Soil Physical Properties Regulate Lethal Heating during Burning of Woody Residues

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Temperatures well in excess of the lethal threshold for roots (60°C) have been measured in forest soils when woody fuels are burned. Whether this heat pulse is strongly moderated by soil moisture or soil texture is not fully understood, however. We measured soil heat profiles during 60 experimental burns, identifying changes in maximum soil temperature and heat duration above 60°C as a function of soil moisture and soil texture. Experimental treatments included a factorial combination of soil moisture (~5, 15, 30, and 45% v/v) and soil textural (sandy loam, sandy loam–pumice, loam, clay loam) gradients, with a surface fuel load comprised of a dense layer of masticated wood. Soil moisture had a strong influence on heat transfer. A volumetric moisture content of 20% or greater quenched the heat pulse in all soils at depths of 2.5 cm and lower. In comparison, soil temperatures in dry soil far exceeded the lethal threshold to a depth of 10 cm. Differences in heating characteristics among the four soil types were minor despite their dissimilarities in texture, porosity, bulk density, and presumed thermal conductivity. It was also shown that intact soil cores were required to produce accurate heat profiles during burning, as maximum soil temperatures in the surface 5 cm were overestimated by 40 to 100°C using disturbed soil (sieved and packed). The empirical results along with a simple predictive model of soil heating show that burning of woody fuels when underlying soils have 20% volumetric moisture or greater is an effective means for limiting lethal heating in a variety of soils.

Mechanical masticating (shredding, chopping, or chipping) of understory trees and shrubs has gained acceptance by land managers as an option for reducing wildfire hazard (Glitzenstein et al., 2006; Kane et al., 2009). By reducing the continuity of ladder fuels in the lower canopy, mastication opens the forest canopy and leaves a compact layer of woody residues of assorted sizes on the soil surface (Kane et al., 2009). The residues may then either decay in place, become slowly incorporated in the mineral soil, or be burned in either a prescribed underburn or a wildfire.

The potential for soil damage exists if these woody residues are burned. Temperatures between 100 and 300°C have been measured near the surface of dry soils during burning (Busse et al., 2005), which is well above the lethal threshold of about 60°C for roots (Zeleznik and Dickmann, 2004) and within the assumed lethal range of 50 to 500°C for soil microorganisms (Wells et al., 1979; Dunn et al., 1985; Guerrero et al., 2005). Temperatures approaching 200 to 500°C may also result in the loss of soil C and N, reductions in soil aggregate stability, and changes in post-fire soil thermal conductivity and diurnal heat flux (García-Corona et al., 2004; Glass et al., 2008; Massman et al., 2008). Whether such temperatures are reached depends in part on the mass of fuels consumed during burning. For example, Busse et al. (2005) found that high fuel loads (100–170 Mg ha^{-1}) were required before temperatures surpassed 60°C in the surface soil layer. They also found considerable spatial variation in fuel loading at field sites following masticating, suggesting that soil damage during burning may be localized within treated units.

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Burning of harvest slash and natural fuels offers a comparative assessment of soil heating extremes, and also points to a fundamental role of soil moisture in regulating heat transfer. Massman and Frank (2004) found a temperature extreme of 400°C immediately below the mineral soil surface during burning of a large slash pile, with elevated temperatures reaching a soil depth of 1.4 m. Monsanto and Agee (2008) estimated that heavy accumulations of downed wood following high-severity wildfire would, if burned, produce lethal soil temperatures covering up to one-fourth of the affected landscape. In contrast, burning of less concentrated (scattered) slash often generates inconsequential soil heating (Shea, 1993; Massman et al., 2003; Penman and Towerton, 2008). Burning when soils are dry increases the likelihood of elevated soil heating regardless of fuel type (Frandsen and Ryan, 1986; Hartford and Frandsen, 1992; Valette et al., 1994; Campbell et al., 1995) due to the low heat capacity of dry soils or the lower energy requirement needed to heat air-filled pores compared with water-filled pores (Jury et al., 1991).

Unlike soil moisture, the influence of soil texture on heat transfer has received little attention in prescribed fire studies. In theory, heat transfer is directly related to soil texture, given the inherent differences in thermal conductivity (ability to conduct heat) among soils of differing texture, porosity, and bulk density (Hopmans and Dane, 1986). Soils with high thermal conductivity (e.g., low-porosity sands and compacted soils) should heat faster and reach higher temperatures than other soils (e.g., high-porosity clays, pumice, and ash soils with high internal porosity). Soil organic matter may also influence heat transfer because its thermal conductivity is considerably lower than that of soil minerals (Montieth and Unsworth 1990). In the only example of soil heating and textural difference we could find, Campbell et al. (1995) reported slight to moderate differences in the heat pulse among sand, silt loam, and clay soils in laboratory simulations, although no statistical comparisons among soils were made.

Soil heat transfer during burning is a complex process involving numerous soil physical properties (moisture, texture, porosity, bulk density, structural arrangement, contact between solid and liquid phases, and temperature gradient) and fuel characteristics (mass, moisture content, surface area, and structural arrangement). Nevertheless, scientific advances in predicting soil heating have been considerable, particularly through the development and validation of heat transfer models (e.g., Aston and Gill, 1976; Steward et al., 1990; Campbell et al., 1995; Preisler et al., 2000; Massman and Frank, 2004; Enninful and Torvi, 2008). Most models are validated using sieved soils (often sands) to control spurious changes in soil heating due to heterogeneous material. In situ testing of soil heating models is less common, although Massman and Frank (2004) developed a soil heating model based on the results from an in situ slash-pile burn, and Preisler et al. (2000) modeled soil heating associated with the burning of litter and duff in pine stands. Instead, most experiments use a constant heat source such as a propane burner and are set within controlled-environment chambers, avoiding any anticipated variation due to weather conditions or heterogeneous fuels and soils that are commonly encountered during field burning.

Whether soil temperatures and heat duration will exceed the predicted thresholds for biological, chemical, or physical damage when woody fuels are burned is not clear from field tests or from predictive models. As an example, our previous study of masticated fuels examined only a limited set of soil physical properties (Busse et al., 2005), leaving several questions unanswered concerning the potential for soil damage during burning. Our objectives in the present study were (i) to assess whether soil moisture regulates heat transfer during moderate to intense burning, and, if so, to identify the range in soil moisture content that effectively dampens lethal heating, and (ii) to determine whether heat transfer varies among soils of differing texture. Results are presented for four soils ranging in texture from sandy loam (8% clay) to clay loam (39% clay), with each soil evaluated across a range of moisture contents from air dry to field capacity.

MATERIALS AND METHODS

Sixty controlled burns were conducted in an open field adjacent to the Redding Silviculture Laboratory in Redding, CA, between September 2005 and February 2007. Factorial treatments included four soils (sandy loam, loam, clay loam, and pumice) in combination with four soil moisture contents (~5, 15, 30, and 45% v/v), with four replications of each treatment combination. Only three moisture contents were tested for the sandy loam (5, 15, and 30%) due to its restricted water-holding capacity. The soils were selected a priori for their wide range of textures and as representatives of common soil types in northern California mixed-conifer forests and central Oregon ponderosa pine forests. Also, we selected nonskeletal soils to avoid any difficulties in collecting intact soil cores with high rock content. Soil and site characteristics are listed in Table 1.

Intact soil cores were used in all burns, with utmost attention given during their field collection and transport to minimize physical distur-

Table 1. Selected properties of the four mineral soils used to study soil heating.

Property	Sandy loam	Loam	Clay loam	Pumice (sandy loam)
Sand/silt/clay, %	65/25/10	39/40/21	30/31/39	72/20/8
Soil organic matter, g kg^{-1}	18	164	138	44
Bulk density, Mg m^{-3}	1.56	0.79	0.92	0.90
Total porosity, m^3 m^{-3}	0.41	0.70	0.65	0.66
Water-holding capacity, m^3 m^{-3}	0.27	0.42	0.42	0.43
Soil structure	single grain	subangular blocky	subangular blocky	single grain
Soil origin	alluvium from decomposed granite	volcanic mudflow	volcanic mudflow	volcanic pumice and ash
Forest type	mixed conifer	mixed conifer	mixed conifer and hardwood	ponderosa pine
Latitude and longitude, °	41.06 N, 123.05 W	39.26 N, 120.78 W	40.37 N, 121.54 W	43.84 N, 121.34 W

bance. Sixteen cores were collected from each site using 30-cm-diameter polyvinyl chloride (PVC) pipe (irrigation pipe with 1-cm-thick walls, 20 cm in height). The mineral soil at each site was premoistened to approximately field capacity (except at the clay loam site; see below) to facilitate insertion of the PVC collar and to ensure optimal stability of the core sample during removal and transport. Understory vegetation plus the forest floor (O horizon) was gently removed, and the PVC collar was inserted gradually into the mineral soil by tapping the top of the collar with a rubber mallet. The soil on the outside perimeter of each collar was loosened and removed with a shovel to facilitate collar insertion and to limit soil compaction within the core. After the collar reached a depth of 15 cm, a 3-mm-thick steel plate was inserted horizontally across the bottom of the PVC collar (pounded in with a hammer as necessary), cutting the soil core away from the underlying substrate. The soil core was then extracted and placed on a waterproof board (~40 by 40 by 1.2 cm) for stability during transport. Each collar had a 5-cm headspace above the soil surface to allow water addition, if needed, to reach its target moisture content.

Two methods were used to equilibrate the soil cores at their target moisture content. At the site closest to our facility (clay loam soil), soil moisture levels were attained in situ. Due to the remoteness of the other field sites, however, all soil cores were collected on the same day at a given site, then equilibrated for moisture content at the Redding Laboratory by wetting them to field capacity, allowing them to dry outdoors at 15 to 28°C for 1 to 3 wk until their target moisture content was reached, then covering them with plastic to prevent moisture loss. At the clay loam site, soil cores were collected at the end of the summer growing season by (i) collecting as is (3–10% v/v moisture content), (ii) wetting to field capacity and allowing to dry in situ to moisture contents of approximately 15 or 30% (monitored daily on extra cores) before collection, or (iii) wetting to field capacity (45% moisture content), then collecting immediately following the loss of gravitational water.

The total soil volume and field-moist soil mass were measured on all intact cores. Gravimetric soil moisture content was determined within 2 h before burning by collecting a 1-cm-diameter sample (0–7.5- and 7.5–15-cm soil depths) from near the perimeter of each core. Loose soil was used to backfill the void. The soil bulk density was calculated for each core using total volume and the soil dry-mass equivalent.

Before burning, a single soil core was placed at the center of each excavated 1-m^2 plot, and its supporting board was removed (Fig. 1). The top surface of the intact core was level with the surrounding ground. Loose soil was packed around the PVC collar, filling the plot except for a narrow opening (~7–12 cm wide) to allow access for installing thermocouple wires. The PVC collar was then removed and additional soil was packed next to the intact core as needed. The integrity of the soil cores, from field collection until burning, appeared intact based on visual inspections for fractures, cavities, or settling.

Soil temperatures were measured every 60 s at 2.5, 5, 10, and 15 cm beneath the mineral soil surface using Omega 30-gauge, type K thermocouples with glass braid insulation (Omega Engineering, Stamford, CT). Omega 24-gauge, type K thermocouples with ceramic insulation were placed on the mineral soil surface and on the top of the fuel bed, where higher temperatures were anticipated. Surface temperatures were measured every 30 s. All wires were attached to Omega OMPL-TC dataloggers that were buried outside the perimeter of the plot. For placement of the thermocouples within the soil, a small opening was made from the outer edge of the intact core to its centerline by inserting a steel wire surrounded by a 2-mm plastic straw at the appropriate soil depth. The steel wire was removed and the thermocouple wire was threaded through the straw. The straw was then removed, leaving the thermocouple wire in contact with the mineral soil. Little soil disturbance occurred during this process because the opening was only slightly larger in diameter than the thermocouple wire. The small access area within the 1-m^2 plot used to install the thermocouples was then backfilled with soil.

Woody residues (135 Mg ha^{-1} dry-mass equivalent) were added to the surface of the 1-m^2 plots at a bulk density matching the high fuel-load conditions found at field sites in the foothills of the Sierra Nevada Mountains near Challenge, CA (Busse et al., 2005). Fuel bulk density averaged 0.14 Mg m^{-3} and the fuel-bed depth averaged 10 cm at these sites. Woody fuels for our study were obtained from a nearby oak–pine woodland with a dense understory of 2- to 4-m-tall shrubs (whiteleaf manzanita [*Arctostaphylos viscida* Parry]). The shrubs were masticated using a Fecon Bull Hog head (Fecon Inc., Lebanon, OH) attached to an excavator, with a resulting mix of 21% 1-h time-lag fuels (0–0.6-cm diam.), 61% 10-h time-lag fuels (0.6–2.5-cm diam.), and 18% 100-h time-lag fuels (2.5–7.6-cm diam.). The fuels were cured for 5 mo in the

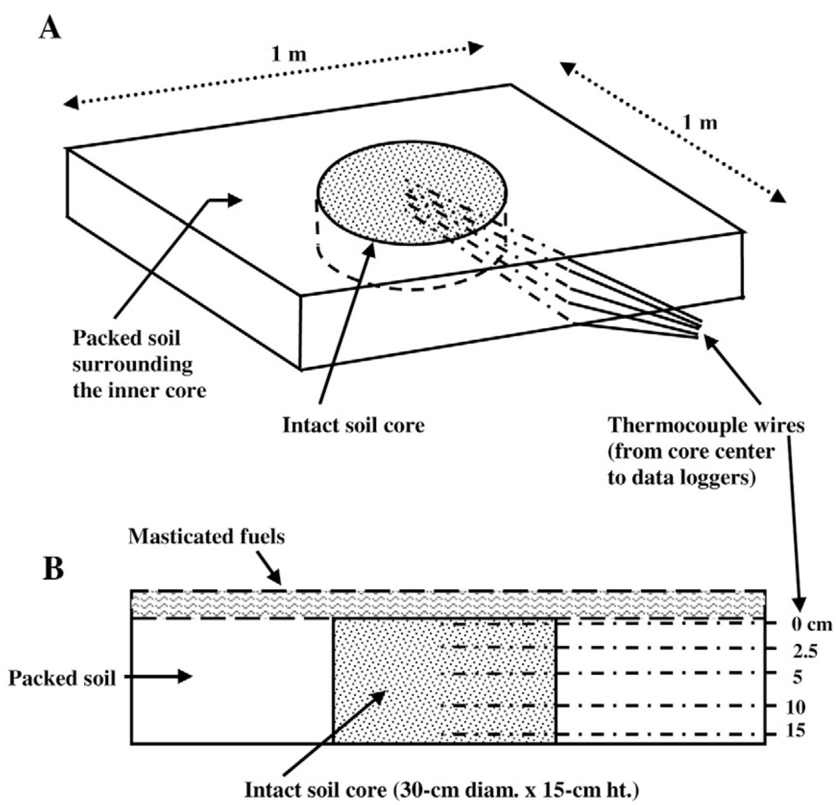

Fig. 1. Plot design: (A) view looking down on plot before fuel layering, (B) side view of plot after fuel layering. The mineral soil surface of each 1- by 1-m plot was level with the surrounding soil.

field (late spring through summer), then placed in a storage shed until use. The moisture contents of each fuel size class were determined immediately before each burn, and the final fuel loads were adjusted as necessary to account for differences in fuel moisture. All fuels were thoroughly mixed by hand before adding to the soil surface. The proportion of the three fuel classes was kept consistent for all burns by adding measured quantities of each to approximate the field mixture.

Four plots were burned simultaneously per day (one soil type, four moisture contents). Backfires were ignited on the downwind edge of the fuel bed using a drip torch. Air temperature, relative humidity, and mean wind speed were measured every 15 min during burning using a Kestrel 3000 Wind Meter (Kestrelmeters.com, Sylvan Lake, MI). Flame heights were measured at 5-min intervals to the nearest 10 cm. The rate of fire spread, total flaming time, and smoldering duration were also measured. Soil temperatures were recorded until they had returned to near ambient at all depths, about 16 to 24 h after ignition. The soil cores were then excavated and examined for possible disturbance fractures or cavities.

Statistical Analysis

The effects of soil moisture, texture, depth, surface heat load, and their interactions on maximum temperature and lethal duration were tested by analysis of variance (PROC MIXED in SAS 9.1 [SAS Institute, Cary, NC], with a covariance structure that accounted for soil depth as a non-random variable). We defined lethal duration as the amount of time that temperatures exceeded 60°C, the commonly used threshold for predicting root mortality (Preisler et al., 2000). All data were normally distributed, including log-transformed values for maximum temperature and surface heat load, based on visual inspection of the distribution of the residuals (plotted as histograms) and normal probability plots. The surface heat load was calculated as the area under the curve of the temperature profile measured at the mineral soil surface using the procedures of Guckert et al. (1996). The units for surface heat load are degree hours (°C h^{-1}), equivalent to the sum of the mean temperature above ambient for all 30-s thermocouple readings. This is analogous in computation to the term *growing degree days*, as used for predicting crop phenology. Statistical significance was set at $\alpha = 0.10$.

Predictive regression equations of maximum soil temperature and lethal heat duration were generated using PROC MIXED, with soil depth (range 2.5–15 cm), soil moisture (0.03–0.45 m^3 m^{-3}), and surface heat load (300–1500°C h^{-1}) as independent variables. A drawback of these equations was that their inference was limited to the single fuel load of 135 Mg ha^{-1}. To address this limitation, we combined our data (60 burns) with the results from our previous study that examined soil heating during burning of woody fuels ranging from 35 to 170 Mg ha^{-1} (24 burns; Busse et al., 2005). The surface heat load during burning was estimated as a function of fuel load in simple linear regression. Regression analyses were run separately for dry soil (0.03–0.08 m^3 m^{-3}; $r^2 = 0.82$) and moist soil (0.27 m^3 m^{-3}; $r^2 = 0.89$) because (i) the surface heat load varied with the soil moisture content, and (ii) our initial study examined only these two soil moisture contents. Thus, the final models for predicting the maximum temperature and lethal duration were based on soil depth (2.5–15 cm), soil moisture (dry or moist), and fuel load (35–170 Mg ha^{-1}) as independent variables.

The maximum soil temperatures during burning were also compared with temperatures predicted by the First-Order Fire Effects Model (FOFEM version 5.7; frames.nbii.gov/metadata/tools/FOFEM_5.7.html; verified 14 Feb. 2010) using input variables that matched the burn conditions for the clay loam soil: total fuel load (135 Mg ha^{-1}), fuel size classes (21% 1-h fuels, 61% 10-h fuels, and 18% 100-h fuels), duff depth (0 cm), soil moisture (5%), fuel moisture (5%), and soil (fine texture). The model was run at the dry soil moisture content only, as simulations at a moisture content of 25% or greater failed for unspecified reasons.

RESULTS AND DISCUSSION

Fire Behavior

A narrow prescription for fuel moisture (5–9%) and wind speed (<5 km h^{-1}) was met on all burns. As a result, the fire behavior was similar among the 60 burns even though they were conducted throughout an 18-mo period (Table 2). Flame length, rate of spread, and flame duration were consistent among the four soils, with the exception that the clay loam soil had a slightly faster rate of spread and shorter flame duration, possibly because of lower fuel moisture content at the time of burning. Smoldering time was relatively short for all burns, reflecting the low fuel moisture content, and fuel consumption was >95% for all burns based on visual inspection.

Soil Heating Profiles

Maximum temperatures on the soil surface ranged from 230 to 867°C during burning, with a mean and standard error of 524 ± 17°C ($n = 56$). We assume that this wide range of surface temperatures resulted from subtle differences in the positioning and arrangement of the woody fuels directly above the surface thermocouple. The heat duration above 60°C was relatively short-lived at the soil surface, ranging from 1.0 to 9.9 h with a mean of 3.6 h, reflective of the dry fuels and fairly rapid burns.

Table 2. Weather conditions, fuel moisture, and fire behavior during burning of masticated residues for each of four soil types. Values are means, with standard errors in parentheses ($n = 4$).

Weather condition and fire behavior	Sandy loam	Loam	Clay loam	Pumice
Air temperature, °C	17.5 (1.1)	22.4 (1.3)	22.8 (0.9)	15.5 (1.5)
Relative humidity, %	40 (3)	26 (4)	41 (3)	62 (3)
Wind speed, km h^{-1}	1.8 (0.3)	3.5 (2.1)	2.0 (0.3)	2.6 (1.3)
Fuel moisture, %	8.8 (0.4)	7.0 (0.3)	5.1 (0.2)	6.0 (0.4)
Maximum flame length, m	0.8 (0.0)	0.8 (0.1)	0.8 (0.1)	1.0 (0.1)
Rate of spread, m min^{-1}	0.03 (0.00)	0.03 (0.00)	0.06 (0.01)	0.03 (0.00)
Flame duration, min	53 (2)	56 (4)	41 (3)	55 (3)
Smoldering duration, min	70(5)	85 (8)	59 (9)	78 (3)
Burn dates	6 Feb.–8 Mar. 2007	16–21 Nov. 2005	7–14 Sept. 2005	26 Oct.–3 Nov. 2005

No differences in maximum temperature or heat duration at the mineral soil surface were found among the four soils ($P > 0.23$); however, the moisture content of the underlying soil had a significant effect on the heat duration at the soil surface ($P < 0.001$). Soils with 10% volumetric moisture or lower had a mean lethal duration of 5.9 ± 0.8 h, whereas soils with >10% moisture averaged 2.8 ± 0.4 h lethal duration. Soil moisture also affected the surface heat load during burning ($P = 0.001$). Dry soils had an average surface heat load of 1530 ± 168°C h^{-1}, whereas soils with >10% moisture averaged 1011 ± 72°C h^{-1}. This observation can be explained by the greater thermal conductivity of moist soil than dry soil (de Vries, 1963), which translated to a more rapid transfer of heat energy into the moist soil and away from the surface thermocouples (Oliveira et al., 1997).

An incremental decline in temperature was found with increasing soil depth for all soil textures and soil moisture contents. Maximum temperatures ranged from 43 to 370°C at 2.5 cm, from 35 to 156°C at 5 cm, from 27 to 74°C at 10 cm, and from 20 to 51°C at 15 cm (Fig. 2). This decline was statistically significant (Table 3) and supports the common principles that soil is not an efficient medium for heat transfer and that high temperatures are most often restricted to the surface layer (de Vries, 1963; Jury et al., 1991). In support of these principles, previous burning of small- to moderate-sized slash piles by Shea (1993) at the site where the pumice soil for our study was collected resulted in soil temperatures barely exceeding 60°C at a depth of 12 cm. Similarly, Monsanto and Agee (2008) found that soil temperatures reached only 50 to 100°C at a depth of 10 cm directly beneath burning logs. Only Massman and Frank (2004) have reported high temperatures deep in the soil profile, a result of burning an extremely large slash pile.

Soil moisture content had a large affect on the maximum temperature during burning. Soil temperatures at the 2.5- and 5-cm depths ranged from 72 to 365°C when soil moisture was below 0.15 m^3 m^{-3}, yet remained near or below 60°C when soil moisture was 0.20 m^3 m^{-3} or greater (Fig. 2). The main effect of soil moisture was significant, as were several treatment interactions involving soil moisture (Table 3). For example, a significant moisture × depth interaction was found, with maximum temperatures varying by moisture content in the surface 5 cm but not at lower soil depths where heat transfer was low.

The heat duration above 60°C also showed a progressive decline with increasing soil moisture and with increasing soil depth (Fig. 3; Table 3). Lethal heating was greatest for moisture contents <0.1 m^3 m^{-3}, ranging from 4 to14 h. In contrast, the lethal threshold was rarely exceeded at moisture contents >0.2 m m^{-3}, except at the surface 2.5-cm depth. This finding suggests that soil damage during burning of high masticated fuel loads will be nominal if burn prescriptions target soil moisture contents of 20% or greater by volume. Conversely, prescribed fires or wildfires burning through masticated fuels during the dry season will probably result in more extreme soil heating, as found for the soils with less than 10 to 20% volumetric moisture. These findings can be explained by the greater heat capacity of water

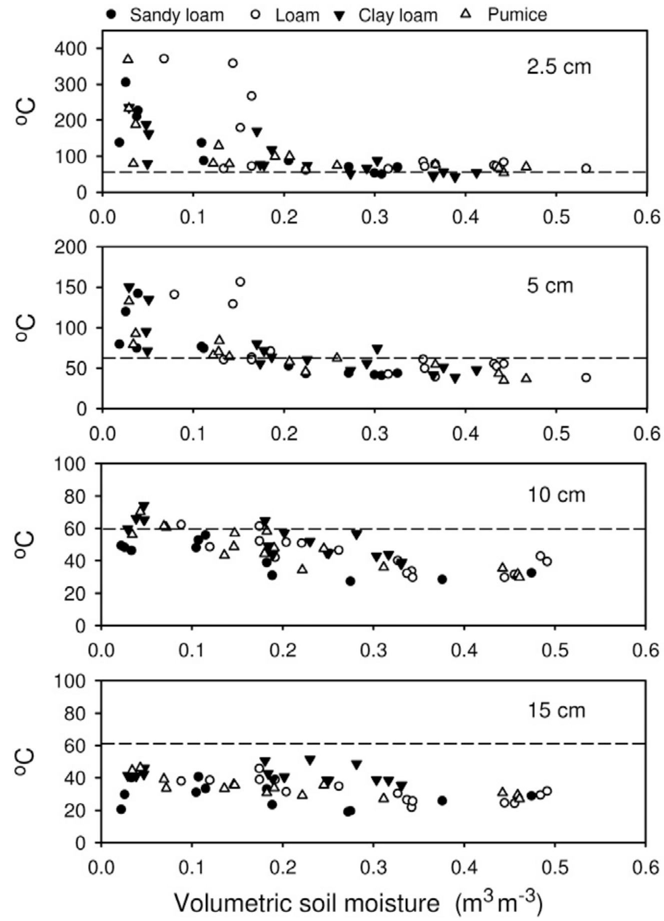

Fig. 2. Maximum soil temperatures during burning. Temperature profiles were recorded at 2.5, 5, 10, and 15 cm beneath the mineral soil surface during controlled burning ($n = 60$). A gradient of pre-burn soil moisture contents, from air dry to field capacity, was compared in each of four soil types. Dashed lines at 60°C represent the lethal threshold for plant roots.

Table 3. Type 3 tests of fixed effects of soil depth, volumetric moisture content (water), surface heat load (heat), soil texture, and their interactions on maximum soil temperature and lethal duration during burning of woody fuels.

Effect	*P* value	
	Max. temp.	Lethal duration
Depth	0.069	0.017
Water	0.037	0.051
Depth × water	0.016	0.241
Heat	0.003	0.001
Depth × heat	0.005	0.002
Water × heat	0.012	0.019
Depth × water × heat	0.007	0.145
Texture	0.722	0.446
Texture × depth	0.689	0.785
Texture × water	0.118	0.528
Texture × heat	0.632	0.445
Texture × depth × water	0.248	0.707
Texture × depth × heat	0.582	0.781
Texture × water × heat	0.104	0.507
Texture × depth × water × heat	0.216	0.688

compared with air, which acts to limit heat flux moving downward through the profile of moist soil (de Vries, 1963).

We believe this is the first empirical evidence of a moisture threshold for restricting damaging soil temperatures during burning. Other studies have compared dry vs. wet soils and have concluded that wet soils are crucial to limiting soil heating (Frandsen and Ryan, 1986; Valette et al., 1994) but have not attempted to identify a soil moisture range where heat transfer is dampened. Interestingly, 20% moisture by volume is considerably drier than field capacity for these soils, as the water-holding capacities ranged from 27% for the sandy loam to 42% for the other three soils (Table 1). Therefore, soils need not be wet nor at field capacity to minimize soil damage when burning. This suggests that a reasonable window of opportunity may exist for burning masticated fuels if limiting the extent of soil heating is an operational objective. In the western United States, the combination of surface fuels dry enough to burn and moist soil is most common in the spring or early summer, after cessation of winter precipitation and before the summer dry period.

In contrast to the effect of soil moisture, there were no significant main effects or interactions of soil texture on the maximum temperature or heat duration during burning (Table 3; Fig.

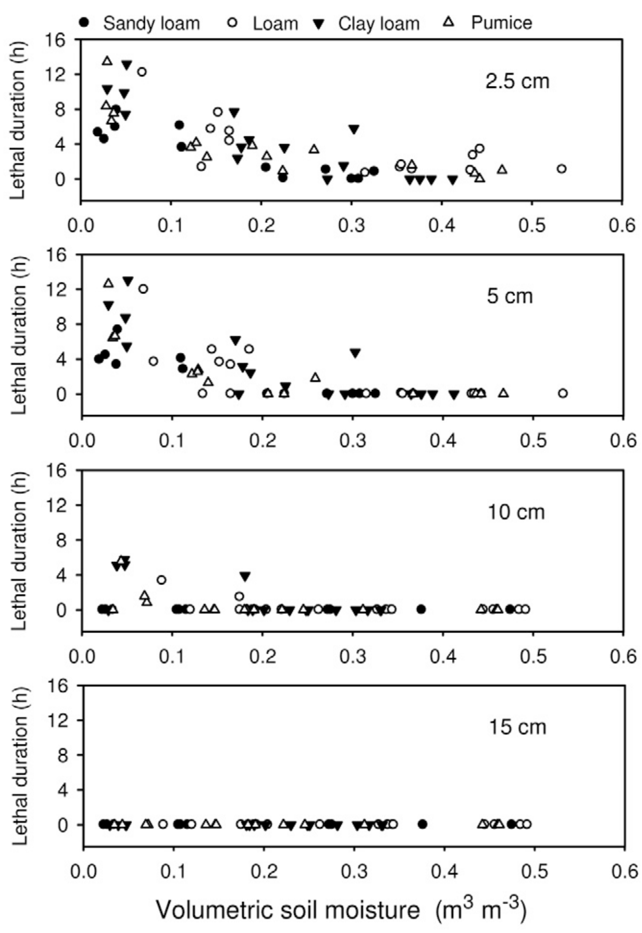

Fig. 3. Lethal heat (>60°C) duration during burning. Temperature profiles were recorded at 2.5, 5, 10, and 15 cm beneath the mineral soil surface during controlled burning (*n* = 60). A gradient of pre-burn soil moisture contents, from air dry to field capacity, was compared in each of four soil types.

2 and 3). Thus, the large range in physical properties among the soils, including a fivefold difference in clay content and nearly twofold differences in total porosity and bulk density (Table 1), were evidently of small consequence. This is somewhat surprising because these physical properties are known to affect the soil thermal conductivity (de Vries, 1963; Aston and Gill, 1976) and have been shown to modify the diurnal and seasonal heat flux of soils at ambient temperatures (Scott, 2000). Two reasons for this observation are probable, based on a simple interpretation of Fourier's law of heat conduction:

$$J_{\mathrm{h}} = -\lambda\left(\frac{\mathrm{d}T}{\mathrm{d}z}\right) \qquad [1]$$

where J_{h} is heat transfer, λ is the apparent thermal conductivity of the soil due to heat conduction and latent heat transfer by water vapor, and $\mathrm{d}T/\mathrm{d}z$ is the temperature gradient. First, λ is usually a small value when soils are dry (de Vries, 1963; Jury et al., 1991), suggesting that the temperature gradient from the surface fire to a given depth in the soil profile, $\mathrm{d}T/\mathrm{d}z$, is the driving force of heat transfer in dry soils during intense burning. Hence, few differences in heating transfer would be expected among soil textures at low moisture content. Second, the thermal conductivity of moist soils (0.1–0.4 $m^3\ m^{-3}$) is primarily determined by soil moisture, not texture-related properties (Hopmans and Dane, 1986; Jury et al., 1991), again suggesting a secondary or minor influence of soil texture. Thus, we conclude that heat transfer is not strongly regulated by soil texture during burning. Furthermore, we argue that the results of our study may be fairly universal across soil types since (i) soil texture and its related properties had a nominal effect on heat transfer, and (ii) the four soils encompassed a wide range of textures, mineralogies, organic matter contents, porosities, structures, and bulk densities. Only lacking in this study were very low clay content soils (sands and loamy sands) and clay soils.

Although the findings may be applicable to an assortment of soil types, the burn conditions used in our study were fairly unique and their extrapolation to field conditions should be made with caution. In particular, only one fuel loading was tested, and it was considerably higher than levels measured at several masticated sites in California (Kane et al., 2009). The soil temperatures measured in our study, therefore, may be higher than expected at sites with average fuel loading. Furthermore, the fuel moisture was quite low in our burns, resulting in greater fuel consumption and higher soil temperatures than would be expected with higher fuel moistures (Monsanto and Agee, 2008). Finally, we did not include an O horizon (litter and duff) beneath the masticated fuels in our burns, which can have a considerable dampening effect on soil temperatures if the duff layer is moist (Hartford and Frandsen, 1992; Valette et al., 1994). Collectively, these conditions suggest that the measured temperatures represent an upper limit for soil heating during the burning of masticated fuels. We also recognize that our burns were contained in small plots and did not have heterogeneity in fuel loading and arrangement, wind conditions, or radiant heating as would be typical in an operational burn. In addition, a slight overestimation of soil temperatures may have resulted because the surrounding soil in each experimental plot (see Fig. 1) was typically drier than the intact soil core. This error was probably small, however, given the large size of each soil core and the placement of the thermocouples at the core center.

Heating Differences between Disturbed and Undisturbed Soils

The soil temperature profiles measured in our study using undisturbed soil cores were considerably cooler than had been predicted by Busse et al. (2005) using disturbed soil, even though the same soil type (clay loam) from the same site was compared (Fig. 4). The maximum temperature at the 2.5-cm depth was about 100°C lower for intact soil than for disturbed soil that had been hand sorted to remove rocks and large organics and then packed to a field-approximate bulk density (Busse et al., 2005). Maximum temperatures were about 40°C higher at a depth of 5 cm for the disturbed compared with the intact soil, and were similar at a depth of 10 cm, where the total heat load was small.

The large difference in predicted temperatures between our two studies underscores the importance of protecting the in situ pore-size distribution when conducting soil heating experiments. By hand sorting and packing the clay loam soil, we presumably eliminated most large pores found within the soil's subangular blocky structure and increased the amount of surface-area contact between soil particles. Both consequences probably lead to greater soil thermal conductivity and higher soil temperatures (Jury et al., 1991), similar to the effects that soil compaction may have on soil heating. Interestingly, the temperature profile predicted by FOFEM using comparable woody fuel profiles and moisture contents was considerably higher than our results, and was more in line with the surface temperatures predicted by Busse et al. (2005) using disturbed soil (Fig. 4). The algorithm for soil heating in FOFEM was developed based on models derived by Campbell et al. (1995) that were verified with packed soil columns. Our finding, although limited to one soil type and moisture content, indicates that heating models that are developed based on disturbed soils may considerably overestimate soil temperatures during moderate to intense burning. Further research is needed to assess this result relative to other soil types, fuel loadings, and the presence of insulating duff layers.

Predictive Model of Soil Heating

Predictive equations for maximum temperature and lethal duration were estimated in the mixed model in SAS to provide a semiquantitative model of soil heating for use by forest managers. The models did not include the main effect or treatment interactions of soil texture because these factors were not statistically significant (Table 3) nor did they improve the model's small-sample-size corrected version of the Akaike information criterion (AICc) values. The maximum temperature, T (in °C), at a given soil depth and moisture content was predicted by

$$T = \exp(0.6106 + 0.1903D + 9.819W + 0.676\text{SH} - 1.140DW - 0.044D\text{SH} - 1.822W\text{SH} + 0.186DW\text{SH}) \quad [2]$$

where D is the soil depth ranging from 2.5 to 15 cm, W is the volumetric water content ranging from 0.03 and 0.53 $m^3\ m^{-3}$, and SH is the natural logarithm of the surface heat load, ranging from 300 to 1500°C h^{-1}. The coefficient of variation for Eq. [2] was 27.3%, with the standard error equivalent to T 0.273. Thus, predicted temperatures of 100, 200, and 400°C would have SE values of 27.3, 54.6, and 109.2°C, respectively. For comparative purposes, multiple linear regression analysis resulted in an r^2 of 0.78 for this model.

The lethal duration above 60°C (LD) during burning was predicted by

$$\text{LD} = (-23.836 + 1.490D + 22.58W + 4.649\text{SH} - 1.593DW - 0.296D\text{SH} - 7.659W\text{SH} + 0.421DW\text{SH}) \quad [3]$$

The coefficient of variation for Eq. [3] was 29.9%, the standard error is LD0.299, and the r^2 from linear regression analysis is 0.70.

Although Eq. [2] and [3] are valid for a wide range of soil properties, their utility is limited to a single masticated fuel load of 135 Mg ha^{-1}. Furthermore, practitioners must determine the surface heat load (SH) using constant-recording thermocouples to predict T or LD, which is not a simple field measurement, nor are data available in the literature to estimate SH based on a common measure such as fuel loading. To overcome these limitations, we combined our estimates of SH with those from our earlier study (Busse et al., 2005), which had a range of fuel loads from 30 to 170 Mg ha^{-1}. This led to predictions of soil heating across a wide range of fuel loads (Fig. 5 and 6). The final predictive models were restricted to two soil

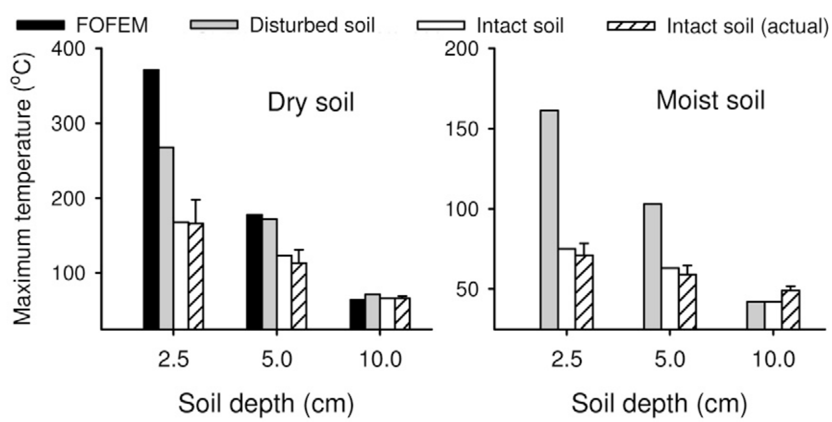

Fig. 4. Comparison of maximum temperatures in the soil profile as predicted using the FOFEM fire-effects model, an equation for disturbed soil (Busse et al. 2005), Eq. [2] from our study, and actual values from our study. All predictions used the same fuel-load profile and fuel moisture input values. Disturbed clay loam soil was collected from a forested site using shovels, then was hand sorted to remove rocks and large organics and packed to approximate the field bulk density value of 1.0 Mg m^{-3} before burning. Intact soil was collected from the same site by excavating large-diameter cores. Volumetric moisture content was 5 and 27% for dry and moist soil, respectively. Error bars represent standard error (n = 4), and are only available for the empirical values for intact soil.

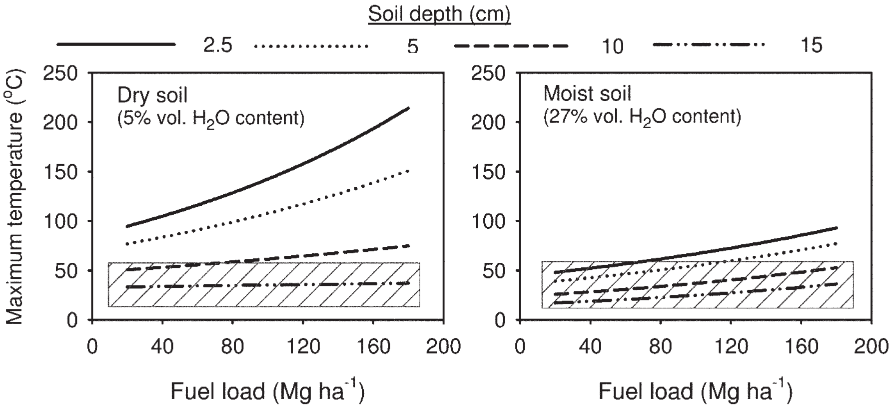

Fig. 5. Predicted maximum soil temperatures when burning woody fuels. Separate predictions are presented for dry (5% volumetric moisture) and moist (27% volumetric moisture) soil. The gray-hatched rectangle in each graph represents temperatures below the lethal threshold for roots of 60°C. The coefficient of variation associated with each response curve is 18.2%.

moisture regimes (dry and moist) because the earlier study did not include a full gradient of volumetric moisture contents.

The models provided in Fig. 5 and 6 offer a guideline for practitioners to estimate maximum temperatures and heat durations associated with the burning of woody fuels. Several interpretive points should be clarified, however. First, soil temperatures will exceed the lethal threshold of 60°C in the surface 5 cm regardless of the soil texture or fuel load (>20 Mg ha^{-1}) if the soil is dry. This may be a concern for fall-season burning before the onset of winter precipitation. Second, temperatures will only exceed 60°C to a depth of 10 cm in dry soil when fuel loads are high. Kane et al. (2009) quantified masticated fuel loads at several sites across northern California and found that they ranged from 15 to 63 Mg ha^{-1}, which would be insufficient to produce lethal temperatures at 10 cm during burning. Third, in contrast to dry soil, 60°C is exceeded only briefly in moist soil when burning high fuel loads (Fig. 6).

CONCLUSIONS

Soil heating is one of many concerns facing managers when burning forest residues. Excessive heating may produce long-term changes in soil productivity if conditions are acute, such as high fuel loads and low fuel moisture contents. The results from our study showed that soil moisture was a primary determinant of downward heat transfer during burning of high woody fuel loads. Burning when soils have >20% volumetric moisture is recommended to ensure limited heat penetration during the burning of high fuel loads. In contrast to the role of soil moisture, soil texture had little effect on the heating characteristics. No differences in maximum soil temperature or heat duration were found among four soils that encompassed a wide range of textures and associated properties. Consequently, a simple model of soil heating based on soil moisture and woody fuel load was presented as a guide for practitioners to estimate the extent of soil heating during the burning of woody fuels.

Soil temperatures during burning were considerably lower in our study, which used intact soil cores, compared with previous results for disturbed soils (sieved and packed), presumably due to differences in structural pore-size distribution. The use of intact cores is recommended, therefore, for empirical studies of soil heating and for calibration of heat transfer models.

From a practical standpoint, our results indicate that most plant roots will be unaffected by the burning of masticated woody fuels in moist soils, typical of burn conditions found during the spring months in the western United States. Burning high fuel loads when soils are moist (>20% volumetric moisture) should limit damaging temperatures to the surface 2 to 5 cm in the mineral soil. On the other hand, summer wildfires or fall prescribed burning when soil moisture is low may produce considerable soil heating.

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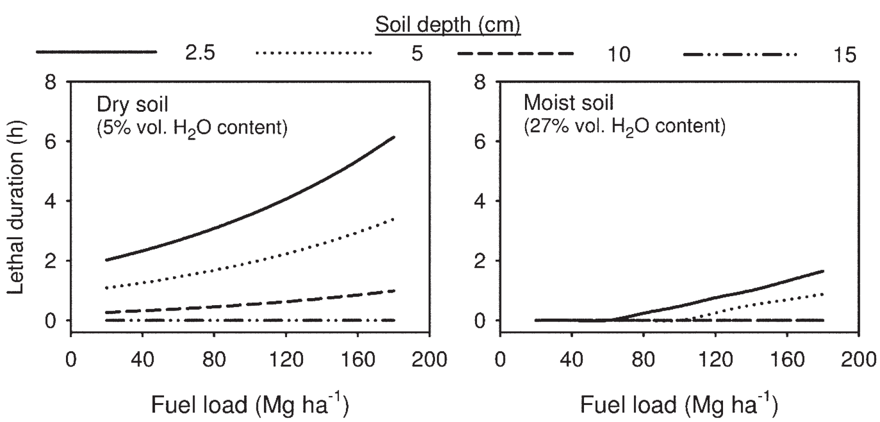

Fig. 6. Predictive model for lethal heat (>60°C) duration when burning woody fuels. Separate predictions are presented for dry (5% volumetric moisture) and moist (27% volumetric moisture) soil. The coefficient of variation associated with each response curve is 17.7%.

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