CSIRO PUBLISHING

www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire*, 2005, **14**, 267–276

Lethal soil temperatures during burning of masticated forest residues

Matt D. Busse[A,C], *Ken R. Hubbert*[B], *Gary O. Fiddler*[A], *Carol J. Shestak*[A] *and Robert F. Powers*[A]

[A]USDA Forest Service, Pacific Southwest Research Station, Redding, CA, USA.
[B]Hubbert and Associates, Apple Valley, CA, USA.
[C]Corresponding author. Telephone: +1 530 226 2530; fax: +1 530 226 5091; email: mbusse@fs.fed.us

Abstract. Mastication of woody shrubs is used increasingly as a management option to reduce fire risk at the wildland–urban interface. Whether the resulting mulch layer leads to extreme soil heating, if burned, is unknown. We measured temperature profiles in a clay loam soil during burning of *Arctostaphylos* residues. Four mulch depths were burned (0, 2.5, 7.5 and 12.5 cm), spanning typical conditions at forested sites in northern California with dense pre-mastication shrub cover. Two soil moisture contents were compared at each fuel depth to simulate spring prescribed burning (moist soil) and late-season wildfire (dry soil). Maximum temperatures reached 600°C on the surface of dry soils and were 100–200°C lower for moist soil. Heating was extensive in dry soil for the two deepest mulch depths, exceeding the lethal threshold for plants (60°C) for a minimum of 7 h throughout the 10-cm soil profile. Minimal heat pulse was found with less mulch. Moist soil also dampened heat penetration; peak temperatures exceeded 60°C only to 2.5 cm in the soil profile for all but the deepest mulch layer. No adverse effects of burning on water repellency were found in dry or moist soil. The potential for biological damage from soil heating during fire exists following mastication, particularly in dry soil with a mulch depth of 7.5 cm or greater. Field projections indicate that up to one-fourth of treated areas with dense pre-mastication vegetation would surpass lethal soil temperatures during a surface wildfire.

Additional keywords: fuel reduction; prescribed fire; soil heating; soil moisture; soil water repellency; wildfire; wildland–urban interface; wood mulch.

Introduction

A century-long policy of fire suppression in the western forests of the United States has resulted in increased fuel loads, wildfire size and fire severity. As a consequence, efforts to reduce fire risk are currently the top priority in these temperate ecosystems. Strategic use of prescribed fire and alternative mechanical treatments is growing, spurred by public concern for the loss of resources and lives in recent catastrophic fires. Perhaps nowhere is the need to reduce fuels greater than at the expanding wildland–urban interface. Here, the use of prescribed fire is typically avoided, leaving mechanical treatment of fuels as a preferred prescription. Mastication of large woody shrubs, mowing of smaller shrubs and overstory thinning are among the common mechanical treatments.

Stand records compiled by the USDA Forest Service show that mastication of understory shrubs and trees has doubled annually on an area basis during the past 5 years in California (USDA Forest Service stand record system, Pacific South-West Region, Vallejo, CA, USA). The treated land base is predominantly at the wildland–urban interface, but also includes strategic fuel breaks designed to protect large forested tracts. State and private owners also are increasing their use of mastication to fire-proof the wildland–urban interface, although actual acreage is not currently known (J. Harter, California Department of Forestry, personal communication). While most credit goes to public awareness of the growing wildfire risk, increased use of mastication also can be attributed to a lack of effective and safe alternatives. Land managers are apprehensive to use prescribed burning at the wildland–urban interface given painful evidence of the destructive capability of escaped fires and the difficulties encountered in meeting air quality and burning prescriptions. Herbicides provide an alternative means of vegetation control; however, their use is controversial and would nevertheless require a follow-up mastication treatment of standing dead vegetation.

Masticated residues typically are left to decay on site as a coarse mulch layer. Two important residue characteristics, total quantity and average particle size, are dictated by the pre-treatment fuel load and the specifications of the masticating equipment. Faster rotating masticator heads result in

 10.1071/WF04062 1049-8001/05/030267

smaller residues, as does slower-moving equipment. Whether fundamental ecological processes and conditions, such as soil temperature and moisture regimes, nitrogen availability, nutrient turnover and carbon sequestration, are affected by the amount or size of masticated residues has not been evaluated in forest ecosystems. Because mastication reduces ladder fuels, it opens a door for prescribing ground fire to reduce fuels further. But whether by prescription or by accident, fire in masticated residues raises an important question. Does residue burning generate sufficient heat to significantly alter soil chemical, physical or biological properties?

Changes in soil properties associated with fire and soil heating can be extreme depending on fire temperature and duration. Soil responses can range from positive increases in plant nutrient availability following moderately severe prescribed fires (Haase and Sackett 1998) to detrimental loss of nutrient capital, soil biota and even physical structure in more severe surface fires (Neary *et al*. 1999). Temperatures required to volatilize soil nutrients range from 200 to 400°C for nitrogen to well above 1000°C for calcium and magnesium (Hungerford *et al*. 1991). Soil organic matter loss begins as temperatures approach 200°C, while death of certain soil bacteria and fungi occurs below 100°C. Comparatively low soil temperatures (40–70°C) result in plant tissue death (Neary *et al*. 1999). In this regard, damage to tree roots and cambial tissue is a particular concern during fire. Preliminary results from a field study conducted in pine-oak woodlands of Northern California indicated substantial tree mortality following surface burning of masticated residues (J. Gibson, National Park Service, personal communication).

Our objective was to evaluate the fire risk to soil and plants posed by masticated residues. Specifically, we quantified soil heating during burning of residues to determine: (1) the threshold quantity of residues required to heat soils above 60°C; (2) the importance of soil moisture in regulating heat pulse during fire; and (3) whether burning of residues from the common shrub species manzanita results in increased soil repellency. In addition, the results were used to predict the percentage of treated ground at two field sites that would surpass 60°C during fire.

Materials and methods

Experimental design

Twenty-four controlled burns were conducted during May 2004 to determine the effects of mastication-derived woody residues on soil heating. The experiment consisted of four surface mulch depths (0, 2.5, 7.5 and 12.5 cm) and two soil moisture contents (4% and 25% on a volumetric basis), replicated three times in a factorial treatment design. Soil heating in small, contained plots (0.9 m $\times$ 0.9 m) was quantified using thermocouples placed at 0, 2.5, 5 and 10 cm below the mineral soil surface (Fig. 1).

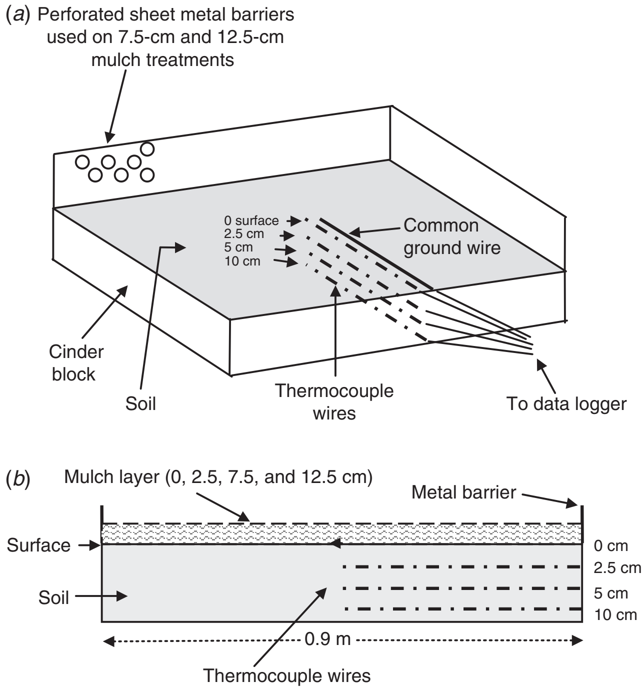

Fig. 1. Plot design. (*a*) View looking down on contained plot before fuel layering. (*b*) Side view of plot after fuel layering.

Mulch treatments were selected to encompass the fuel conditions found at our mechanical fuel-reduction study sites in Northern California. The sites are located at the wildland–urban interface near the rural towns of Whitmore and Challenge, CA, USA. Whitmore is an 18-year-old ponderosa pine plantation that was planted following a wildfire, received no early vegetation control, and has a dense understory dominated by whiteleaf manzanita (*Arctostaphylos viscida* C. Parry) and Parry manzanita (*A. manzanita* Parry). Other species include poison oak (*Rhus diversiloba* Torr. & Gray), mahala mat (*Ceanothus prostratus* G. Bentham) and black oak (*Quercus kelloggii* Newb.). Shrub height on untreated plots ranges from 1.5 to 4 m, and coverage is 100% or greater (>100% cover due to summation of individual shrubs). Preliminary estimates of pre-treated understory biomass are 75 Mg/ha (R. Powers, unpublished report). Challenge is an 18-year-old pine plantation with an extremely dense understory of tanoak (*Lithocarpus densiflorus* Hook. & Arn.), madrone (*Arbutus menziesii* Pursh), deerbrush (*C. integerrimus* H. & A.), greenleaf manzanita (*A. patula* Greene) and poison oak, estimated at 91 Mg/ha (R. Powers, unpublished report). Understory height on untreated plots ranges from 2 to 6 m, and coverage is greater than 100%. Herbaceous species are sparse at both sites.

Understory vegetation was masticated in May 2002 at Whitmore and February 2002 at Challenge using a Rayco 275 Horizontal Shaft Masticator (Rayco Manufacturing, Wooster, OH, USA). Four replicate, 0.4-ha plots were treated per site, leaving a surface mulch of assorted woody material ranging from 0.5 to 4 cm in diameter and 3 to 20 cm in length. The mean depth of the mulch layer was determined from 60 systematically located points in each plot. The bulk density was determined by measuring the depth and oven-dry mass of all woody material within 15 plot frames (10 cm diameter). Mulch biomass on an area basis was calculated by multiplying the mean depth by the bulk density.

Mineral soil and surface mulch were collected from the Whitmore site in April 2004, 6 days after a saturating rainfall. The soil is a Xeric Haplohumult with 340 g/kg clay (clay loam texture), 39.1 g/kg organic matter, and fine granular structure (Busse *et al.* 2001). Half of the mineral soil and mulch was kept containerized to maintain spring-moist conditions. The remaining material was air-dried for 3 weeks under shade cover on the grounds of the Redding Silviculture Laboratory. Moisture contents were determined within 48 h of burning.

Soil was added to the burn plots in 2.5-cm layers. This allowed for appropriate horizontal placement of thermocouple wires at the center of the contained plots, and for gentle packing of soil to match the field bulk density of 1.0 Mg/m^3 (Busse *et al.* 2001). A common ground wire was placed within 2 cm of each thermocouple wire to reduce spurious variation in temperature readings due to soil moisture conditions. The soil was not sieved, although large roots and rocks were removed before packing. Each burn unit was lined with cinder block to the height of the mineral soil surface. Moist soil was kept covered between burn sequences and was packed within 30 min of ignition to limit evaporative losses, while the dry soil was packed no more than 12 h before burning.

Mulch was placed on the mineral soil surface and packed to treatment height immediately before burning. Appropriate weights (to the nearest 1 g on an oven-dry basis) for each mulch treatment were calculated using a field bulk density value of 0.133 Mg/m^3. Moisture contents at the time of ignition were 2% for the dry soil treatments and 16% for the moist soil treatments. The control treatment (0-cm mulch) received a 2.0-cm layer of pine and shrub litter collected from non-masticated, control plots at Whitmore. This represented the mean litter depth ($n = 60$) in untreated plots at the site. Final fuel loads were 12, 34, 101 and 169 Mg/ha for the 0, 2.5, 7.5 and 12.5 cm mulch treatments respectively.

Test burns indicated that unrestricted air flow from exposed sides of the mulch resulted in uncharacteristic heat loss to the atmosphere for the 7.5-cm and 12.5-cm mulch layers. Thus, to approximate a continuous mulch layer beyond the perimeter of our small plots, we constructed semi-restrictive barriers made of perforated (~35% pore space) 2-mm sheet metal, which surrounded the 7.5-cm and 12.5-cm mulch treatments. The barriers were removed from each burn plot once flames had subsided and the mulch was primarily consumed.

Data collection and analysis

All burns were conducted between 0700 and 1800 hours, 4 May to 6 May 2004. Sixteen thermocouple wires were connected to a multiplexer and CR10X data logger (Campbell Scientific, North Logan, UT, USA), which permitted four concurrent burns with four thermocouple wires per burn. Thermocouples were constructed of 30-gauge chromel–alumel (measuring range −100 to 1370°C) silica-insulated thermocouple wire (Omega Engineering, Stamford, CT, USA). Nextel sleeving (Omega Engineering) was added as insulation from the point where the wire entered the plot frame to the thermocouple. Soil temperatures were recorded every 30 s and monitored using real-time downloading to Microsoft Excel. Mulch layers were ignited at a single point in the up-wind corner of each plot, and soil temperatures were recorded until the heating front dropped at least below 60°C at all soil depths. Air temperature, relative humidity, wind speed, maximum flame height and flame duration were measured during each burn. Following burning, ash and unconsumed organics were collected, oven-dried at 60°C for 48 h, and weighed to determine fuel consumption. Soil water repellency was tested using the water drop penetration time method (Krammes and DeBano 1965) at 0, 2.5, 5 and 10 cm below the mineral soil surface, and on unburned samples.

Our intent in designing the experiment was to present the mean temperature profile for each treatment by averaging the three replicate burns. Although statistically valid, the average profiles underestimated the observed maximum temperatures by ~100°C due to the variation in time required to reach maximum temperature between replicates. Instead, the temperature profiles from all burns are shown to highlight within-treatment variation. Analysis of variance (SAS version 8.2, SAS Institute, Cary, NC, USA) was used to test the effects of mulch depth and soil moisture on lethal heat duration and degree hours exceeding 60°C. Multiple linear regression models were used to predict maximum soil temperatures and heat duration, using mulch depth, soil moisture and soil depth as independent variables. The dependent variables were transformed (natural log, square root) to stabilize the error variance (Kutner *et al.* 2004). All partial regression coefficients were statistically significant at $t < 0.0001$. The regression equations were then used to predict soil heating at Challenge and Whitmore based on actual mulch depths for each site.

Results and discussion

Fire intensity

Weather conditions were mild during burning. Nonetheless, differences in air temperature and relative humidity between dry soil and moist soil burns were noted (Table 1). Air temperature was 7°C higher and relative humidity was 15% lower for dry soil compared to moist soil burns. These differences primarily reflected the time of day of burning. Most dry

Table 1. Weather conditions and fire behavior during burning of wood mulch
Values are means ($n = 3$) plus standard errors in parentheses

Soil	Mulch depth (cm)	Air temperature (°C)	Wind speed (km/h)	Relative humidity (%)	Flame height (m)	Flame duration (min)	Fuel consumption (Mg/ha)	Fuel consumption (%)
Dry	0	25.9 (3.2)	3.6 (2.0)	37 (4)	0.6 (0.1)	4 (1)	9 (1)	77 (5)
	2.5	28.3 (2.2)	4.7 (1.6)	32 (4)	0.4 (0.1)	20 (4)	27 (1)	79 (1)
	7.5	28.3 (2.2)	4.7 (1.6)	32 (4)	1.0 (0.1)	23 (2)	93 (3)	91 (3)
	12.5	28.3 (2.2)	4.6 (1.4)	32 (4)	1.3 (0.1)	28 (10)	154 (4)	91 (2)
Moist	0	22.5 (3.3)	3.6 (1.1)	43 (9)	0.6 (0.1)	5 (1)	9 (1)	78 (4)
	2.5	19.4 (2.0)	3.0 (0.2)	50 (5)	0.3 (0.1)	26 (4)	26 (3)	76 (7)
	7.5	19.4 (2.0)	3.2 (0.2)	50 (5)	1.1 (0.2)	26 (3)	90 (4)	89 (3)
	12.5	19.5 (2.0)	3.2 (0.2)	49 (5)	1.7 (0.2)	27 (3)	159 (4)	94 (2)

soil burns (eight out of 12) were conducted in the afternoon, while a similar majority of moist soil burns were conducted in the morning when the weather was more cool and moist. We arranged our morning and afternoon tests with the aim of approximating the climatic conditions common to spring (cool and moist) and summer (hot and dry). Fire intensity appeared independent of the differences in weather conditions, however, as maximum flame heights and fuel consumption were similar between soil moisture treatments. Fuel consumption was high for all treatments, and generally increased with increasing mulch depth.

We were particularly interested in the burning pattern of the residues, and whether they would burn rapidly or, alternatively, produce a smoldering fire. The potential for damaging soil effects is often greatest during smoldering fires due to an extended duration of heating (Hungerford *et al*. 1991; Haase and Sackett 1998). Slow-burning tree stumps and large downed wood are common examples of smoldering fires that can produce considerable soil damage (Haase and Sackett 1998). In contrast, the residues in our study burned rapidly: average flame duration did not exceed 28 min, peak temperatures were reached within 8 h and soil temperatures dropped below 60°C within 17 h of ignition regardless of treatment. Although the rapid burn pattern may have reflected the artificial conditions of our constructed plots, a more likely explanation is that the small-to-intermediate physical size and low moisture content of the residues led to their rapid consumption. Small, loosely packed residues have proportionally more evaporative surface area and oxygen availability during burning than large residues. Also, the residues used for the moist-soil treatment dried rapidly in the field before burning (16% final moisture content) even though they were left on site for less than 1 week following a saturating rainfall. Perhaps densely packed residues, such as those produced during a chipping operation, would retain greater moisture and thus burn more slowly.

Temperature profiles

Temperature profiles for the 24 burns were distinct, with peak temperature and heat duration varying strongly as a function of mulch depth, soil depth and moisture content (Figs 2, 3). Primary responses included a stair-step increase in soil heating with increasing mulch depth, a large temperature gradient with soil depth and a dampening of temperatures in moist soil. Within-treatment variation ($n = 3$) also was observed, particularly in the upper soil profile of the 7.5-cm and 12.5-cm mulch depths, yet did not overshadow the gross treatment responses.

Variation in soil heating is common between replicate prescribed burns (Preisler *et al*. 2000). Assurance of uniform fuel loads, fuel and soil moisture contents, weather conditions and soil physical properties is virtually impossible in natural settings. In contrast, we were able to construct fuel loads with identical masses, thoroughly mix and pack mineral soil to ensure consistent moisture and bulk density, and burn within a 3-day window to capture consistent weather conditions. Thus, greater uniformity in soil heating was expected in our study compared with field burns almost by definition. Still, the temperature profiles were not identical between replicate burns at the heaviest fuel loads. Evidently, small differences in the physical arrangement of wood residues plus slightly shifting wind conditions were sufficient to produce unique fire patterns.

Maximum temperatures on the soil surface ranged from 500 to 600°C for dry soil and from 400 to 500°C for moist soil (Figs 2, 3). Downward heat pulses were generally negligible or limited to the surface 2.5 cm when mulch depths were 2.5 cm or less. Considerable heat was transferred in the soil profile with greater mulch depths, however, particularly in dry soil. For example, maximum temperatures in dry soil with a 12.5-cm mulch layer averaged 313, 209 and 105°C at soil depths of 2.5, 5.0 and 10.0 cm respectively. Respective temperatures in moist soil were 116, 82 and 61°C.

While these temperature profiles are unique for masticated woody fuels and for the conditions of our burns, they provide an interesting contrast to profiles of other fuel types. Surface temperatures in our study were roughly double the temperatures expected during prescribed burning of litter and duff in conifer forests, which typically range from 200 to 300°C (Neary *et al*. 1999). Instead, they more closely match

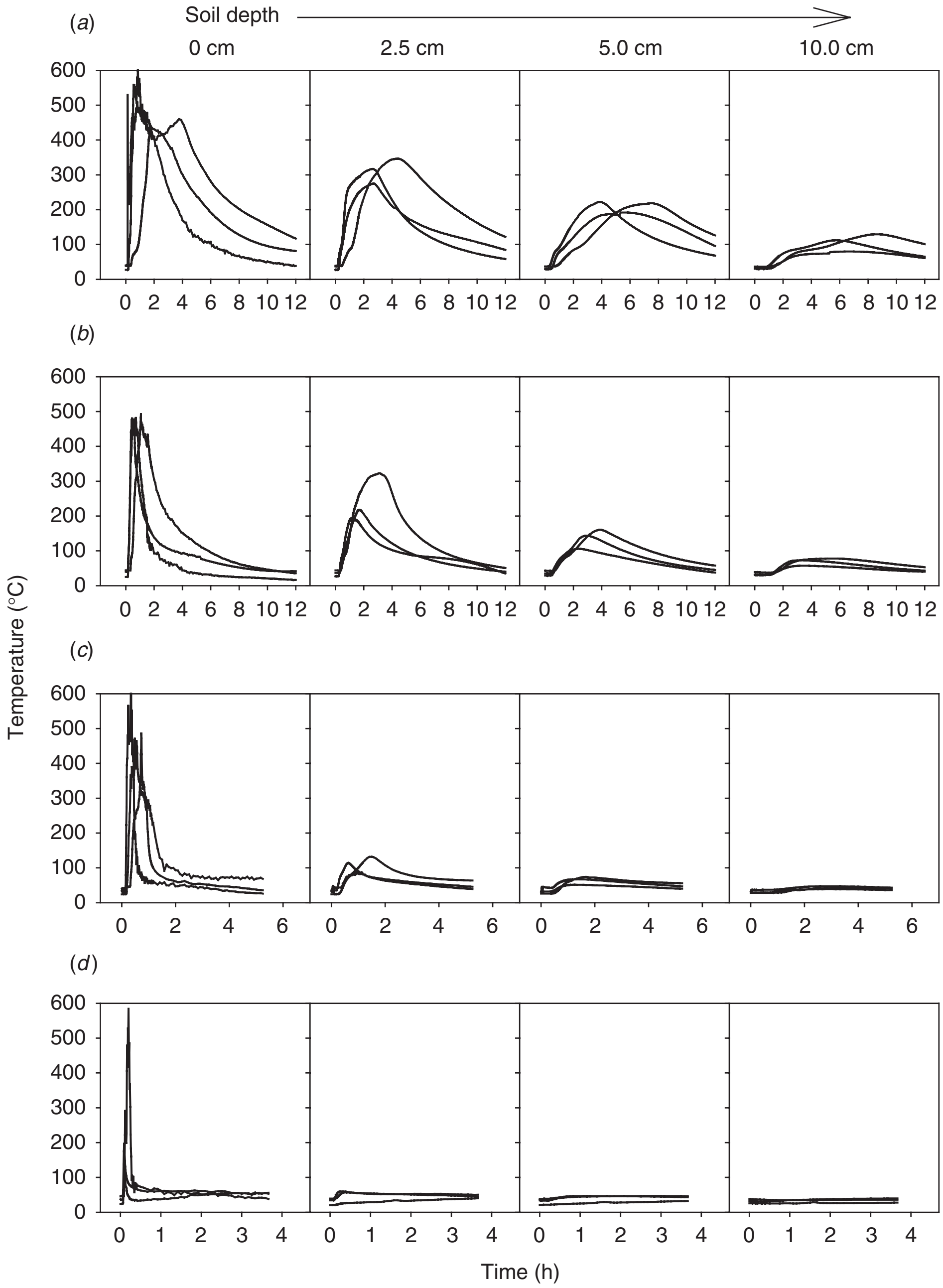

Fig. 2. Temperature profiles for dry soil with mulch depths of (*a*) 12.5 cm, (*b*) 7.5 cm, (*c*) 2.5 cm and (*d*) 0.0 cm. Lines represent three replicate burns for each treatment. Adjoining graphs, from left to right, represent 0, 2.5, 5.0 and 10.0 cm in the mineral soil.

the peak temperatures of 500 to 800°C measured for heavy slash fires (Shea 1993; Neary *et al.* 1999; Giardina *et al.* 2000). Downward heat pulse in our study was intermediate between prescribed burns and slash fires. We found peak temperatures between 40 and 105°C at 10-cm soil depth. In comparison, Preisler *et al.* (2000) found temperatures ranged from 40 to 70°C at 10 cm during burning of thick (2–18 cm) litter and duff layers, and Shea (1993) found negligible heating in the mineral soil profile during burning of moderately thick (2–6 cm) ponderosa pine litter and duff. Slash fires with appreciable amounts of large wood result in peak soil temperatures well above 100°C for extended lengths of time (Roberts 1965; Shea 1993). Potential soil damage from burning of masticated residues, therefore, ranks between the mild effects of most moderate-severity prescribed fires and the damaging effects of heavy slash fires.

Soil temperatures were monitored until they dropped at least below 60°C, considered the threshold temperature for

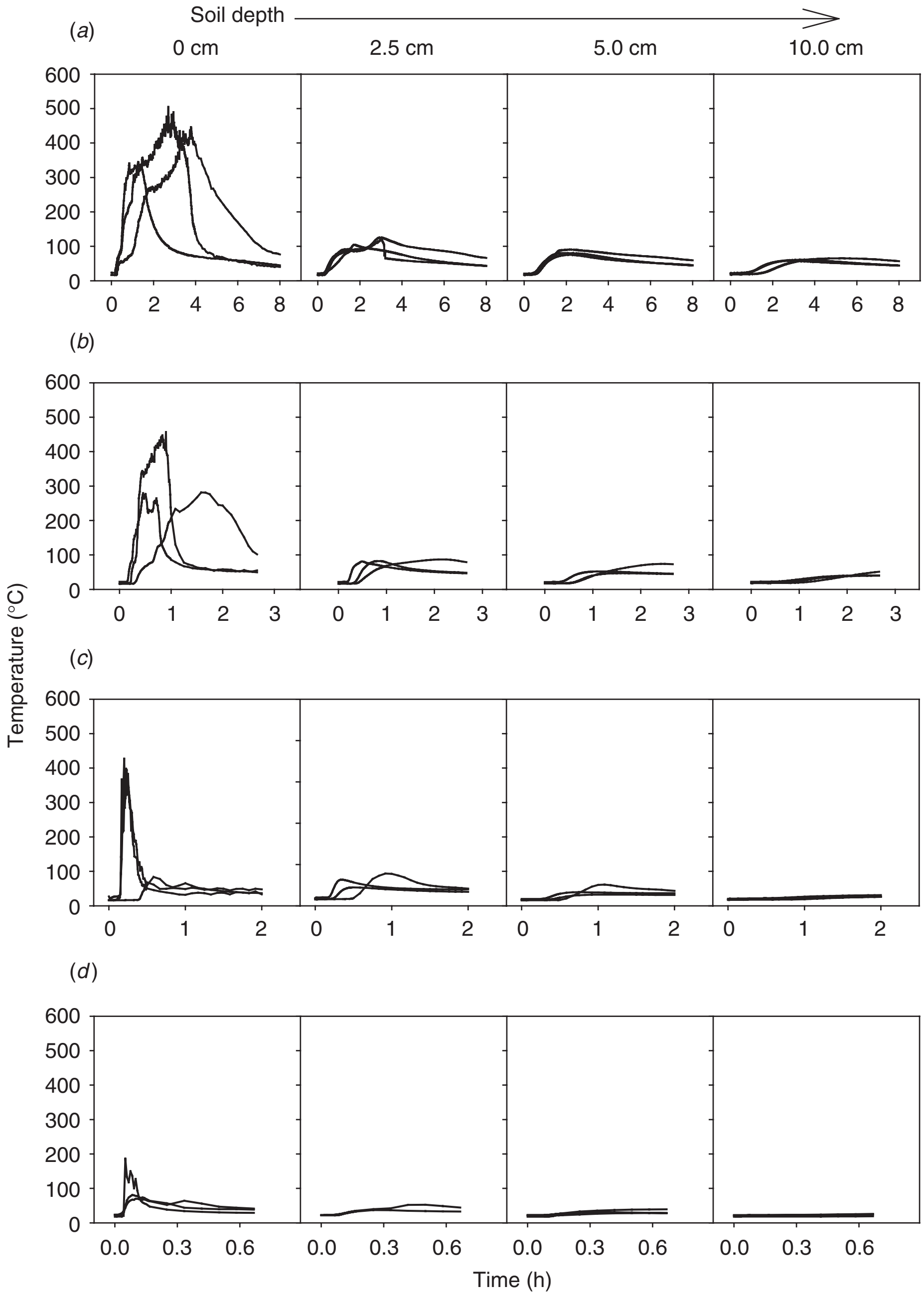

Fig. 3. Temperature profiles for moist soil with mulch depths of (*a*) 12.5 cm, (*b*) 7.5 cm, (*c*) 2.5 cm and (*d*) 0.0 cm. Lines represent three replicate burns for each treatment. Adjoining graphs, from left to right, represent 0, 2.5, 5.0 and 10.0 cm in the mineral soil.

plant survival (Preisler *et al*. 2000). This allowed us to estimate the lethal heat duration during burning of masticated residues. Early studies indicated plant tissue death between 40 and 70°C (cited in Neary *et al*. 1999; Preisler *et al*. 2000). Our use of 60°C as a biological threshold, therefore, is somewhat arbitrary as it represents the upper end of the lethal range and, more importantly, fails to account for differences in heat sensitivity between plant species or phenologic stage. In addition, the threshold value does not account for the effects of soil moisture, nor does it consider duration above 60°C as a factor. Instead, its use is strictly for interpretational purposes.

The threshold temperature was exceeded at nearly all depths in dry soil when wood mulch was present (Fig. 4). Duration above 60°C increased linearly with increasing mulch depth, and was three to seven times greater in dry soil

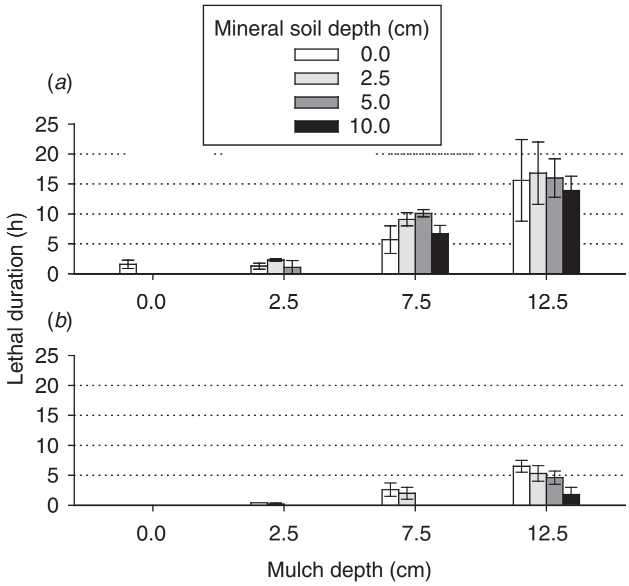

Fig. 4. Heat duration exceeding the plant lethal temperature of 60°C during burning of wood mulch in (*a*) dry and (*b*) moist soil. Bars are means ($n = 3$) plus standard errors for four depths in the soil profile.

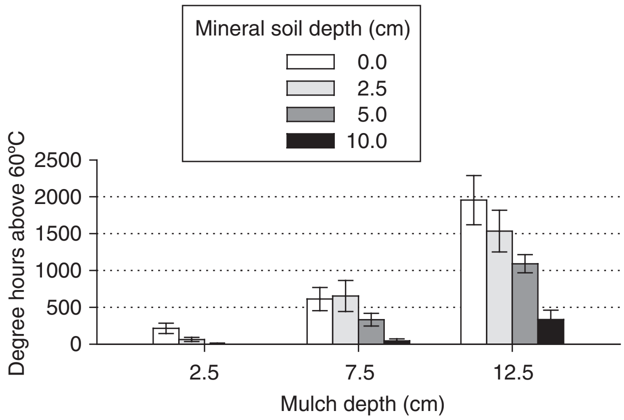

Fig. 5. Degree hours exceeding the plant lethal temperature of 60°C in dry soil during burning of wood mulch. One degree hour above 60°C equals soil heating to 61°C for 1 h, as does heating to 70°C for one-tenth of an hour.

than moist soil. The main effects of mulch depth and soil moisture were statistically significant ($P < 0.0001$). Only in one case (2.5-cm mulch) did dry soil temperatures fail to surpass 60°C at the lowest soil depth. In contrast, moist soil did not reach 60°C at depths greater than 2.5 cm in the profile for all but the 12.5-cm mulch treatment.

Interestingly, the heat duration above 60°C in dry soil was generally consistent with soil depth (Fig. 4). This is counterintuitive based on the large temperature gradient within the soil profile, and suggests that the threshold temperature is an overly simplistic measure of heat duration. An alternative, integrative means to incorporate lethal duration and absolute temperature is the use of degree hours above 60°C (e.g. 10 degree hours are equivalent to 70°C for 1 h, as is 61°C for 10 h). A clear decline in degree hours is seen with depth in dry soil (Fig. 5), and thus may be a more appropriate expression for potential plant or soil damage.

Soil heating during surface fires is a complex process driven by fuel load, fuel moisture, weather conditions, landscape position and heat transfer mechanisms. Primary soil factors influencing heat transfer are thermal conductivity, heat capacity and moisture content (Hungerford *et al*. 1991), which, in turn, depend on a complex array of soil physical properties such as pore volume and tortuosity, texture, mineralogy, vapor diffusivity and organic matter content. While surface soil temperatures spike rapidly during a burn (Robichaud *et al*. 2000), below-ground temperatures rise slowly in both dry and moist soils. In dry soil, air acts as a good insulator (Agee 1973), and in wet soils, all moisture must be evaporated before temperatures will exceed 95°C (Jury *et al*. 1991).

Soil texture and moisture are key variables regulating the downward and lateral transport of heat. Most of the heat conduction takes place through a relatively small cross-sectional area at the point of surface contact between particles. The presence of a water film at the point of contact increases the effective surface area for thermal contact, leading to greater heat transfer. Equally important, water has ~23 times greater thermal conductivity than air (Jury *et al.* 1991). At higher moisture contents, however, thermal conductivity is reduced per unit of water as additional energy is required for evaporation. Clearly, additional studies are needed to identify soil moisture thresholds and to provide practical guidelines for limiting excessive soil heating in different textured soils.

Predicting soil temperatures during burning is challenging without detailed knowledge of fire conditions and soil physical properties (Campbell *et al*. 1994, 1995). What is clear from our results, however, is the dominant role of soil moisture as a predictive factor in limiting soil heating. Peak temperatures and heat duration were reduced considerably in moist soil, particularly at heavier fuel loads. This finding agrees with the results of others (Frandsen and Ryan 1986; Hartford and Frandsen 1992; Valette *et al*. 1994). Frandsen and Ryan (1986) found that belowground heat flux was reduced 80% in wet compared to dry sand, and recommended that operational burns be conducted when soils are near saturation if avoiding soil and plant damage was a priority.

Finally, predictive equations of peak temperatures and heat duration were developed using the combined data from the 24 burns (Table 2). Collectively, the independent variables (mulch depth, soil depth, soil moisture) provided good estimates of soil temperature characteristics using multiple regression analysis. The equations are valid for mulch depths 0–12.5 cm, which encompasses the entire range of depths found on masticated plots at Whitmore and 93% of depths measured on masticated plots at Challenge. Because

Table 2. Predictive equations of maximum soil temperature and heat duration as a function of mulch depth (MD), soil moisture (SM) and soil depth (SD)

Units: MD (cm); SM (1 = summer dry; 2 = spring moist); SD (cm)

Soil characteristic	Predictive equation	r^2	*P* value
Maximum temperature (°C)	$y = e^{(5.709+0.084[MD]-0.510[SM]-0.178[SD])}$	0.743	<0.0001
Heat duration above 60°C (h)	$y = (2.197 + 0.207[MD]-1.035[SM]-0.109[SD])^2$	0.745	<0.0001
Degree hours above 60°C	$y = (20.354 + 1.767[MD]-9.783[SM]-1.341[SD])^2$	0.733	<0.0001

Table 3. Estimated soil temperature characteristics at Challenge and Whitmore using a surface fire simulation

Values were determined using regression equations (Table 2) and measured residue depths ($n = 60$ per plot). Standard errors (in parentheses) are based on three plots per site

Soil temperature characteristic	Site	Dry soil depth (cm)		Moist soil depth (cm)	
		5	10	5	10
Maximum (°C)	Challenge	124 (8)	51 (3)	75 (5)	31 (2)
	Whitmore	90 (2)	37 (1)	54 (1)	22 (1)
Duration above 60°C (h)	Challenge	3.6 (0.6)	1.6 (0.3)	1.2 (0.3)	0.4 (0.1)
	Whitmore	1.3 (0.1)	0.2 (0.0)	0.2 (0.0)	0.0 (0.0)
Degree hours above 60°C	Challenge	227 (40)	86 (17)	66 (16)	18 (4)
	Whitmore	72 (7)	9 (30)	6 (2)	0 (0)

these two sites are representative of heavy pre-mastication fuel types, the equations are likely applicable for many treated areas at the wildland–urban interface. The limitations of the equations are that they: (1) are only valid to 10 cm in the soil profile; (2) may have little applicability in coarser-textured soils; and (3) oversimplify soil moisture conditions into two broad categories.

Field projections of soil heating

The Challenge and Whitmore field sites are located at the wildland–urban interface and possess visually daunting levels of live woody fuel. Prior to mastication, understory vegetation at Challenge was extremely dense 2–6 m tall tan oak, madrone, deerbrush, manzanita and poison oak. Mean wood mulch depth at Challenge was 5.1 cm (range 0–24 cm) with biomass measured at 78 Mg/ha. Vegetation at Whitmore was dense 1.5–4 m tall manzanita. Mean wood mulch depth at Whitmore was 2.0 cm (range 0–10 cm) with biomass measured at 35 Mg/ha. Both mulch depth and biomass at Challenge were more than twice the amounts measured at Whitmore, indicative of its more dense fuel type dominated by tanoak and deerbrush.

Soil heating during simulated wildfire was estimated using regression equations from Table 2 and systematically sampled mulch depths ($n = 180$ per site). We assumed that the energy release per unit biomass of woody residue was similar between sites, even though the understory species differed. Not surprisingly, soil heating was greatest at Challenge due to higher pre-fire biomass loads. Average maximum temperatures were 9–34°C higher at Challenge than Whitmore depending on soil depth and moisture content (Table 3). Degree hours above 60°C were 3–10 times greater at Challenge than Whitmore. Site differences aside, the predicted average peak temperature at 10 cm for both sites was beneath the lethal threshold of 60°C.

Estimating soil heat pulse based on the average mulch depth, as above, provides an overall risk assessment for a given fuel type, yet can be misleading if within-site variability is overlooked. The importance of spatial variability in assessing soil heat projections is demonstrated in Fig. 6. A diverse arrangement of mulch depths, partitioned into four depth classes based on 60 sample points, was found at Challenge. In contrast, the majority (73%) of mulch depths at Whitmore were between 0 and 2.5 cm. Only 4% of the treated area had mulch depths greater than 7.5 cm at Whitmore. Predicted soil temperatures during a simulated wildfire also are presented in Fig. 6. Again, the spatial variability in soil temperatures was far greater at Challenge than Whitmore. Most of the treated area at Whitmore (96%) was below the lethal threshold of 60°C at 10 cm soil depth, while above-lethal temperatures are scattered across 23% of the treated area at Challenge.

Heat-induced water repellency

We found no evidence of water repellency at the soil surface or any depth in burned or unburned soils. Soil water repellency develops during fire as hydrophobic compounds from litter and plant material vaporize and move downward along a temperature gradient until cooler temperatures result

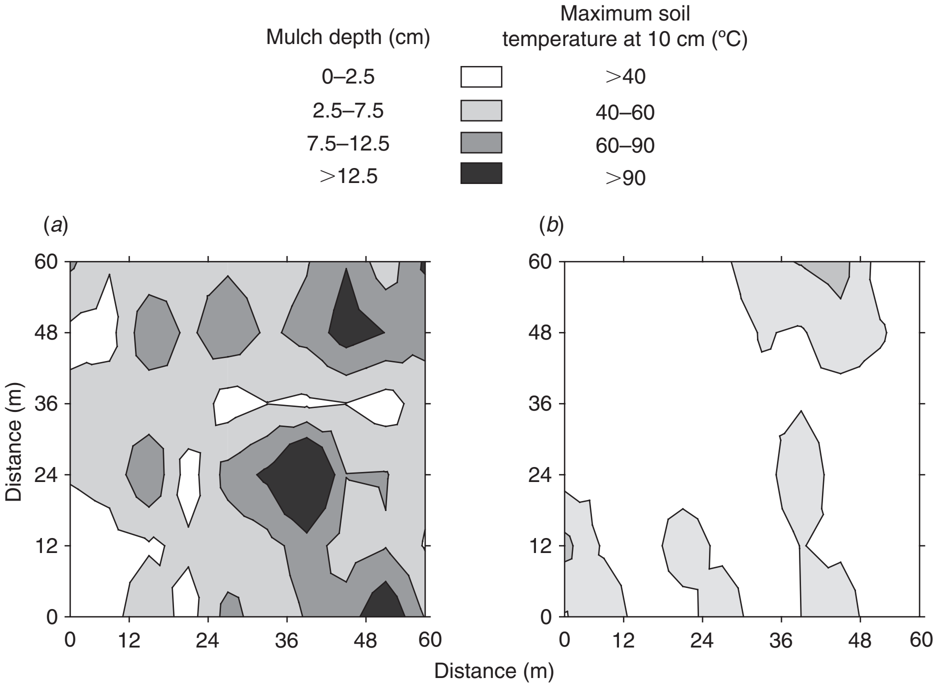

Fig. 6. Example of the spatial distribution of wood mulch following mastication of understory vegetation at (*a*) Challenge and (*b*) Whitmore ponderosa pine stands in northern California. Maximum soil temperatures for a simulated wildfire were estimated using results from the dry soil burns at 10 cm soil depth.

in their condensation (DeBano *et al*. 1976). It is possible that water repellent compounds were destroyed at temperatures between 260 and 340°C (Doerr *et al*. 2004), but even soil heating to the optimal range of 175 to 200°C (DeBano 2000) in the surface 2.5 cm (dry soil, 7.5 cm mulch) had no effect on repellency. Organic residues of manzanita, therefore, should be considered a low risk for increasing soil water repellency.

Management implications

Reducing fire risk at the wildland–urban interface remains a priority of land managers in the western United States. Mechanical treatments, including mastication of woody plants, are important tools in this drive to improve fire safety. Unforeseen risks associated with masticated residues are secondary to the creation of fire-safe landscapes, yet should be recognized in order to limit potential damage to desired vegetation and soil resources. The results from our study offer practical information to managers considering mastication treatment of dense understory vegetation.

- Soil temperatures can surpass the biologically lethal threshold of 60°C if masticated residues burn. However, the fuel levels necessary to meet this condition are fairly extreme and likely atypical of the wildland–urban interface. Mulch depths of 7.5 cm or greater are generally required to generate peak temperatures above 60°C at 10-cm soil depth. As a point of reference, mastication of large (2–4 m), continuous-cover manzanita yielded an average residue layer less than 2.5 cm, while our most extreme understory condition of mixed hardwood shrubs and trees produced an average mulch layer of 5 cm.
- Spatial variability may be high within treated areas, resulting in numerous 'hotspots' if burned. As an example, nearly one-fourth of the treated area at Challenge had a mulch depth greater than 7.5 cm. Mapping treated areas for risk assessment based on site average and a simple index of variability is recommended.
- Prescriptions for masticated fuels should emphasize burning when soils are near saturation. Our results concur with Frandsen and Ryan (1986) and Campbell *et al*. (1995) that soil heating is substantially reduced at higher moisture contents.

Acknowledgements

The current study was supported by funds from the National Fire Plan, an interagency programme of the United States. We are grateful to Bob Carlson, Don Jones, Bert Spear and Dave Young for their hard work during the construction and burning of the plots, and to George Riechers for providing software and technical support during the measurement of soil temperatures.

References

Agee JK (1973) Prescribed fire effects on physical and hydrologic properties of mixed-conifer forest floor and soil. University of California

Water Resources Center contribution 143. (Water Resources Center: Davis, CA)

Busse MD, Ratcliff AW, Shestak CJ, Powers RF (2001) Glyphosate toxicity and the effect of long-term vegetation control on soil microbial communities. *Soil Biology and Biochemistry* **33**, 1777–1789. doi:10.1016/S0038-0717(01)00103-1

Campbell GS, Jungbauer JD Jr, Bidlake WR, Hungerford RD (1994) Predicting the effect of temperature on soil thermal conductivity. *Soil Science* **158**, 307–313.

Campbell GS, Jungbauer JD Jr, Bristow KL, Hungerford RD (1995) Soil temperature and water content beneath a surface fire. *Soil Science* **159**, 363–374.

DeBano LF (2000) The role of fire and soil heating on water repellency in wildland environments: a review. *Journal of Hydrology* **231–232**, 195–206. doi:10.1016/S0022-1694(00)00194-3

DeBano LF, Savage SM, Hamilton DA (1976) The transfer of heat and hydrophobic substances during burning. *Soil Science Society of America Journal* **40**, 779–782.

Doerr SH, Blake WH, Shakesby RA, Stagnitti F, Vuurens SH, Humphreys GS, Wallbrink P (2004) Heating effects on water repellency in Australian eucalypt forest soils and their value in estimating wildfire soil temperatures. *International Journal of Wildland Fire* **13**, 157–163. doi:10.1071/WF03051

Frandsen WH, Ryan KC (1986) Soil moisture reduces belowground heat flux and soil temperatures under a burning fuel pile. *Canadian Journal of Forest Research* **16**, 244–248.

Giardina CP, Sanford RL Jr, Dockersmith IC (2000) Changes in soil phosphorus and nitrogen during slash-and-burn clearing of a dry tropical forest. *Soil Science Society of America Journal* **64**, 399–405.

Haase SM, Sackett SS (1998) Effects of prescribed fire in giant sequoia-mixed conifer stands in Sequoia and Kings Canyon National Parks. In 'Proceedings Tall Timbers Fire Ecology Conference, Vol. 20'. (Eds TL Pruden, LA Brennan) pp. 236–243. (Tall Timbers Research Station: Tallahassee, FL)

Hartford RA, Frandsen WH (1992) When it's hot, it's hot … or maybe not! Surface flaming may not portend extensive soil heating. *International Journal of Wildland Fire* **2**, 139–144.

Hungerford RD, Harrington MG, Frandsen WH, Ryan KC, Niehoff GJ (1991) Influence of fire on factors that affect site productivity. In 'Proceedings – Management and productivity of western-montane forest soils'. (Eds AC Harvey, LF Nuenschwander) pp. 32–50. USDA Forest Service Intermountain Research Station General Technical Report INT-280.

Jury WA, Gardner WR, Gardner WH (1991) 'Soil physics.' (John Wiley and Sons: New York)

Krammes JS, DeBano LF (1965) Soil wettability: a neglected factor in watershed management. *Water Resources Research* **1**, 283–286.

Kutner MH, Nachtsheim CJ, Neter J (2004) 'Applied linear regression models.' (McGraw-Hill: Irwin, New York)

Neary DG, Klopatek CC, DeBano LF, Ffolliott PF (1999) Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management* **122**, 51–71. doi:10.1016/S0378-1127(99)00032-8

Preisler HK, Haase SM, Sackett SS (2000) Modeling and risk assessment for soil temperatures beneath prescribed forest fires. *Environmental and Ecological Statistics* **7**, 239–254. doi:10.1023/A:1009615032159

Roberts WB (1965) Soil temperatures under a pile of burning logs. *Australian Forest Research* **1**, 21–25.

Robichaud PR, Beyers JL, Neary DG (2000). 'Evaluating the effectiveness of post-fire rehabilitation treatments.' USDA Forest Service, Rocky Mountain Research Station, General Technical Report, RMRS-GTR-63.

Shea RW (1993) Effects of prescribed fire and silvicultural activities on fuel mass and nitrogen redistribution in *Pinus ponderosa* ecosystems of central Oregon. MS Thesis, Oregon State University, Corvallis, USA.

Valette J-C, Gomendy V, Marechal J, Houssard C, Gillon D (1994) Heat transfer in the soil during very low-intensity experimental fires: the role of duff and soil moisture content. *International Journal of Wildland Fire* **4**, 225–237.