that soil bulk density nearly always increases as a result of fire (e.g., Badía and Martí, 2003; Seymour and Tecle, 2004; DeBano et al., 2005), but our earlier study (Massman and Frank, 2004) seems to be the only other study of the impact fire may have on the thermal conductivity of soil. The present study is the second in our efforts to determine if soil thermal properties, particularly soil thermal conductivity, are affected by fire.

2. Site and Soil Descriptions

Because detailed descriptions of MEF and its associated soils can be found in Massman et al. (2003), Massman and Frank (2004), and Massman et al. (2006), only summary descriptions are provided here.

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MEF is a forested, high elevation, semi-arid, site dominated by ponderosa pine (*Pinus ponderosa*) and by soils that are derived mostly from biotite granite and associated igneous rocks of the Pikes Peak batholith. Two different MEF experimental burn sites were used for this study. The first site, burned in January 2002, is described by Massman et al. (2003) and Massman and Frank (2004). The second site, described by Massman et al. (2006), was burned during April of 2004. Both these sites have moderately disturbed soils, but the first burn site had once been used as an access road to other parts of the forest, so the soils there are more compacted (hence denser) than at the second site. The consequences of this additional complication to the sampling strategy at the first site are discussed in more detail below.

At the time we sampled the soils more than 3.5 years had passed after the first burn and about 1.5 years had elapsed after the second. By this time the vegetation had recovered at the first burn site, but the second burn area was virtually free of vegetation and still discolored (black in color).

3. Instrumentation and Data Analysis

Because soil moisture (θ_v) [m^3 m^{-3}] is the primary determinant of thermal conductivity and bulk density the second, θ_v was measured at the same time and locations as ρ_b and λ_s. All soil bulk density, thermal conductivity, and volumetric moisture data used in the present study were obtained during April 2005 (second MEF burn site) and September 2005 (first burn site).

Soil thermal conductivity measurements were acquired in situ using 0.06 m long single (heated) needle conductivity probes (East 30 Sensors; Pullman, WA) (Bristow, 2002) by inserting the probe horizontally into the side of a (freshly dug) pit, which was usually about 0.30 m deep, 0.5 m wide, and 0.75 m long. Vertical profiles of λ_s were obtained by sequentially sampling at 0.02, 0.05, 0.10, 0.15, and 0.20 m depths with the same probe for two different sides of each pit. During the 2 to 5 minutes the probe required to thermally equilibrate, the pit was covered with an large piece of Styrofoam (commercially available household insulator) to minimize any external heating of the sides of the pit by solar radiation.

Bulk density and gravimetric soil moisture measurements were obtained by weighing and drying soil samples taken near each pit using an AMS split-core sampler (12" length, 2" diameter) with a core tip (Forestry Suppliers; Jackson, MS). Each soil core was subsampled for a vertical profile every 0.05 m with depths centered at 0.05, 0.10, 0.15, and 0.20 m. All soil samples were extracted from the corer, sealed in plastic bags, and brought back to the Rocky Mountain Research Station for analysis.

At the first burn site a total of 14 pits were dug: 5 within the burned area itself, 3 controls near, but outside, the burn area (which we could not clearly identify as having been used as the access road), 3 in a nearby unburned area (which we could identify as having been used as a road), and 3 in nearby areas which we could clearly identify as having never been driven on or otherwise significantly disturbed. At the second site a total of 9 pits were dug: 3 in the center of the burned area, 3 at the edge of the burned area, and 3 near the control sites.

Data analyses employed the multiple regression software subroutine SAS PROC GLM (part of the software package SAS 9.1 for Windows) (SAS Institute; Cary, NC).

4. Bulk Density Results

Bulk density was tested with the base data (burned area + control only) using site, treatment, and depth. The final model yielded:

$$\rho_b = 1.405 + 0.0118z \ \ \text{[Site 1]}$$

$$\rho_b = 1.203 + 0.0118z \ \ \text{[Site 2]}$$

where z is soil depth [cm]. The model Root Mean Square Error = 0.127 g cm^{-3}, its $R^2 = 0.504$, and its significance, $p < 0.0001$.

Conclusions from this analysis are that (*i*) the burns themselves did not cause any statistically significant changes in soil bulk density, (*ii*) the bulk densities at these two sites increase with depth, and (*iii*) soils at the first site are denser than at the second. This last conclusion was further tested using the bulk density observation obtained from the pits dug in areas that could clearly be identified as being either road or undisturbed. The results indicate that only the bulk densities within the top 0.05 m of clearly undisturbed soil were significantly (p = 0.0013) less than any other densities measured at 0.05 m. But, because the soil density profiles below 0.05 m are not statistically different, it is likely that any compaction effects are limited to the upper 0.05 m only. Although we cannot prove it, we suggest that the upper 0.05 m of soil was compacted years earlier during logging operations at this site. Finally, we note that there were no statistically significant differences between the bulk densities at the center and edge of the burn area at the second site.

5. Thermal Conductivity Results

Thermal conductivity was tested in a manner similar to bulk density and we found that it tended to increase with depth, confirming the results of our previous study (Massman and Frank, 2004), which was based on measured profiles of soil temperature and heat flux at the first burn site. However, a more appropriate model of λ_s is one that explicitly includes the effects of bulk density and soil moisture as independent variables and that does not rely on soil depth. In general, the functions used to describe $\lambda_s = \lambda_s(\rho_b, \theta_v)$ are nonlinear (e.g., Farouki, 1986; Campbell and Norman, 1998). For the purposes of this study, which is focused mostly on possible change in λ_s as a result of fire, we choose the simplest model possible. We regressed the measured thermal conductivity against the corresponding measurements of bulk density and soil moisture (i.e., $\lambda_s = A\rho_b + B\theta_v$). The result, which is given next, was the same for both the first and second sites (with a model $R^2 = 0.428$ and $p < 0.0001$).

$$\lambda_s = 0.123\rho_b + 8.21\theta_v \ \ \text{[Unheated Soils]}$$

$$\lambda_s = 0.486\rho_b + 2.70\theta_v \ \ \text{[Fire-Heated Soils]}$$

These last two relationships indicate that λ_s has changed as a result of the fire. But, the nature of the change is a bit surprising. Both sites show that thermal conductivity is about four times more sensitive to bulk density after the burn than before. While λ_s appears to be about a third less sensitive to soil moisture after the fire than before. These results would seem to suggest some change in soil structure as a result of the burns. However, the nature of this change is not clear from this particular data set. Our present results are different than those of our previous study (Massman and Frank, 2004), in which we did not detect any fire-induced change in λ_s during the first two months after the burn.

Nonetheless, given that there has been no clear change in soil density at MEF as a result of the fire, the present results suggest that whenever $\theta_v <$ about 0.1, λ_s will be greater after the fire than it would have been if the soil had not been unaffected. Whereas the opposite is true whenever $\theta_v >$ about 0.1. However, there is a complicating factor. As discussed in the companion paper (Massman et al., 2006), soil moisture is likely to be somewhat higher in the burned areas at the second site than in the corresponding unburned areas, which, because MEF is a semiarid region (i.e., climatologically $\theta_v <$ about 0.1), will ameliorate the effects of the change in λ_s there. But because the vegetation has recovered at the first site, which should tend to decrease soil moisture through increased transpiration, we cannot be sure that the soil moisture there is still greater than at the nearby unburned areas. [Note the statistical analyses of the soil moisture data did not yield any clear evidence on this issue.]

In general, we can conclude that the consequences of the fire-induced change in λ_s to the daily and seasonal heating of the soil (and thereby to the soil recovery) is likely to be modulated by the daily and seasonal rainfall patterns and amounts and the resulting soil moisture amounts. But, because λ_s of the fire-heated soils is less sensitive to θ_v, the daily and seasonal heat pulses in burned areas will also be less sensitive to the natural variations in soil moisture than the unburned areas.

6. Conclusions

This study examined the consequences of burning slash to the bulk density and thermal conductivity of soils at two sites within the Manitou Experimental Forest. Results are that:

A. The soil bulk density was unaffected by the fires; although bulk density was different between the two sites.

B. The thermal conductivity of the soil was affected by the fire, but in a surprising way. The thermal conductivity after the fire showed less sensitivity to the presence of soil moisture after the fire than before. But it showed greater sensitivity to the bulk density. Both sites displayed virtually the same pattern of change.

C. The consequences of the fire-induced change in soil thermal conductivity to soil recovery is difficult to predict. For dry periods ($\theta_v <$ about 0.1) the soil heating of the burn areas will be greater and extend deeper into the soil than in nearby unburned areas. Whereas, for moist periods ($\theta_v >$ about 0.1) the soil heating of the burn areas will be less and shallower than in the nearby unaffected areas.

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