Forum: Issues, Management, Policy, and Opinions

Advancing Investigation and Physical Modeling of First-Order Fire Effects on Soils

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ABSTRACT

Heating soil during intense wildland fires or slash-pile burns can alter the soil irreversibly, resulting in many significant long-term biological, chemical, physical, and hydrological effects. To better understand these long-term effects, it is necessary to improve modeling capability and prediction of the more immediate, or first-order, effects that fire can have on soils. This study uses novel and unique observational data from an experimental slash-pile burn to examine the physical processes that govern the transport of energy and mass associated with fire-related soil heating. Included in this study are the descriptions of 1) a hypothesized fire-induced air circulation within the soil, and 2) a new and significant dynamic feedback between the fire and the soil structure. The first of these two hypotheses is proposed to account for the almost instantaneous order-of-magnitude increase in soil CO_2 observed during the initiation of the burn. The second results from observed changes to the thermal conductivity of the soil, thought to occur during the fire, which allow the heat pulse to penetrate deeper into the soil than would occur without this change. The first ever X-ray computed tomography images of burn area soils are consistent with a change in soil structure and a concomitant change in soil thermal conductivity. Other ways that current technology can be used to aid in improving physically-based process-level models are also suggested.

Keywords: dynamic feedbacks, pore structure, soil mass transport, soil thermal forcing, surface boundary conditions

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INTRODUCTION

Intense wildland fires can alter the successional trajectories of plant communities and soil biota and transform the physical, chemical, and structural properties of soils. Many of these changes are synergistic, often irreversible, and can have impacts on both local and large-scale climate and hydrologic processes. In particular, soil microbial effects and soil carbon effects are long-term, often lasting years to decades (e.g., Bissett and Parkinson 1980, Amiro *et al*. 1999, Tiedemann *et al.* 2000, Litton *et al.* 2003, O'Neill *et al.* 2003, Gough *et al.* 2007). Such long-term fire-related changes to the status of soil carbon and the soil's ability to cycle carbon have implications to global climate (e.g., Page-Dumroese *et al.* 2000, Richter *et al.* 2000). In addition, the physical changes to the soil surface (altered albedo and increasing potential for enhanced convection due to increased surface heating) may also affect local atmospheric circulations and precipitation patterns (e.g., Beringer *et al.* 2003, Mölders and Kramm 2007). To better understand these long-term post-fire soil effects requires careful consideration of the immediate or first-order effects that severe heating during intense fires can have on soils.

Because all first-order fire-related effects on soils are the result of soil heating, this study focuses on the critical processes that govern the transport of energy and mass during more extreme fires, with the intent of providing guidance for developing the next generation of models of soil heating during such fires. As far as possible, this paper emphasizes observations, data, and current and developing technology to elucidate the issues and physical processes involved with fire-related soil heating. In so doing, we hope to advance the modeling capabilities and prediction of fire effects, and to make those advances accessible to researchers and land-managers and their support agencies and institutions.

FIRST-ORDER FIRE PHYSICAL EFFECTS ON SOILS

Overview

First-order fire effects include tree mortality, consumption (or oxidation) of surface and soil organic material, emissions of particulates and trace gases produced during the fire, and soil heating. Improving our ability to quantify these first-order effects and to predict their consequences requires improving our ability to measure and model the physical and chemical processes that occur during fires. In the case of soils, this largely involves measuring and modeling the flow of energy and mass through the soil matrix during a fire.

For soils, the general theory of thermal energy (heat) flow has been well known for decades (see van Wijk and de Vries 1963, Aston and Gill 1976, Nerpin and Chudnovskii 1984). But using this theory to develop a model of the soil heating associated with a fire requires specifying the initial state of the soil (the model's initial conditions) and the surface thermal forcing associated with the fire (the model's boundary conditions, or more specifically, the heat flux, G, imposed at the soil surface by the fire).

Initializing a one-dimensional model of heat flow in a soil is relatively straightforward given the initial (pre-fire) vertical profiles of soil temperature, soil moisture, and the thermal properties of the soil, all of which are amenable to direct measurement and mathematical parameterization (Kay and Goit 1975, Farouki 1986, Campbell *et al.* 1994, Massman *et al.* 2007). Unfortunately, the surface boundary conditions (or the soil thermal forcing functions) are difficult to know precisely for any given fire and may be impossible to generalize from one fire to the next (e.g., Stewart *et al.* 1990, Haiganoush *et al.* 2000). Spreading wildland fires, as opposed to stationary slash-pile burns, can further complicate formulating boundary conditions because these fires may also require mathematical descriptions of the surface variations of the combustible fuel and the horizontal movement of the fire front (e.g., Oliveira *et al.* 1997). Nevertheless, the boundary conditions of the current version of the First Order Fire Effects Model (FOFEM 5.0) include specific parameterizations for the soil thermal properties and soil heating rates and can predict reliable soil temperatures during fires (Reinhardt 2003). But because FOFEM is designed for large-scale or stand-level simulations, it predicts average soil heating across a user-specified area. So FOFEM's ability to resolve the fine detail that characterizes the heating of highly variable soils and soil surface conditions is limited.

In addition to specifying the initial and boundary conditions, models of fire-induced heat penetration into soils also need to be coupled to models describing the vaporization of soil moisture and the subsequent transport of water vapor by possible fire-induced air currents within the soil. (A conceptual model of fire-induced air flow in soil is presented in a later section.) Such fire-associated air motions will transport and redistribute other trace gases and thermal energy within the soil. To date, advective air flows have not been incorporated into any model of soil heating during fires. This absence may, at least in part, account for why accurate simultaneous simulations of soil temperatures (heat flow) and water vapor (or mass) transport during a fire remains a significant challenge (e.g., Campbell *et al.* 1994, Campbell *et al.* 1995). Nonetheless, despite the complexity and difficulty of modeling heat and mass flow through a soil during a fire, the need for and use of such models will remain high because they are the principal method for assessing the risk of a negative consequence from soil heating by fire (e.g., Stewart *et al.* 1990, Haiganoush *et al.* 2000).

Besides direct soil heating and possible induced advective air flows, there are other first-order soil effects associated with fire. These include changes to bulk density, mineralogy, soil structure and other physical properties, the formation of a hydrophobic layer, the formation of an ash layer, and alterations to the otherwise normal (daily and seasonal) soil moisture and water relationships and heating regimes (Ketterings *et al.* 2000, Badia and Marti 2003, Seymour and Tecle 2004, DeBano *et al.* 2005, Neary and Ffolliott 2005, Massman *et al.* 2007).

Including all the above processes into a comprehensive dynamic model of soil heat and mass flow during a fire is not possible at present. But, as outlined in the remainder of this study, it is possible to examine these effects and related processes in greater detail than in the past.

Soil Heating during Fires: Surface Boundary Conditions

The best known metric for estimating the degree of soil heating and its consequences is the soil temperature achieved during a fire (e.g., Figure 1). Soil temperature is a convenient metric because it is easily measured during a fire (pre-fire installation is required, of course). But soil temperature is more a consequence of soil thermal forcing than the driving variable itself. Improving predictive models of fire-related heat penetration into soils requires the ability to quantify soil heat conduction and radiation absorption, which are the physical processes responsible for the thermal energy flow through the soil surface during a fire. The surface boundary condition is always formulated in terms of the thermal energy at the soil surface. But within the soil matrix, the vaporization, transport, and possible recondensation of water also need to be considered to accurately predict soil temperatures. Describing this latent energy transfer requires the ability to describe the soil moisture dynamics during the fire, which is discussed in more detail in the following mass transport section.

The difficulty with formulating the thermal forcing (soil surface heat flux) results from the imprecision inherent in 1) characterizing the thermophysical and radiative properties of the surface, and 2) formulating the dynamic aspects of the thermal forcing. The first issue requires knowledge of the amounts and types of organic (litter and duff) and mineral materials comprising the soil surface, the physical structure of the soil surface (porosity, micro-roughness, etc.), the surface moisture status, and how these variables determine the reflectivity, transmissivity, absorptivity, and thermal properties of the surface. The second issue in-

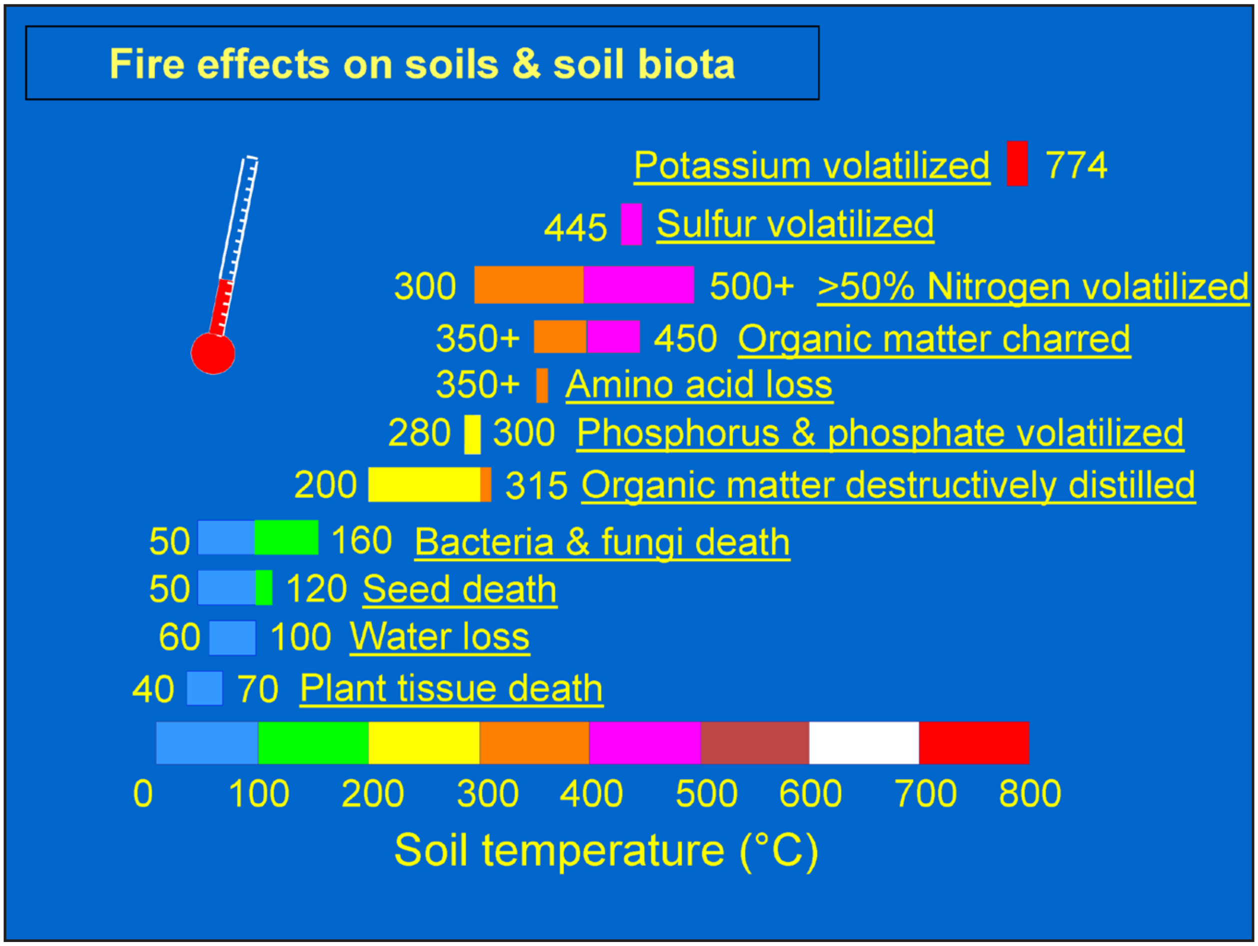

Figure 1. Temperature thresholds and ranges associated with various fire effects on soil organic matter and some soil nutrients. This figure is an expanded and updated version of Figure 8 of Hungerford *et al.* (1991) and Figure 7 of Ryan (2002). Also see Figure 8.8 of Walker *et al.* (1986) and Table 1 of Moody and Martin (2009).

volves describing the duration and type of energy (radiant or conductive) to which the soil is exposed. This factor can depend critically on whether the fire is stationary (e.g., slash-pile burn) or dynamic (e.g., a wind-driven fire front associated with a wildfire or maybe a prescribed burn). In the case of a slash-pile burn, for example, the soil directly beneath a slash pile is likely to be exposed almost exclusively to conductive energy from the burning material, whereas the soil outside the pile area is likely to receive mostly radiant energy. But in the case of a dynamic fire front, the thermal forcing is likely to be far more difficult to partition in a simple area-based manner or to formulate in time. For a moving wildfire or prescribed burn, the area (of exposed soil) ahead of the approaching fire front will likely receive increasing radiant energy until the fire front arrives; during the time the fire front passes over this area it is likely to be exposed to both types of energy; and as the fire front passes, the radiant energy flux will diminish, but the conductive forcing could either increase or decrease depending on the amount of burning material that remains in contact with the soil. Consequently, we might expect greater uncertainties with the boundary conditions for modeling soil heating during a wildfire than during a slash-pile burn.

Although the model boundary conditions are obviously difficult to formulate precisely, they are amenable to investigation with current technology. Figures 2 and 3 present examples of how the radiant and conductive surface energy fluxes were partitioned during a slash-pile burn. The surface radiant energy, $G_{rad}(0,t)$, is shown in Figure 2 at six different radial distances from the edge of the slash pile. (Note: 1) That the radiant energy is measured outside the slash-pile burn area. 2) Not all of the radiant energy would have necessarily been absorbed by the soil because some of it would have been reflected away from the surface. So this figure presents the maximum radiant soil surface heating rate that could have been achieved during this slash pile burn. 3) G is used here to refer generically to soil heat flux [Wm^{-2}], t = time [s], and the 0 refers to the soil surface or a depth of 0 m into the soil.) The surface conductive heat flux, $G_{con}(0,t)$, is shown in Figure 3 and was inferred from measurements made with soil heat flux transducers buried at 0.02 m depths beneath the slash pile.

The ideal upper boundary condition for modeling soil heat flow during a fire is a linear combination of $G_{con}(0,t)$ and $G_{rad}(0,t)$ that can be determined from the type of fire and the physical properties of the surface. Unfortunately this ideal may never be completely achieved. But, as Figures 2 and 3 demonstrate, it is currently possible to make measurements

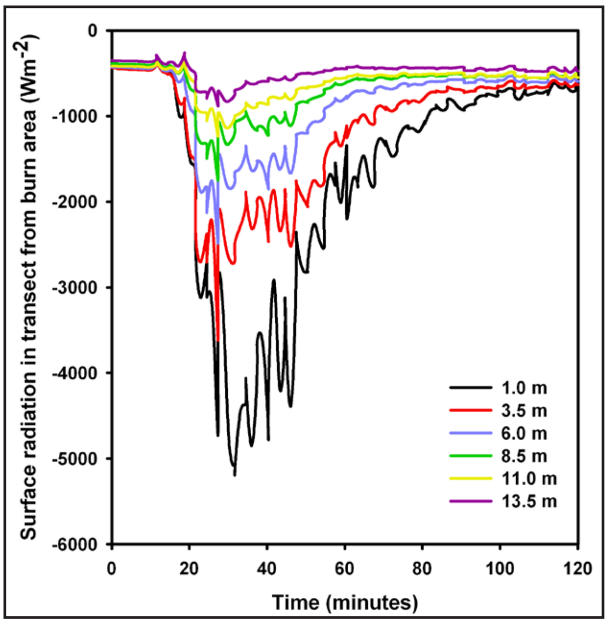

Figure 2. Time course of one-minute-mean surface radiant energy flux measured outside the burn area during an April 2004 experimental slash-pile burn performed at the Manitou Experimental Forest, located in the Rocky Mountains of Central Colorado (Massman *et al.* 2007), using water-cooled Medtherm Corp. (Huntsville, Alabama, USA) Series 64 heat flux transducers spaced radially between 1.0 m to 13.5 m from the edge of the pile. Negative fluxes indicate that the heat flow is downward or into the soil. For the purposes of documenting the temporal sequence of events depicted in this figure and the next three figures, it should be noted that the fire was initiated at the edge of the slash pile at 10:10 AM on day 117 = 117.43 of 2004.

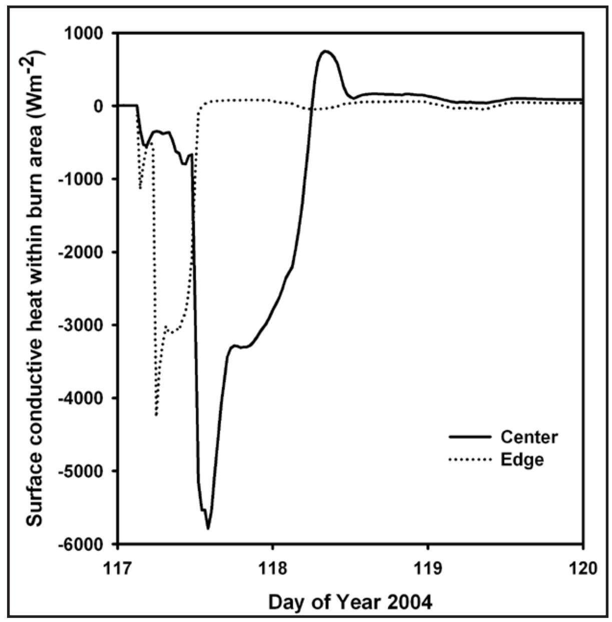

Figure 3. Time course of half-hourly-mean surface conductive heat flux inside the burn area (or underneath the slash pile) during the same burn as discussed in Figure 2 and inferred from soil heat flux transducers manufactured by Thermonetics Corporation (La Jolla, California, USA) and buried at a soil depth of 0.02 m. These sensors, their temperature sensitivities and calibrations, and thermal conductivity effects are described by Massman and Frank (2004). These heat flux data include corrections for underestimations in the true heat flux caused by incomplete contact with the soil (e.g., Sauer *et al.* 2003) and for the time lag between the heating observed at 0.02 m depth and the forcing at the surface. Negative fluxes indicate that the heat flow is downward or into the soil.

of the type necessary for improving formulations of model boundary conditions for simulating heat flow during fires. In particular, and concurrent with measurements of soil temperature, measurements of both $G_{con}(0,t)$ and $G_{rad}(0,t)$ should be made inside and outside slash-pile burns, and, if possible, for prescribed burns as well. Improving a fire model's parameterization for soil heating (the surface boundary condition) would then be possible by comparing the observed and predicted soil temperatures and evaluating different formulations of that boundary condition. Improving models of the soil heat flux during fires will lead not only to improved modeling capability and improved understanding of the thermal impacts of fire on soil, but also to improved understanding and modeling of the mass (and soil moisture) transport in soils during fires.

Mass Transport within Soils during Fires

Mass transport in soils occurs by molecular diffusion and air movement through the soil. These two processes occur naturally whether there is a fire or not. Nonetheless, fire has the potential to enhance these processes significantly by increasing the rate of molecular diffusion, which increases as temperature increases, and by creating advective air currents in soils. An example of these air currents can be easily be imagined (or hypothesized) for the case of a burning slash-pile (see Figure 4). Such a fire is usually ignited near the bottom of the pile and very quickly intensifies to the point that the whole (external) portion of the pile is burning. During the period of intensification, the convective air currents above the pile will also intensify and thereby intensify horizontal inflow above the soil outside the pile. This accelerating horizontal air flow will

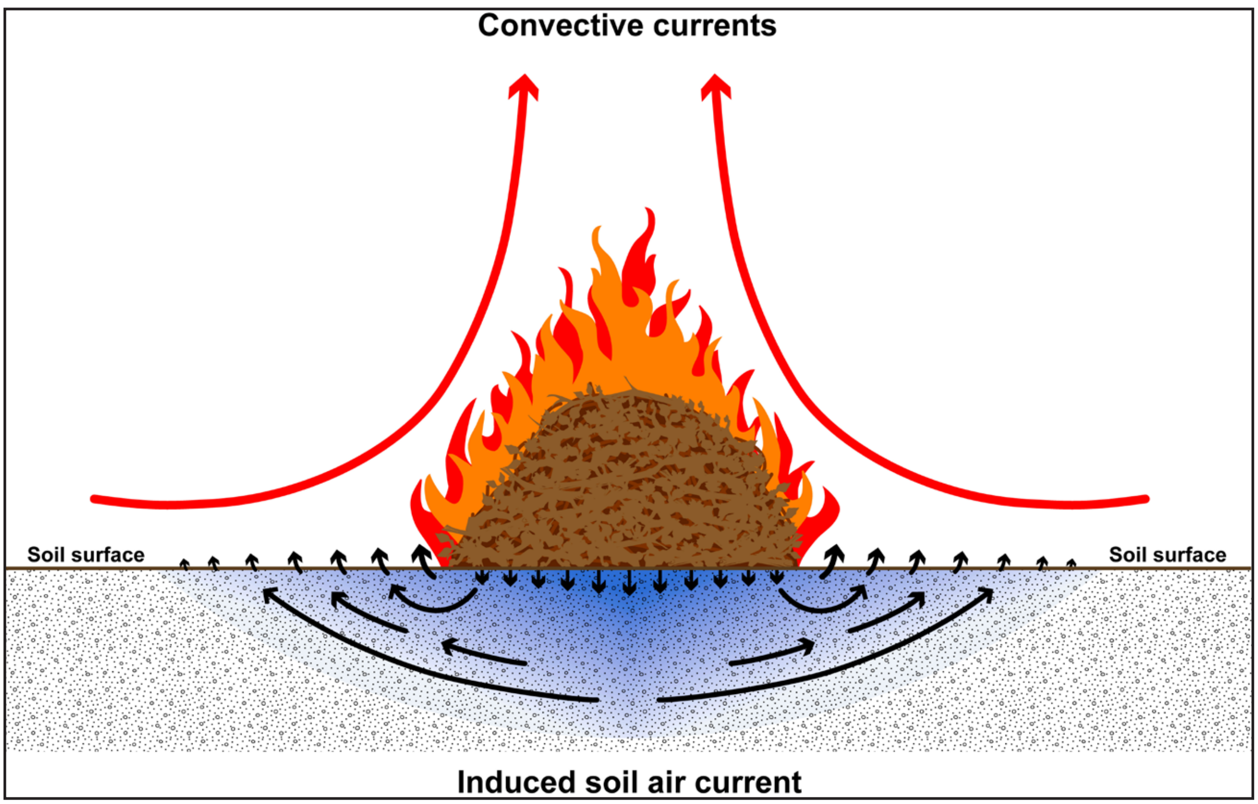

Figure 4. Schematic of fire-induced air flow within soils. The arrows indicate the direction of the air flow.

lead to a localized pressure drop at the soil surface in the area outside the burning pile, thereby "pulling" the air from the soil around the pile and from the soil underneath the pile. In turn, this will set up a pressure differential inside the soil underneath the pile, which will then "pull" the air inside the pile into the soil. To complete this induced circulation, there must also be some near-surface return flow into the pile, but this part of the flow could be extremely complex due to physical arrangement of burning and non-burning (interior) pile material. In addition to this localized pressure differentials associated with the intensifying convective air currents, the radiant energy impinging on the soil surface outside the pile area will very quickly add to (or maybe even independently create) the effect by causing the near-surface soil air to expand as it is heated. (From Figure 2, it can be surmised that the soil heat flux within a couple meters of the edge of the pile could well exceed normal soil heat flux by a factor of 10 or more.) As the near-surface soil air expands (out of the soil) it will again create a pressure differential in the soil that will tend to "pull" air upward from deeper or cooler soil layers, thereby enhancing (or maybe causing) this secondary air circulation from inside the pile and through the soil. The existence of this fire-induced soil air current was suggested from the data shown in the next two figures.

Figure 5 shows the temporal evolution of soil moisture during the slash-pile burn discussed above (Figures 2 and 3). (We wish to emphasize here that these soil moisture data are the first *in situ* observations of moisture dynamics during a slash-pile burn, and consequently are not completely free of error or uncertainty. See the Appendix for further details concerning these data and the performance of the instruments.) The two time series at 0.15 m depth show some indication of soil moisture increasing and then decreasing during the fire. But the support for a similar fire-driven transient in soil moisture at 0.05 m depth is weaker.

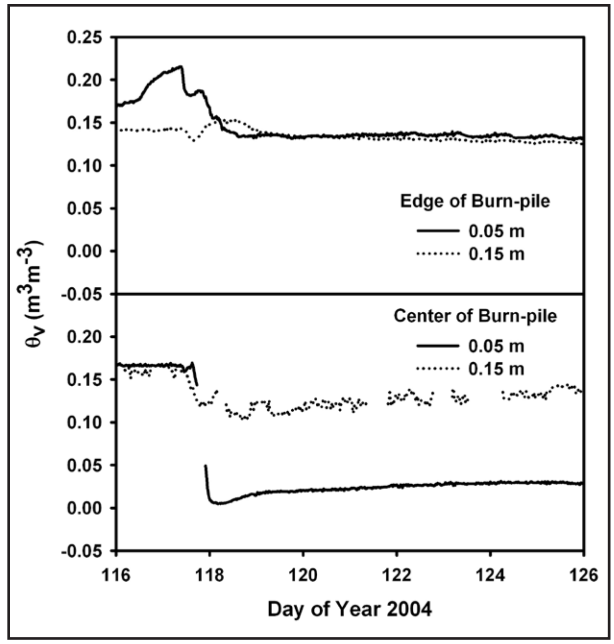

Figure 5. Time course of half-hourly soil moisture at 0.05 m and 0.15 m depths and at two locations (center and near the edge) under a slash pile during the April 2004 experimental burn at Manitou Experimental Forest. These data were obtained using a specially designed high-temperature TDR (Zostrich Geotechnical; Pullman, Washington, USA). The design of this particular probe is fairly standard, but the material used to house the steel needles and the connectors attaching them to the coaxial (data/signal) cables had a much higher melting temperature than normal. Additionally, those external portions of the coaxial cables that were likely to be exposed to high temperatures were wrapped in silicon tape. The data gaps at the center location result from eliminating some extremely noisy data during the burn. The cause of this noise is not known, but we speculate that it could have resulted from (1) sensor damage, which was confirmed for at least one probe (at 0.15 m) during laboratory tests performed several months after it had been retrieved from the field, or (2) change in the internal impedance of the TDR probes due to sensor warming in the presence of soil moisture. Note that these data include an empirical correction for temperature effects on the TDR measurements (see Appendix). Consequently, some of the variability in the measured soil moisture during the burn is a result of inaccuracies of the corrections.

This type of soil moisture transient is consistent with the hypothesis that moisture, vaporized during the heating of the soil or generated within the pile during the burn, is carried into the soil by the fire-induced circulation where it recondenses on the cooler soil particles.

As the soil heating continues to lower depths, the soil moisture is again vaporized, causing it not only to decrease but, as the data at the 0.05 m depth under the center of the slash pile indicate, to almost completely vanish. Of course, whenever water is vaporized or condenses within the soil, latent energy is exchanged between the water and the soil matrix, thereby coupling soil heating with moisture transport. This coupled system is the basis for describing a soil water vaporization-transport-condensation-revaporization (VTCV) process, which has been modeled and tested using soil moisture data obtained during burns performed in laboratory settings (Campbell *et al.* 1995). Both the laboratory data and the model show temporal behavior and also suggest that the VTCV interpretation is plausible. But the only transport mechanism included in the soil moisture model is vapor diffusion, which without advective air flow may explain why the model consistently underpredicted the amplitude of the soil moisture transient (Campbell *et al.* 1995).

Figure 6 provides a more convincing case for the existence of advective flows in soils at least during slash-pile fires. This figure shows the temporal evolution of the soil CO_2 during the same April 2004 slash-pile burn. The most remarkable feature of these data is the rapid (almost instantaneous) increase in soil CO_2 after the fire was initiated. In less than half an hour after this burn was started, the soil CO_2 under the slash pile increased from about 800 ppm (CO_2 density of about 1.1 g m^{-3}) to over 20 000 ppm (or about 26.8 g m^{-3}), exceeding the maximum range of the CO_2 gas analyzer. Diffusion alone cannot account for such a rapid increase in soil CO_2 at both the 0.05 and 0.15 m depths. This can be most easily seen during the recovery period when diffusion probably dominates and the CO_2 levels begin to fall and approach their original pre-fire values. This recovery period literally takes days. Consequently, it is more likely, during the period of rapidly increasing soil CO_2, that the initial combustion released large amounts of CO_2, which were then carried almost immediately into the soil by fire-induced air flows. Although this is one interpretation of the CO_2 data, we cannot be completely sure what path the combustion-generated CO_2 followed to those soil depths. Aside from purely advective flow paths through the homogeneous porous soil, it is also possible that there are preferred conductive paths in the soil in the form of cracks, which could have formed as the back-filled soil settled after burying the instruments

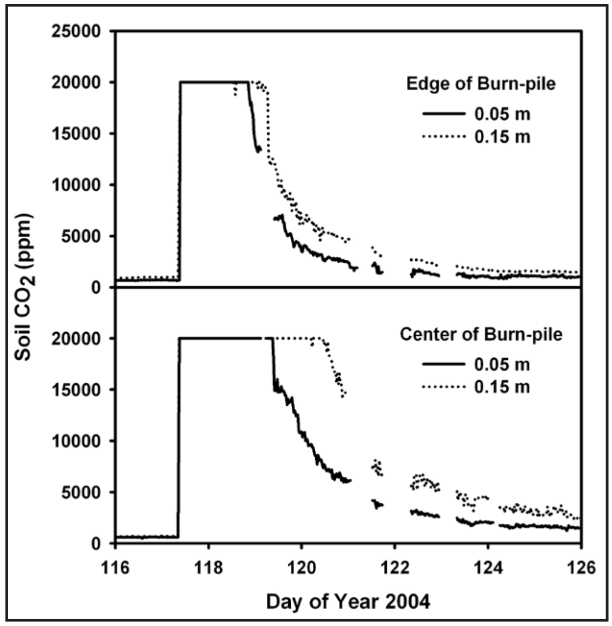

Figure 6. Time course of half-hourly soil CO_2 at 0.05 m and 0.15 m depths and at two locations (center and near the edge) under a slash pile during the April 2004 experimental burn at Manitou Experimental Forest. These data were obtained from a 30 s sampling period every half hour from a flow of soil CO_2 drawn through a tube and into an infrared gas analyzer (LiCor 820; Lincoln, Nebraska, USA) using a pump downstream of the analyzer. The maximum concentration that the instrument can measure is 20 000 ppm, which was exceeded in less than 30 min after the fire was initiated. These data appear on the graphs as horizontal lines (approximately) between days 117.4 and 119.

and constructing the slash pile over them. If this is the case, then the combustion-generated CO_2 would likely have followed such a preferred (or less resistive) path. But even the existence of preferred paths does not negate the possibility of advective flows in the soil. In general, these data strongly suggest that slash-pile burns not only induce convective atmospheric currents, but soil advective or convective flows as well. Because other burn types, e.g., wildfires and prescribed burns, create convective air flows, it is likely that they too can induce advective flows in soils, but the strength and scale of these flows will vary with the intensity and scale of the fire.

Before summarizing this section, it is worthwhile to explore some of the possible consequences of exposing the soil fauna to such abnormally high amounts of CO_2. For the present study, the peak soil CO_2 amount was estimated by fitting the decaying branch of the CO_2 time course (right hand portion of the curve in Figure 6) with two different models and then extrapolating these model fits back in time to the point of the initiation of the fire. The two models used for curve fitting were: a simple exponential decay model and a model based on a decaying solution to the one-dimensional diffusion equation with a step function as the initial condition. The results from these models were similar and yielded an estimated maximum CO_2 amount in the soil between 60 000 and 200 000 ppm. The duration of such high soil CO_2 amounts is much more difficult to estimate. But the fire burned vigorously for several hours, so any exposure to high amounts of CO_2 (we speculate) could easily have been maintained for 12 h to 24 h. (Note: Figure 6 indicates that the CO_2 level at the center of the slash pile exceeded 20 000 ppm for over 50 h.) Exposure to amounts of CO_2 this high for this period of time is likely to been fatal to a great many soil organisms long before the maximum in soil temperature occurred.

Although these soil CO_2 results are the first of their kind for slash-pile burns and wildfires, they are not the first observations of soil CO_2 during a fire. In a study of the impacts of prescribed burning, O'Brian *et al.* (2006) found that within the nesting cavities of ground nesting parrots, CO_2 amounts reached approximately 2100 ppm CO_2 for 15 min. This was not sufficient to cause any significant alteration to any nest's habitat, but it does suggest that at least some form of fire-induced advective flows can occur even during a much less extreme fire. Furthermore, it also confirms that investigations of soil CO_2 during fires are valuable in their own right quite aside from fire-induced transport mechanisms. (Note: Engstrom [2010] explores other immediate effects of fires on soil fauna and the long-term impact that first-order fire effects can have on faunal habitat.)

Both the soil moisture data (Figure 5) and the CO_2 data (Figure 6) suggest the notion that including fire-induced advective flows in models of soil energy and mass transport should improve their performance. But to accomplish this is more easily said than done. The key issues of course are how to measure this hypothesized (3-dimensional) fire-induced velocity field in the soil and how to formulate a model of such a field. There are two approaches that come to mind. The first is to assume that CO_2 behaves as a passive tracer on relatively short time scales and estimate the vertical and horizontal velocities needed to produce the observed increases in the soil CO_2. (Note: We are not proposing to deal with any specific details of the velocity field here. Rather, we wish only to suggest possible methods that offer some potential for observationally inferring important aspects of the fire-induced velocity field.) But a tracer-based method need not be limited to CO_2; there are other gaseous species, or even isotopes of H_2O and CO_2, that would likely prove useful for this approach. Second, if the fire-induced currents are strong enough, then the associated differential pressure fields, particularly those within the soil, may be amenable to detection. The velocity field could then be inferred from the measured pressure gradients and knowledge of the soil's permeability using Darcy's law (see Scanlon *et al.* 2000 for a discussion of Darcy's law). Detecting small pressure differences is not only possible with current technology, but such pressure forces have been used as the basis for modeling temporal variations in wintertime soil and snowpack CO_2 (e.g., Massman 2006).

A better understanding of advective flows in soils during fires should improve models of soil moisture transport during fires and improve the predictability of the soil moisture distribution after the fire. It could also improve the predictability of the formation of the within-soil hydrophobic layer, which is discussed next.

Hydrophobicity: A Physiochemical Mass Transport Phenomenon

Conceptually, the physical processes governing the fire-related VTCV process for soil moisture are, in broad terms, the same as those governing the formation of the fire-induced hydrophobic layer (FIHL). But the goal of modeling fire-induced hydrophobicity is not the transport phenomenon itself, but the depth at which a FIHL is likely to form and possibly some measure of the strength or quality of the FIHL as well. But, before this is possible, much more must be known about the specific compounds that form such layers. These compounds have been hypothesized to belong to the family of aliphatic hydrocarbons (Doerr *et al.* 2000), and studies have attempted to identify some of the compounds that constitute the FIHL (e.g., Hudson *et al.* 1994, Horne and McIntosh 2000). Only recently has convincing evidence been found that suggests that the FIHL includes aliphatic structures (Simkovic *et al.* 2008). Unfortunately, without knowledge of the volatilization or condensation temperatures of the specific compounds involved, it is likely to prove difficult to predict the depth of the formation of the FIHL very precisely.

Nevertheless, there is a significant empirical body of knowledge concerning the FIHL. For example, it is known that, below a minimum temperature of 176 °C, a soil FIHL will not form; that heating a soil to temperatures above 288 °C will destroy the hydrophobic layer (DeBano *et al.* 1998); and that a FIHL is a transient phenomenon (Doerr *et al.* 2000, Mac Donald and Huffman 2004, Certini 2005), which rarely forms below 0.08 m (Henderson and Golding 1983, Robichaud and Hungerford 2000, Huffman *et al.* 2001). On the other hand, heating soil above the minimum temperature does not guarantee the formation of a FIHL because not all ecosystems or forest types will necessarily form a FIHL when burned (e.g., Boerner 2006). Furthermore, the amount of soil moisture present during a fire can also impact the formation of a FIHL (e.g., Robichaud and Hungerford 2000, Luce 2005), with higher soil moisture amounts tending to discourage the formation of the FIHL. Clearly, this association between the amount of soil moisture present at the time of a fire and the formation of the FIHL suggests that a model of the FIHL must be coupled to any VTCV soil moisture model. This, in turn, introduces other complications for a processed-based model of first-order fire effects because the physiochemical interactions between the hydrophobicity-forming compounds, the soil moisture, and their respective vapors are not known (Doerr *et al.* 2000). Without a better understanding of these physiochemical processes, developing a process-based model to estimate where a FIHL layer will form and how long it may persist in any particular climate or ecosystem is not likely.

In addition to the fire-induced transport and physiochemical complexities involved with modeling the FIHL, there may yet be a third important dynamic process involved. Hudson *et al.* (1994) suggested that qualitative differences in hydrophobic layers (at a particular site) may in part be due to physical or structural differences in the soil (at that same site). Because it is reasonable to assume that at least some aspect of soil structure is involved with the formation of the FIHL and that fire can alter soil structure, it therefore follows that the fire-induced changes in soil structure may have a significant impact on the formation or suppression of the FIHL. This possibility yields the following hypothesis: that the fire may alter the physical arrangement of the soil particulate surfaces so as to enhance or suppress the condensation of the organic vapors responsible for the formation of the FIHL. Furthermore, these changes in soil structure may be independent of or coupled to the formation of the FIHL itself. In general, not a lot is known about the nature of fire-induced changes to soil structure. Nevertheless, this is an important first-order fire effect with potentially long-term implications for the soil microclimate and so is discussed in greater detail in the next section.

Despite these serious handicaps to a process-based model, it still may be possible to address some of these complex (FIHL) issues and to improve the empirical data base relating to FIHLs by performing more detailed studies of the FIHL in conjunction with heavily instrumented slash-pile burns similar to that discussed in Figures 2, 3, 5, and 6. Much of the technology and capability for such *in situ* studies of the FIHL are readily available, as attested by the many studies previously cited in this section.

Effects of Heating on Soil Structural and Physical Properties: Dynamic Feedbacks

Fire can cause significant changes to soil structure (Dyrness and Youngberg 1957). In particular, with the loss of soil organic matter, the soil aggregate stability is compromised, the contact surfaces between the soil particles change, and the bulk density usually increases, resulting in a corresponding decrease in soil porosity (Badia and Marti 2003, Seymour and Tecle 2004, DeBano *et al.* 2005). In turn, such structural changes alter the soil porous environment and make it more difficult for water to penetrate the soil, which like the FIHL, will increase the soil's susceptibility to water and wind erosion (DeBano *et al.* 1998, Ravi *et al.* 2006).

In addition to these well known consequences to fire-induced structural changes, there is also another less well known consequence. With an increase in soil bulk density, the soil thermal conductivity is also likely to increase (e.g., Farouki 1986), which presumably results from the increase in the contact surfaces area of the soil particles associated with the increase in soil bulk density. But this change in thermal conductivity indicates that the fire-associated heat pulse has the potential to dynamically interact with the soil structure to create conditions that allow the heat pulse to penetrate deeper into the soil than would have occurred without a change in bulk density. At present, no first-order fire effects model includes this dynamic positive feedback between the heat pulse and soil structure. This feedback is different from the positive feedback associated with the increase in the soil's thermal conductivity as the soil temperature rises or the negative feedback in the soil's thermal conductivity as the soil moisture decreases, both of which are included in current first-order fire effects models (Campbell *et al.* 1994, Campbell *et al.* 1995, Massman and Frank 2004, Massman *et al.* 2007).

Yet there may be a second, previously unknown, dynamic feedback between the soil structure and fire-associated heat pulse. Massman *et al.* (2007) found the thermal conductivity of soil at two slash-pile burn sites (at Manitou Experimental Forest [MEF], Central Rocky Mountains of Colorado, USA) was affected for years after a burn, even without a detectable change in soil bulk density. Specifically, they found that the relationship between soil thermal conductivity and soil water content can be drastically altered as a result of a slash-pile fire, such that a dry soil will conduct much more heat than it would have before the burn and that the same soil when wet will conduct less heat than it would have pre-burn. Massman *et al.* (2007) demonstrated that such a change in thermal conductivity could have rather profound effects on post-fire climatically-driven soil heat flow and hypothesized that the intense heating of the soil during the burn must have altered the soil structure.

Figures 7 and 8 provide some of the first photographic indication of this possible alteration of soil structure. These figures were obtained with a microscale X-ray computed tomography scanner from soil samples procured about four years after the burn from soil beneath the second of two slash-pile burns (Massman *et al.* 2007) and from the untreated control area. For the purposes of the present discussion, the control sample is considered a surrogate for the burn area soil before the slash-pile burn. Comparing these "before" and "after" images illustrates the gross changes in the pore structure associated with the fire. In particular, the mean pore size after the fire appears to have been significantly reduced to a scale below the resolution of the images (1 pixel = 18 μm) and certainly well below what it was before the burn. This is displayed in both the horizontal (Figure 7) and vertical (Figure 8) orientations.

The exact nature of this structural change is not understood and is still being investigated. Consequently, it is possible that such changes are unique to MEF soils. These soils, except for a few that are derived from red arkosic sandstone, are all derived from biotite granite and associated igneous rocks of the Pikes Peak batholith. Previous grazing and mechanical harvesting throughout the area has resulted in a moderately disturbed soil. The particular soil shown in these two figures is a deep (>1.0 m), fine-loamy, mixed, frigid Pachic Argiustoll, and is typical of soils throughout the experimental area and are approximately 66% sand, 21% silt, and 13% clay. Soil organic material comprises about 1% to 2% of the soil by volume. The bulk densities in the general area of the burn increase with depth and range between 1.1 Mg m^{-3} and 1.5 Mg m^{-3}. Yet despite the possible uniqueness of the MEF soils and the small sample size (n = 1), it is

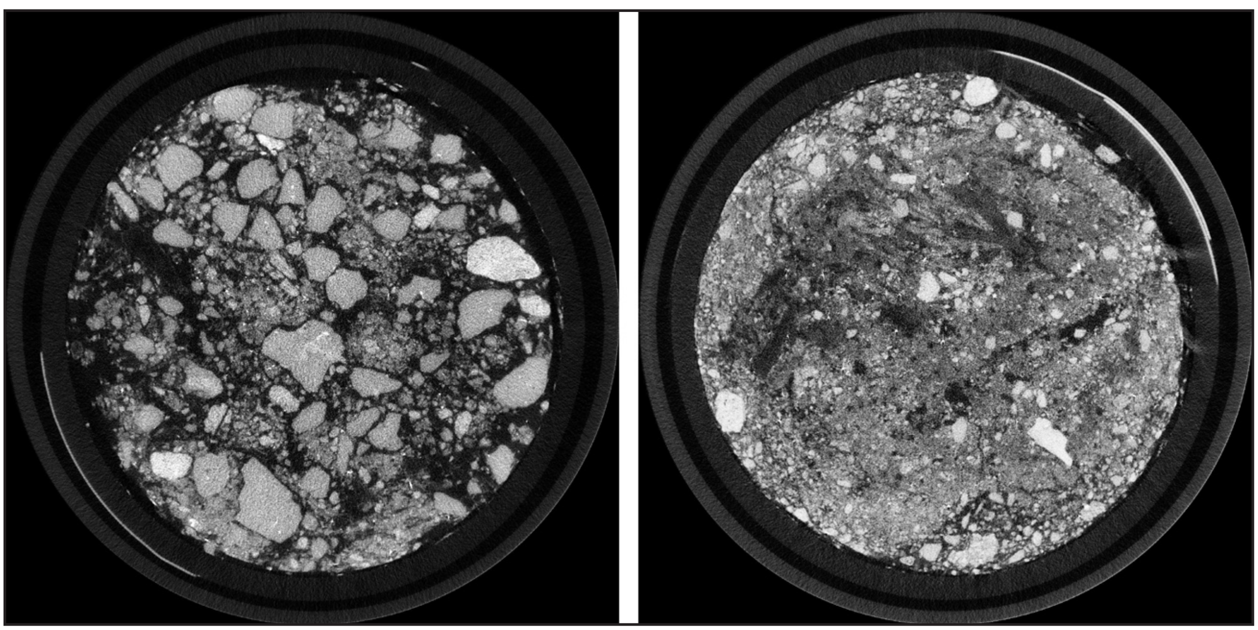

Figure 7. Horizontal cross sections (derived from X-ray computed tomography) of Manitou Experimental Forest soil. Black areas of the photographs correspond to soil pore space. The figure on the left corresponds to a depth of about 0.01 m below the soil surface from an area unaffected by the slash-pile burn. The figure on the right is also a horizontal cross section corresponding to the same depth, but was obtained from a sample of the soil beneath the slash-pile burn. The diameter of each sample is about 36 mm and each image has a pixel resolution of 18 μm.

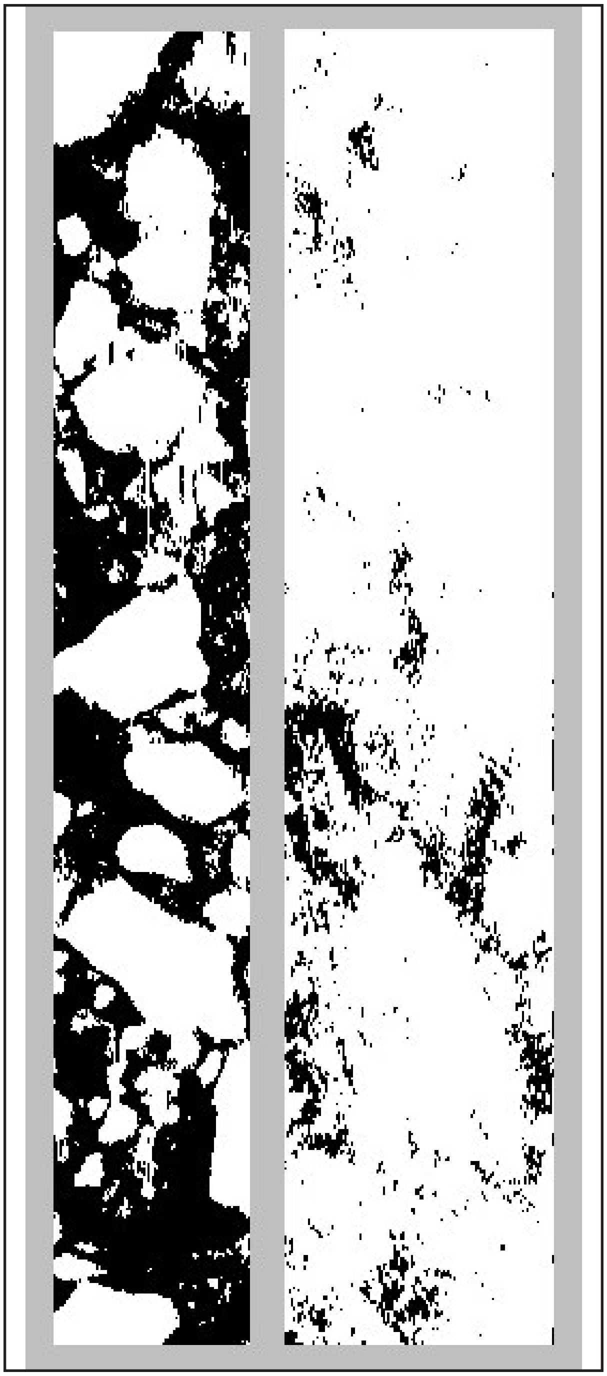

Figure 8. Vertical cross sections (derived from X-ray computed tomography) of Manitou Experimental Forest soil. Black areas of the photographs correspond to soil pore space. The figure on the left corresponds to the upper 0.05 m of the soil from an area unaffected by the slash-pile burn. The figure on the right was obtained from a sample of the soil beneath the slash-pile burn. Cross sections have been calculated from about 200 horizontal slices. The horizontal length of each image is about 2 mm. The pixel resolution is 18 µm.

still valuable to explore possible causes and consequences of this apparent change in the structure.

Because many of the soil particles are decomposing granite, one general hypothesis for the cause of this change is that the particles may have fractured (or disintegrated) into smaller particles during the burn, thereby changing the particle size and pore structure of the soil. There are at least two specific soil heat-mediated mineralogical changes that are consistent with this hypothesis. First, the loss of hydroxyl water from clay minerals, which occurs at somewhere between 300 °C (Arocena and Opio 2003) and 420 °C (Walker *et al.* 1986), might promote such disintegration. For example, Arocena and Opio (2003) suggested that this process was responsible for the reduction of sand-sized amphibole into silt-sized or finer soil particles during a slash-pile burn in British Columbia, Canada. The second change is the disintegration of kaolinized feldspar grains (e.g., Ulery and Graham 1993). But this latter process requires temperatures exceeding 500 °C, which were not observed in the soil during the MEF burn (see Massman *et al.* 2007). Nevertheless, such a heating induced fracturing is consistent with Figure 7 by an "infilling" of the pore space with fine soil matrix recorded primarily in the middle of the core. If so, then the resulting smaller soil particles are likely to be in much better contact after the fire than before and consequently the thermal conductivity of the dry soil would be greater after the fire than before (as was observed). The observed reduction in the thermal conductivity of a moist post-burn soil (vs. a moist pre-burn soil) is more difficult to intuit from these photographs. One possibility is that the pore connectivity may also have changed so that a contiguous (water-filled pore) path is more difficult to form in the post-burn soil. This is again in agreement with Figure 8 where in the control image most of the pore space appears connected at this high resolution, whereas for the burned area sample, only a small number of isolated pore networks are connected vertically. In turn, this might implicate the formation of a hydrophobic layer within the soil, which can influence the thermal conductivity of a heated wet soil (Ju *et al.* 2008).

Nevertheless, since this change appears to have taken place during the burn and is a result of the burn itself means that it represents a dynamic feedback between the heat pulse and the soil that enhances or augments the impact of the burn on the soils. These "before" and "after" soil structures are so significantly different that one can only assume a profound fire-induced affect on the thermal and hydraulic properties of the soil has taken place. Moreover, this feedback is potentially coupled to more than the heat pulse and the thermal conductivity because, as discussed in the previous section and as can be inferred from Figures 7 and 8, the transport properties of the soil may also have been significantly (and possibility permanently) altered by the fire. If so (and to reiterate), then the feedback between the transport of gases and chemicals through the soil during the fire can have important consequences to the formation of the FIHL as well.

Understanding this and the other (previously mentioned) feedback phenomena is important for improving first-order fire effects models. These feedback processes clearly indicate that the fire-associated heat pulse dynamically interacts with the soil to create positive feedback conditions, which augment the heat pulse's ability to penetrate the soil and which dynamically alters the soil's ability to transport chemicals and gases during the fire. None of these dynamic feedbacks have ever been included in a soil heating model. Although observational studies of any of these dynamic feedback processes during a wildfire or a slash-pile burn are probably not possible with current technology, the emerging use of X-ray computed tomography to visualize the internal structure of undisturbed soil samples (e.g., Mooney *et al.* 2006), as demonstrated here in Figures 7 and 8, suggests that further effort and analysis in future studies could be worthwhile. Accompanying these changes in soil structure and mineralogy are changes in soil chemistry, which is discussed in the next and last section.

Effects of Heating on Soil Nutrient Status and Soil Chemistry

By changing the chemical composition of the soil, fire impacts the availability of many soil nutrients to soil biota and can fundamentally alter soil nutrient cycling (e.g., Raison *et al.* 1985, DeBano *et al.* 1998, Gray and Dighton 2006, Jimenez Esquilin *et al.* 2007). Although there is a large number of soil nutrients, the three that are particularly important are nitrogen, phosphorus, and potassium and, in very general terms, losses of these and other soil nutrients increase with increasing fire severity (e.g., Figure 1). Consequently, as soil heating increases, the probability that fire will detrimentally impact soil nutrient cycling and soil productivity also increases (Jimenez Esquilin *et al.* 2007).

During a fire, soil nutrient loss occurs by two transport processes: 1) transport of the volatilized compounds containing those nutrients by both molecular diffusion and the fire-induced soil and atmospheric air currents, and 2) the transport of particulates away from the area of the burn. The priority for improving first-order fire effects models (at least for moderate to severe fires) could easily be the development of algorithms quantifying the oxidation and transport of phosphorus and phosphate compounds. In general terms, fire effects on soil P and P availability are likely quite complex (e.g., Murphy *et al.* 2006). But for some soils and fires, phosphorus is relatively easily lost by these transport processes and is generally slow to recover by natural processes after a fire (Raison *et al.* 1985). In addition, because the processes associated with post-fire recovery of soil phosphorus are aided somewhat by any remaining ash (because ash particles usually are a source of some phosphorus) (Raison *et al.* 1985), model improvements could also be made by the ability to predict amounts of post-fire ash left on the soil surface. Consequently, any improvements to phosphorus chemistry and transport and ash formation that can be made to current modeling capabilities would improve our ability to quantify the fire-caused loss of soil productivity as well.

Clearly, the same conclusions and recommendations about phosphorus can also be made about the other soil nutrients, nitrogen, potassium, sulphur, etc.; it is simply a matter of how hot the soil is heated (Figure 1). Consequently, the key to minimizing the impacts on soil nutrient status of slash-pile burns for certain, and possibly prescribed burns as well, is to minimize the soil temperatures during the burn. This suggests that empirical studies should be made of the soil heating associated with different geometrical arrangements and amounts of fuels in order to find an optimum amount and geometric arrangement of the fuel loading that will minimize the soil heating. Such studies should include investigations of post-burn soil nutrient status as well.

CONCLUSIONS: IMPROVEMENTS IN PROCESS-BASED MODELS OF SOIL HEATING USING CURRENT TECHNOLOGY

Several improvements in current process-based models of soil heating during fires are possible with current technology but, as we have argued here, should be based on increasing the observational data base. First, modeling the fire-induced soil heat pulse could probably be improved with more measurements of the soil radiation and conductive heat fluxes during fires (probably using slash-pile and prescribed burns). This should lead to improved parameterizations of model forcing functions and upper boundary conditions. Second, including the dynamic feedback processes between the soil structure and the fire-induced heat pulse should improve simulations of the depth of penetration of fire-associated heat pulse. This will require photomicrographic and other detailed studies of the vertical structure of the soil physical and thermal properties before and after fires. Third, developing and verifying algorithms to describe fire-induced advective flows in soils should improve not only the reliability of the soil heat pulse predictions, but also should improve predictions of the vaporization, transport, and condensation of soil moisture and the formation of the fire-induced hydrophobic layer. Studies of advective transport may require soil tracer releases or studies of soil CO_2 amounts (and possibly isotopes) during slash-pile burns. They could be aided by photomicrographic studies of the structure of the fire-induced hydrophobic layer as well. Fourth, improved understanding of the physiochemical and transport processes of key soil nutrients should improve the ability to predict and maybe minimize changes in soil nutrient status. Such studies can also be performed using experimental slash-pile and prescribed burns.

LITERATURE CITED

Amiro, B.D., J.I. MacPherson, and R.L. Desjardins. 1999. BOREAS flight measurements of forest-fire effects on carbon dioxide and energy fluxes. Agricultural and Forest Meteorology 96: 199-208. doi: 10.1016/S0168-1923(99)00050-7

Arocena, J.M., and C. Opio. 2003. Prescribed fire-induced changes in properties of sub-boreal forest soils. Geoderma 113: 1-16. doi: 10.1016/S0016-7061(02)00312-9

Aston, A.R., and A.M. Gill. 1976. Coupled soil moisture, heat and water vapour transfers under simulated fire conditions. Australian Journal of Soil Research 14: 55-66. doi: 10.1071/SR9760055

Badia, D., and C. Marti. 2003. Plant ash and heat intensity effects on chemical and physical properties of two contrasting soils. Arid Land Research and Management 17: 23-41. doi: 10.1080/15324980301595

Beringer, J., L.B. Hutley, N.J. Tapper, A. Coutts, A. Kerley, and A.P. O'Grady. 2003. Fire impacts on surface heat, moisture and carbon fluxes from a tropical savanna in northern Australia. International Journal of Wildland Fire 12: 333-340. doi: 10.1071/WF03023

Bissett, J., and D. Parkinson. 1980. Long-term effects of fire on the composition and activity of the soil microflora of a subalpine, coniferous forest. Canadian Journal of Botany 58: 1704-1721.

Boerner, R.E.J. 2006. Soil, fire, water, and wind: how elements conspire in the forest context. Pages 104-122 in: M.B. Dickinson, editor. Fire in eastern oak forests: delivering science to land managers. USDA Forest Service General Technical Report NRS-P-1. Northern Research Station, Newtown Square, Pennsylvania, USA.

Campbell, G.S., J.D. Jungbauer Jr, R. Bidlake, and R.D. Hungerford. 1994. Predicting the effect of temperature on soil thermal conductivity. Soil Science 158: 307-313.

Campbell, G.S., J.D. Jungbauer Jr, K.L. Bristow, and R.D. Hungerford. 1995. Soil temperature and water content beneath a surface fire. Soil Science 159: 363-374. doi: 10.1097/00010694-199506000-00001

Certini, G. 2005. Effects of fire on properties of forest soils: a review. Oecologia 143: 1-10. doi: 10.1007/s00442-004-1788-8

DeBano, L.F., D.G. Neary, and P.F. Ffolliott. 1998. Fire's effects on ecosystems. John Wiley & Sons, New York, New York, USA.

DeBano, L.F., D.G. Neary, and P.F. Ffolliott. 2005. Chapter 2: soil physical properties. Pages 29-51 in: D.G. Neary, K.C. Ryan, and L.F. DeBano, editors. Wildland fire in ecosystems: effects of fire on soil and water. USDA Forest Service General Technical Report RMRS-GTR-42-vol.4. Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Doerr, S.H., R.A. Shakesby, and R.P.D. Walsh. 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth-Science Reviews 51: 33-65. doi: 10.1016/S0012-8252(00)00011-8

Dyrness, C.T., and C.T. Youngberg. 1957. The effect of logging and slash-burning on soil structure. Soil Science Society Proceedings 21: 444-447.

Engstrom, R.T. 2010. First-order fire effects on animals: review and recommendations. Fire Ecology 6(1): 115-130. doi: 10.4996/fireecology.0601115

Farouki, O.T. 1986. Thermal properties of soils. Trans Tech Publications, Clausthal-Zellerfeld, Germany.

Gough, C.M., C.S. Vogel, K.H. Harrold, K. Georges, and P.S. Curtis. 2007. The legacy of harvest and fire on ecosystem carbon storage in a north temperate forest. Global Change Biology 13: 1935-1949. doi: 10.1111/j.1365-2486.2007.01406.x

Gray, D.M., and J. Dighton. 2006. Mineralization of forest litter nutrients by heat and combustion. Soil Biology and Biochemistry 38: 1469-1477. doi: 10.1016/j.soilbio.2005.11.003

Haiganoush, K.P., S.M. Haase, and S.S. Sackett. 2000. Modeling and risk assessment for soil temperatures beneath prescribed forest fires. Environment and Ecological Statistics 7: 239-254. doi: 10.1023/A:1009615032159

Henderson, G.S., and D.L. Golding. 1983. The effects of slash burning on the water repellency of forest soils at Vancouver, British Columbia. Canadian Journal of Forest Research 13: 353-355. doi: 10.1139/x83-052

Horne, D.J., and J.C. McIntosh. 2000. Hydrophobic compounds in sands in New Zealand—extraction, characterisation and proposed mechanisms for repellency expression. Journal of Hydrology 231-232: 35-46. doi: 10.1016/S0022-1694(00)00181-5

Hudson, R.A., S.J. Triana, and W.W. Shane. 1994. Organic matter comparison of wettable and nonwettable soils from bentgrass sand greens. Soil Science Society of America Journal 58: 361-367.

Huffman, E.L., L.H. MacDonald, and J.D. Stednick. 2001. Strength and persistence of fire-induced hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. Hydrological Processes 15: 2877-2892. doi: 10.1002/hyp.379

Hungerford, R.D., M.G. Harrington, W.H. Frandsen, K.C. Ryan, and G.J. Niehoff. 1991. Influence of fire on factors that affect site productivity. Pages 32-50 in: A.E. Harvey, L.F. Neuenschwander, and F. Leon, compilers. Proceedings—Management and productivity of western-montane forest soils. USDA Forest Service General Technical Report INT-280. Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Jimenez Esquilin, A.E., M.E. Stromberger, W.J. Massman, J.M. Frank, and W.D. Shepperd. 2007. Microbial community structure and activity in a Colorado Rocky Mountain forest soil scarred by slash pile burning. Soil Biology and Biochemistry 39: 1111-1120. doi: 10.1016/j.soilbio.2006.12.020

Ju, Z., T. Ren, and R. Horton. 2008. Influences of dichlorodimethylsilane treatment on soil hydrophobicity, thermal conductivity, and electrical conductivity. Soil Science 173: 425-431. doi: 10.1097/SS.0b013e31817b6658

Kay, B.D., and J.B. Goit. 1975. Temperature-dependent specific heats of dry soil materials. Canadian Geotechnical Journal 12: 209-212. doi: 10.1139/t75-025

Ketterings, Q.M., J.M. Bigham, and V. Laperche. 2000. Changes in soil mineralogy and texture caused by slash-and-burn fire in Sumatra, Indonesia. Soil Science Society of America Journal 64: 1108-1117.

Litton, C.M., M.G. Ryan, D.H. Knight, and P.D. Stahl. 2003. Soil-surface carbon dioxide efflux and microbial biomass in relation to tree density 13 years after a stand replacing fire in a lodgepole pine ecosystem. Global Change Biology 9: 680-696. doi: 10.1046/j.1365-2486.2003.00626.x

Luce, C.H. 2005. Land use and land cover effects on runoff processes: fire. Pages 1831-1838 in: M.G. Anderson, editor. Encyclopedia of Hydrological Sciences. Volume 3. John Wiley & Sons, New York, New York, USA.

Kremens, R.L., A.M.S. Smith, and M.B. Dickinson. 2010. Fire metrology: current and future directions in physics-based measurements. Fire Ecology 6(1): 13-35. doi: 10.4996/fireecology.0601013

MacDonald, L.H., and E.L. Huffman. 2004. Post-fire soil water repellency: persistence and soil moisture thresholds. Soil Science Society of America Journal 68: 1729-1734.

Massman, W.J. 2006. Advective transport of CO_2 in permeable media induced by atmospheric pressure fluctuations: 1. An analytical model. Journal Geophysical Research 111: G03004. doi: 10.1029/2006JG000163

Massman, W.J., and J.M. Frank. 2004. 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 plate. International Journal of Wildland Fire 13: 427-442. doi: 10.1071/WF04018

Massman, W.J., J.M. Frank, and N.B. Reisch. 2007. Long term impacts of prescribed burns on soil thermal conductivity and soil heating at a Colorado Rocky Mountain site: data/model fusion study. International Journal of Wildland Fire 17: 131-146. doi: 10.1071/WF06118

Mölders, N., and G. Kramm. 2007. Influence of wildfire induced land-cover changes on clouds and precipitation in interior Alaska—a case study. Atmospheric Research 84: 142-168. doi: 10.1016/j.atmosres.2006.06.004

Moody, J.A., and D.A. Martin. 2009. Forest fire effects on geomorphic processes. Pages 41-79 in: A. Cerdà and P.R. Robichaud, editors. Fire effects on soils and restoration strategies. Science Publishers, Enfield, New Hampshire, USA.

Mooney, S.J., C. Morris, and P.M. Berry. 2006. Visualization and quantification of the effects of cereal root lodging on three-dimensional soil macrostructure using X-ray computed tomography. Soil Science 171: 706-718. doi: 10.1097/01.ss.0000228041.03142.d3

Murphy, J.D., D.W. Johnson, W.W. Miller, R.F. Walker, E.F. Carroll, and R.R. Blank. 2006. Wildfire effects on soil nutrients and leaching in a Tahoe basin watershed. Journal of Environmental Quality 35: 479-489. doi: 10.2134/jeq2005.0144

Neary, D.G., and P.F. Ffolliott. 2005. The water resource: its importance, characteristics, and general responses to fire. Pages 95-106 in: D.G. Neary, K.C. Ryan, and L.F. DeBano, editors. Wildland fire in ecosystems: effects of fire on soil and water. USDA Forest Service General Technical Report RMRS-GTR-42-vol.4. Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Nerpin, S.V., and A.F. Chudnovskii. 1984. Heat and mass transfer in the plant-soil-air system. Oxonian Press, New Delhi, India.

O'Brian, J.J., C. Stahala, G.P. Mori, M.A. Callaham Jr, and C.M. Bergh. 2006. Effects of prescribed fire on conditions inside a Cuban parrot (*Amazona Leucocephala*) surrogate nesting cavity on Great Abaco, Bahamas. The Wilson Journal of Ornithology 118: 508-512. doi: 10.1676/05-118.1

Oliveira, L.A., D.X. Viegas, and A.M. Raimundo. 1997. Numerical predictions on the soil thermal effect under surface fire conditions. International Journal of Wildland Fire 7: 51-63. doi: 10.1071/WF9970051

O'Neill, K.P., E.S. Kasischke, and D.D. Richter. 2003. Seasonal and decadal patterns of soil carbon uptake and emission along an age sequence of burned black spruce in interior Alaska. Journal of Geophysical Research—Atmospheres 108(1D): FFR 11-11 to 11-15. doi: 10.1029/2001JD000443

Or, D., and J.M. Wraith. 1999. Temperature effects on the soil bulk dielectric permittivity measured by time domain reflectometry: a physical model. Water Resources Research 35: 371-383. doi: 10.1029/1998WR900008

Page-Dumroese, D., M.F. Jurgensen, and A.E. Harvey. 2003. Fire and fire-suppression impacts on forest-soil carbon. Pages 201-210 in: J.M. Kimble, L.S. Heath, R.A. Birdsey, and R. Lal, editors. The potential of US forest soils to sequester carbon and mitigate the greenhouse effect. CRC Press, Baton Rouge, Louisiana, USA.

Raison, R.J., P.K. Khanna, and P.V. Woods. 1985. Mechanisms of element transfer to the atmosphere during vegetation fires. Canadian Journal of Forest Research 15: 132-140. doi: 10.1139/x85-022

Ravi, S., P. D'Odorico, B. Herbert, T. Zobeck, and T.M. Over. 2006. Enhancement of wind erosion by fire-induced water repellency. Water Resources Research 42: W11422. doi: 10.1029/2006WR004895

Reinhardt, E.D. 2003. Using FOFEM 5.0 to estimate tree mortality, fuel consumption, smoke production and soil heating from wildland fire. Pages P5.2: 1-6 in: Proceedings of the Second International Wildland Fire Ecology and Fire Management Congress and Fifth Symposium on Fire and Forest Meteorology. Association for Fire Ecology and American Meteorological Society, 16-20 November 2003, Orlando, Florida, USA.

Richter, D.D., K.P. O'Neill, and E.S. Kasischke. 2000. Postfire stimulation of microbial decomposition in black spruce (*Picea mariana* L.) forest soils: a hypothesis. Pages 197-213 in: E.S. Kasischke and B.J Stocks, editors. Fire, climate change, and carbon cycling in the boreal forest. Springer-Verlag, New York, New York, USA.

Robichaud, P.R., and R.D. Hungerford. 2000. Water repellency by laboratory burning of four northern Rocky Mountain forest soils. Journal of Hydrology 231-232: 207-219. doi: 10.1016/S0022-1694(00)00195-5

Ryan, K.C. 2002. Dynamic interactions between forest structure and fire behavior in boreal ecosystems. Silva Fennica 36: 13-39.

Sauer T.J., D.W. Meek, T.E. Ochsner, A.R. Harris, and R. Horton. 2003. Errors in heat flux measurement by flux plates of contrasting design and thermal conductivity. Vadose Zone Journal 2: 580-588. doi: 10.2113/2.4.580

Scanlon, B.R., J.P. Nicot, and J.M. Massmann. 2000. Soil gas movement in unsaturated systems. Pages A-277-A-319 in: M.E. Sumner, editor. Handbook of soil science. CRC Press, Boca Raton, Florida, USA.

Seymour, G., and A. Tecle. 2004. Impact of slash pile size and burning on ponderosa pine forest soil physical properties. Journal of the Arizona-Nevada Academy of Science 37: 74-82. doi: 10.2181/1533-6085(2004)037<0074:IOSPSA>2.0.CO;2

Steward, F.R., S. Peter, and J.B. Richon. 1990. A method for predicting the depth of lethal heat penetration into mineral soils exposed to fires of various intensities. Canadian Journal of Forest Research 20: 919-926. doi: 10.1139/x90-124

Tiedemann, A.R., J.O. Klemmedson, and E.L. Bull. 2000. Solution of forest health problems with prescribed fire: are forest productivity and wildlife at risk? Forest Ecology and Management 127: 1-18. doi: 10.1016/S0378-1127(99)00114-0

Ulery, A.L. and R.C. Graham. 1993. Forest fire effects on soil color and texture. Soil Science Society of America Journal 57: 135-140.

van Wijk, W.R., and D.A. de Vries. 1963. Periodic temperature variations in a homogeneous soil. Pages 102-143 in: W.R. van Wijk, editor. Physics of plant environment. John Wiley & Sons, New York, New York, USA.

Walker, J., R.J. Raison, and P.K. Khanna. 1986. Fire. Pages 185-216 in: J.S. Russell and R.F. Isbell, editors. Australian soils: the human impact. University of Queensland Press, St. Lucia, Australia.

Wraith, J.M., and D. Or. 1999. Temperature effects on the soil bulk dielectric permittivity measured by time domain reflectometry: experimental evidence and hypothesis development. Water Resources Research 35: 371-383. doi: 10.1029/1998WR900006