CSIRO PUBLISHING

International Journal of Wildland Fire **2016**, *25*, 1202–1207
http://dx.doi.org/10.1071/WF16016

Research Note

Soil heating during the complete combustion of mega-logs and broadcast burning in central Oregon USA pumice soils

Jane E. Smith[A,C], *Ariel D. Cowan*[B] *and Stephen A. Fitzgerald*[B]

[A]USDA Forest Service, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR 97331, USA.
[B]Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR 97331, USA.
[C]Corresponding author. Email: jsmith01@fs.fed.us

Abstract. The environmental effect of extreme soil heating, such as occurs with the complete combustion of large downed wood during wildfires, is a post-fire management concern to forest managers. To address this knowledge gap, we stacked logs to create 'mega-log' burning conditions and compared the temperature, duration and penetration of the soil heat pulse in nine high intensity burned (HB) plots paired with adjacent masticated and broadcast burned low intensity burned (LB) plots at different soil depths (0, 5, 10 and 30 cm) in a *Pinus ponderosa* stand with volcanic pumice soils. Maximum soil surface temperatures ranges were 424–1168°C with a mean and standard error of 759 ± 9°C in the HB treatment and 42–360°C (107 ± 43°C) in the LB treatment. In the HB treatment, temperatures causing fine root and soil organism mortality (>60°C) penetrated the soil to at least 10 cm, but were not recorded at 30 cm. In the HB treatment, mean duration above 60°C at 0–10 cm persisted for 4–13 h (7.61 ± 1.02 h). Soils in the LB treatment experienced lethal temperatures at the surface for about an hour (1.19 ± 0.70 h) and at 5 cm were mostly well below lethal temperatures with the exception of one at 57°C and another at 100°C that remained above 60°C for 1.4 h. Large areas of high burn severity may affect long-term forest productivity. Our quantification of soil heating establishes conditions for ongoing studies investigating the effects of soil burn severity on tree seedling growth, soil fungi and nutrients.

Additional keywords: fire intensity, fire severity, fuel reduction, post-fire impacts.

Received 27 January 2016, accepted 26 July 2016, published online 12 September 2016

Introduction

Conditions resulting in extreme soil heating during fire contribute to structural changes in the landscape and alter soil productivity (Goforth *et al.* 2005; Schoennagel *et al.* 2008) and soil fungal communities (Cowan *et al.* 2016, Reazin *et al.* 2016). Soil temperatures exceeding the lethal threshold for fine roots (60°C) and most soil organisms (50–200°C) (Neary *et al.* 1999) have been recorded in burns beneath slash and wood piles (Massman and Frank 2004; Jiménez Esquilín *et al.* 2007; Busse *et al.* 2013, 2014), masticated fuels (Busse *et al.* 2005) and log segments on cement platforms (Monsanto and Agee 2008). Slash pile burning in conditions that limit smouldering (e.g. piles containing a mixture of fuel sizes) results in moderate soil heating (Busse *et al.* 2013) as most of the heat rises (Hungerford *et al.* 1991). In contrast, the presence of large wood in pile burning is a primary factor leading to high soil temperatures (Busse *et al.* 2013) that alter soil aggregate stability and cause changes in soil microbiology and mineralogy (Chambers and Attiwill 1994; Badía and Martí 2003*a*, 2003*b*). Logs on the ground potentially increase the area of high severity burned soil in wildfires (Poff 1989; Brown *et al.* 2003; Holden *et al.* 2010; Dunn and Bailey 2015) because heat is radiated downward for a long duration (Neary *et al.* 1999).

Temperatures ranging from 155°C to 500°C at 5 cm soil depth and from 100°C to 400°C at 10 cm depth beneath piles with large wood (Busse *et al.* 2013) reinforce the concern for irreversible damage to soil properties. Combustion of organic matter begins at around 200–250°C (Agee 1993). High severity soil heating significantly reduces nutrient content and availability (Korb *et al.* 2004; Bormann *et al.* 2008; Hebel *et al.* 2009) and changes soil thermal conductivity (Massman *et al.* 2008). Areas that burn with greater severity retard reinvading vegetation longer than lightly burned areas (Hebel *et al.* 2009), reducing competition for the establishment of conifer seedlings (Cooper 1960, 1961; White 1985).

In the present study, mega-logs were constructed by stacking logs in parallel to simulate very large pieces of downed wood and later ignited to ascertain soil heating effects on soil nutrients, soil microbiota and ponderosa pine (*Pinus ponderosa*) seedling growth (Cowan *et al.* 2016). We monitored changes throughout the burning process and in this paper report on extreme soil heating beneath mega-logs in direct contact with the forest floor. Our aim was to record the soil heat pulse during the complete combustion of logs and compare maximum temperature and duration of temperatures lethal to most soil organisms (>60°C) at a series of depths and between the high intensity log burn plots (HB) and adjacent masticated and broadcast burned low intensity burn (LB) plots. Our use of mega-logs is a novel approach to investigate the extreme case of soil heating.

Methods

Site description

A thinning and fuels reduction experiment (Youngblood 2009) created the open stand condition and available logs necessary for our study conducted within the Lookout Mountain Unit (43°42′N, 121°37′ W) of the Pringle Falls Experimental Forest, Deschutes National Forest in central Oregon. Our study occurred within a 199 ha prescribed burn at an elevation of ~1372 m, on relatively flat ground (0–20% slope) with a south-east aspect dominated by ponderosa pine. Timber was harvested in summer 2011 and non-commercial material and understory bitterbrush (*Purshia tridentata* Pursh) and snowbrush (*Ceanothus velutinus* Dougl. Ex Hook) was masticated in summer 2012. Mastication was accomplished with a Takeuchi TL 150 (Takeuchi Manufacturing, Pendergrass, GA, USA) with a Fecon head (Fecon, Lebanon, OH, USA) and left surface mulch ranging from 0.5 cm to 6.0 cm (averaging 3 cm) in depth. Surface fuels after mastication but before burning consisted of 1-h, 10-h and 100-h fuels (0–7.6 cm) in metric tons per hectare of 49.5, 46.8 and 26.7 (Brown *et al.* 1982). The soils, classified as Xeric Vitricryands in the La Pine Soil Series, consist of well drained loamy coarse sands and volcanic pumice and ash deposits from the eruption of Mount Mazama ~7000 years ago (http://websoilsurvey.nrcs.usda.gov/app/help/citation.htm, accessed 20 August 2016; Powers and Wilcox 1964). Cold winters and hot, dry summers with high temperatures ranging from 21°C to 32°C result in average annual temperatures of 6.4°C with a mean annual precipitation of 519 mm, typically occurring as winter snow (Youngblood *et al.* 2004).

Mega-log construction

To investigate extreme soil heating, mega-logs, to approximate the footprint and volume of very large downed wood, were created in summer 2011 by stacking logs in parallel to maximise ground contact (Fig. 1). Mega-logs (≈1.5–2 m wide, 8–10 m long and 1 m high) were covered with plastic and left to cure for two years. Logs were mostly of low decay with intact bark. Mega-log placement was non-random and dependent on areas accessible with log-lifting machinery and availability of nearby logs.

In spring 2013, 9 mega-logs were selected based on size criteria, tight stacking of logs to minimise airspace, bottom logs in contact with the ground and placement in areas without underlying rocky substrate that would prevent trenching necessary for datalogger placement. Adjacent to and ~20 m from the centre of each mega-log HB treatment plot, we established 2-m wide and 10-m long LB treatment plots as described and diagrammed by Cowan *et al.* (2016).

Log moisture and volume calculations

A week before the burn, disks from 2 to 4 logs within each mega-log were chainsaw-cut and removed for measuring moisture content. Disks were immediately sealed in plastic bags and processed for moisture content within one week. Log moisture content as a percentage of dry wood mass was calculated after oven-drying for 48 h at 65°C. Wood moisture ranged from 11.02% to 25.68% with means and standard errors of 17.5 ± 1.87% (Table 1). Most mega-logs were half-cylinders and volume ranged from 7.4 m^3 to 22.1 m^3 (Table 1) (Wright *et al.* 2010).

After removing the O horizon, mineral soil was collected at 0–10 cm depth from the centre of each plot using a 6.35 cm diameter impact coring device. Soil samples were placed in plastic zip-lock bags and stored at 4°C. Soils were weighed, dried at 105°C for 24 h and reweighed to calculate percent gravimetric water content (%MC) in July 2013. Pre-burn %MC values beneath mega-logs are presented in Table 1.

Fig. 1. High intensity burn treatment (HB) applied by the combustion of a parallel stack of large downed logs ('mega-log'): (*a*) pre-burn and (*b*) post-burn photos. Black tarps were removed before combustion. (*c*) Low intensity burn treatments (LB) were established adjacent to and ~20 m from the centre of HB treatment plots in the surrounding broadcast burned area. Photos: Ariel D. Cowan.

Table 1. Mega-log size, underlying forest floor depth, wood and soil moisture content at the time of burning, and maximum temperature and duration at the soil surface during combustion

Site (mega-log)	Length (m)	Width (m)	Height (m)	Mega-log shape	Volume[A] (m^3)	Forest floor depth[B] (cm)	Wood moisture[C] (%)	Soil moisture[D] (%)	Maximum temperature soil surface (°C)	Duration above 60°C soil surface (h)
43–4	10.1	1.3	0.9	rectangular	11.8	0.5	16.05	16.7	436.3	13.14
43–5	9.2	1.4	1.0	half-cylinder	10.1	3.0	11.41	15.3	423.9	7.97
43–7	9.4	1.7	1.0	half-cylinder	12.6	2.0	11.61	13.9	618.0	7.34
43–9	9.0	1.6	0.8	half-cylinder	9.1	3.0	24.19	15.3	659.7	11.72
44–1	9.3	2.0	0.9	rectangular	16.7	4.0	21.14	18.0	986.7	6.83
44–5	10.2	2.3	1.2	half-cylinder	22.1	3.0	20.44	18.5	1058.4	3.60
44–7	10.4	1.5	1.3	half-cylinder	15.9	2.0	25.68	17.0	582.5	6.63
44–8	9.2	1.5	0.9	half-cylinder	9.7	3.0	11.02	14.7	899.4	4.87
44–10	9.6	1.4	0.7	half-cylinder	7.4	0.5	16.19	22.1	1167.6	5.95

[A]Volume for half-cylinder = ($\pi \times w \times l \times h$)/4, and for rectangle = ($l \times w \times h$) based on formulae by Wright *et al.* (2010).
[B]Forest floor measurements taken next to mega-log at length centre.
[C]Wood moisture is an average of 2–4 disks.
[D]Pre-burn soil moisture content 0–10 cm depth.

Treatment preparation and soil heating measurements

At the centre of each mega-log, ≈1.5 m wide sections were chainsaw-cut and rolled away to access the pile centre for installing the soil thermocouples. A week before the burn, thermocouple probes were installed to record soil temperatures below the mega-log centre at 0-, 5-, 10- and 30-cm depths. Type K thermocouples (24-gauge, ceramic braid insulation; Omega Engineering, Inc., Stamford, Connecticut, USA) were inserted at 0 cm in HB and LB treatments, and 24-gauge, glass braid insulation with 0.3 cm diameter, 15 cm long stainless steel tips were used at all other soil depths. Thermocouples were attached by PVC-insulated, type K extension wire to Omega OMPL-TC dataloggers, which were placed in waterproof cases containing desiccant packs, wrapped in foil insulation and buried 5 m beyond plot edge. Soil was replaced and log sections were rolled back into place. Datalogger set-up was duplicated at the centre of the LB plots and thermocouples were placed at 0- and 5-cm depths. Dataloggers were set to record every 90 s.

On May 14, 2013, mega-logs and the surrounding forest floor, including the LB plots, were ignited with drip torches. Air temperatures ranged from 12°C to 17°C at the ignition times. Weather conditions were comprised of clear skies, light W to NW winds (wind speed at 6 m was 5–16 kph, 12–19°C (dry bulb), and 25–40% relative humidity). Ten- and 100-h fuels were the primary carriers of the fire. Flame lengths were 0.6–1.8 m with a 12–18 m flame zone depth. Soil temperatures were recorded for a total of 269 h, beginning 4 days before the burn and concluding 7 days after.

Statistical analyses

Comparisons were made using analysis of variance (R version 2.8.0, http://www.r-project.org/, accessed 20 August 2016). When appropriate, a natural log-transformation was applied to satisfy analytical assumptions and for better fit of the models. Where more than one level of treatment was tested (i.e. three depths) and ANOVA was significant ($\alpha \leq 0.05$), regression was used to detect differences between the levels. Means and standard error values were calculated.

Results

Soil heating during mega-log and broadcast burning

Based on visual inspection, consumption of the mega-logs was estimated to have been 98–100% complete at all plots (Fig. 1); ~90% of the contiguous fuels were removed from the LB plots which appear similar to the area surrounding the HB plot (Fig. 1). Maximum temperatures on the soil surface ranged from 424°C to 1168°C in the HB treatment (Table 1) and from 42°C to 360°C in the LB treatment (Table 2). Mean maximum temperature at the soil surface was higher in the HB treatment (759 ± 9°C) than in the LB treatment (107 ± 43°C) ($F = 78.38$, $P < 0.0001$). Maximum temperatures decreased exponentially within the shallow soil profile and at 5-cm soil depth, where the mean for the HB treatment (123 ± 23°C) was higher than that for the mean for the LB treatment (32 ± 4°C) ($F = 14.20$, $P = 0.009$) (Fig. 2).

In the HB treatment, the mean maximum temperature in the HB treatment was higher at 0 cm compared with all other depths ($F = 45.42$, $P < 0.0001$). The mean maximum temperatures at

Table 2. Maximum temperature and duration at soil surface and at 5-cm depth during broadcast burning of the low intensity burn treatment sites
NA: data recorder failed

Site (mega-log)	Maximum temperature soil surface (°C)	Duration above 60°C soil surface (h)	Maximum temperature 5 cm depth (°C)	Duration above 60°C 5 cm depth (h)
43–4	62.9	0.02	23.1	0
43–5	NA	NA	18.1	0
43–7	76.9	4.68	56.5	0
43–9	58.3	0	33.6	0
44–1	52.4	0	31.6	0
44–5	NA	NA	25.2	0
44–7	41.8	0	33.8	0
44–8	95.2	0.87	34.6	0
44–10	360.3	2.79	99.8	1.37

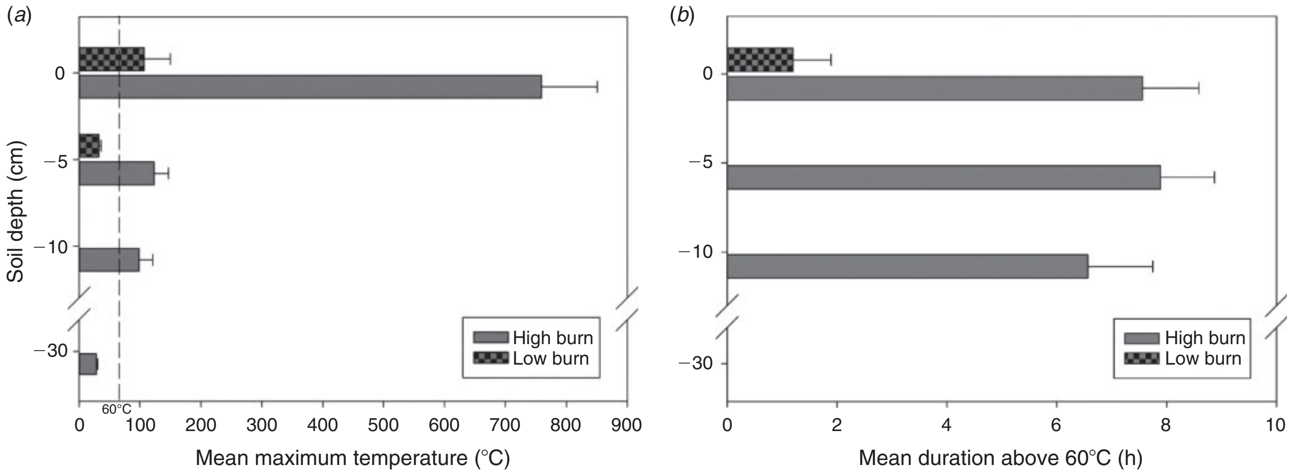

Fig. 2. (*a*) Mean maximum temperature (°C) and (*b*) mean duration (h) of heat above 60°C recorded under low intensity (Low burn) and high intensity (High burn) soil burn treatments at 0-, 5-, 10-, and 30-cm depths from micro-site centre ($n = 9$ sites per treatment). Approximate lethal temperature threshold for fungi is 60°C (Neary *et al.* 1999). Temperatures of 10-cm and 30-cm depths in Low burn treatment were not recorded. Error bars denote ± 1 standard error. Part (*a*) reprinted from *Forest Ecology and Management*, 378, AD Cowan, JE Smith, SA Fitzgerald. Recovering lost ground: effects of soil burn intensity on nutrients and ectomycorrhiza communities of ponderosa pine seedlings, pp. 160–172, copyright 2016, with permission from Elsevier.

5 cm (123 ± 23°C) and 10 cm (98 ± 22°C) were similar, as were their ranges (78–283°C) and (68–277°C), exceeding a lethal temperature (>60°C) on all HB plots. In contrast, the mean maximum temperature at 30 cm was 28 ± 2°C, ranging from 21°C to 43°C (Fig. 2).

The mega-logs generated a longer heat pulse than the broadcast burns. On the soil surface, the mean duration with temperatures above 60°C ranged from 3.60 h to 13.14 h in the HB treatment compared with 0 h to 4.68 h in the LB treatment (Tables 1, 2, Fig. 2), and the mean duration above 60°C was greater in the HB treatment (7.61 ± 1.02 h) than in the LB treatment (1.19 ± 0.70 h) ($F = 19.37$, $P = 0.004$). No temperatures above 60°C were recorded for the 30 cm depth in the HB treatment (Fig. 2). Soils in the LB treatment at 5 cm were mostly well below lethal temperatures with the exception of one at 57°C that remained above 55°C for 2.6 h and another at 100°C that remained above 60°C for 1.4 h (Table 2). Comparing only the 0-cm, 5-cm and 10-cm depths in the HB treatment, the mean duration above 60°C at 10 cm (6.56 ± 1.18 h) was shorter than at 0-cm and 5-cm depths (7.56 ± 1.02 h and 7.89 ± 0.98 h) ($F = 4.29$, $P = 0.03$).

Discussion

Our intent in this study was to quantify the soil heat pulse of extreme soil burn conditions such as occurs with large log combustion during wildfire in old-growth mixed conifer forests dominated by ponderosa pine and Douglas-fir (*Pseudotsuga menziesii*; Hebel *et al.* 2009). As described by Hebel *et al.* (2009), the complete combustion of large decaying logs leaves areas of severely burned reddened soil commonly found as long linear strips ≤1 m and ≥3 m long. As 1 m diameter logs were not available for our study, we stacked logs in parallel to mimic volume and surface ratio of old-growth logs. Although the size, quantity, arrangement and quality of fuel in contact with the forest floor all influence the depth and degree of soil burn intensity (Busse *et al.* 2013), complete combustion of our mega-logs created reddened soil conditions similar to those described by Hebel *et al.* (2009) and temperatures recorded in our study indicated extreme soil heating.

Declines of temperature have been recorded from the centre to the edge in the burning of slash piles. Temperatures of 300°C were recorded beneath the centre and 175°C beneath the pile edge in the study by Jiménez Esquilín *et al.* (2007) and Busse *et al.* (2013) noted a decline of mean maximum soil temperature at 5-cm depth from 428°C to 48°C near the pile centre to the pile edge. In our study, temperatures at the soil surface beneath the mega-logs all exceeded 400°C and may have been more uniformly distributed from the centre to the edge due to the more continuous contact of large wood with the ground. In a comparison of burning forest slash and wood piles, extreme or extensive soil heating occurred only when piles were dominated by large wood occupying a high percentage of the ground surface (Busse *et al.* 2013).

We recorded temperatures above 60°C at a depth of 10 cm in the soil below all the mega-logs, and heat duration above 60°C for 7 of the 9 mega-logs at this depth was 5.5–8.5 h (Table 1). These findings sharply contrast with those of Busse *et al.* (2013) who recorded 6 out of 7 wood piles producing temperatures above 200°C for 20 h or more at a soil depth of 10 cm in loamy soils. Only one of our mega-logs produced temperatures above 200°C for 3.75 h at the 10-cm soil depth. Low conductivities and low heat capacities by volume compared with denser mineral soils are characteristic of pumice soils (DeVries 1963; Cochran 1965). Burns were conducted in spring when underlying soils were likely less conducive to heat penetration than late season dry soils (Busse *et al.* 2010), potentially resulting in less severe soil heating effects. The mean temperature at 10 cm was similar to more moderate temperatures recorded in loamy soils beneath slash piles in studies by Jiménez Esquilín *et al.* (2007), who recorded temperatures above 60°C (to ~100)°C for ~8 h at soil depths of 5–15 cm, and Busse *et al.* (2013), who recorded temperatures below 100°C at the 10 cm depth in the soil profile. The insulating effect of forest soils has been shown by precipitous declines in temperature of 500°C and 800°C at the 0-A horizon interface to 75°C and 132°C at 2 cm Ah in unaltered forest soil blocks burned under laboratory conditions (Aznar *et al.* 2013; Badía-Villas *et al.* 2014).

Temperatures lethal to soil organisms occurred at a depth of less than 30 cm in the HB treatment. In contrast to the lethal mean maximum temperatures recorded at 30 cm beneath wood piles (75°C) in the study by Busse *et al.* (2013), temperatures beneath mega-logs at 30 cm in our study averaged 28°C. Intermediate temperatures (150°C) as found in our 5- and 10-cm depths (Fig. 2), as well as high temperatures (500°C), have been shown to reduce microbiological properties for up to nine months in upper soil profiles (0–15 cm) suggesting long-term effects of soil burning (Badía and Martí 2003*a*).

Our maximum temperatures on the soil surface beneath masticated fuels, ranging from 42°C to 360°C (Table 2), are consistent with expected temperatures for prescribed burning of litter and duff in conifer forests, which typically range from 200°C to 300°C (Neary *et al.* 1999). Duration for temperatures above 60°C ranged between 0 h and nearly 5 h (Table 2). At 5 cm, recordings were mostly well below lethal temperatures with two exceptions (Table 2) where the presence of buried woody material likely contributed to higher temperatures.

Extreme soil burning from large concentrations of downed wood is limited to the size and scope of the amount of large wood on the ground. High severity burned soils from pile burning can create persistent canopy openings (Rhoades and Fornwalt 2015), but if limited in scale may not require rehabilitation treatments (Rhoades *et al.* 2015). However, large amounts of downed wood from other disturbances (e.g. wind, bark beetles) can potentially set up a site for more severe soil heating in a subsequent fire. Ecosystem response to extreme fire severity will depend on the size and spatial distribution of areas of severely degraded soil structure (Shakesby *et al.* 2000; Busse *et al.* 2014). Our burning of mega-logs provided a novel approach to studying the effects of burning coarse woody debris on soils in high severity fires. Continued monitoring of the effects of temperature-related changes to soils (e.g. soil fungi and nutrients, seedling growth) will provide insight for achieving ecological objectives and appropriate management responses under increasing forest fire risk.

Acknowledgements

We thank Matt Busse and Carol Shestak (Pacific Southwest Research Station) for loaning temperature sensors and data loggers, B and S Logging for mega-log construction, Loretta Ellenberg, Dan Mikowski, Brett Morrissette, and Mike Vernon for fire line construction, Alex Enna, Deana Wall and Bend-Redmond Hotshot crews for prescribed burning, Greg Brenner (Pacific Analytics) for data analyses, the Page-Dumroese Laboratory (Rocky Mountain Research Station) for soil analysis, and David Badía, Jeff Hatten, Ari Jumpponen, Jim Trappe, and an anonymous reviewer for suggestions to improve the original manuscript. Mention of trade or company names does not constitute an endorsement by the US Department of Agriculture.

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