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Soil heating during burning of forest slash piles and wood piles

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Abstract. Pile burning of conifer slash is a common fuel reduction practice in forests of the western United States that has a direct, yet poorly quantified effect on soil heating. To address this knowledge gap, we measured the heat pulse beneath hand-built piles ranging widely in fuel composition and pile size in sandy-textured soils of the Lake Tahoe Basin. The soil heat pulse depended primarily on fuel composition, not on pile size. Burn piles dominated by large wood produced extreme temperatures in soil profile, with lethal heating lasting up to 3 days. In contrast, the heat pulse was moderate beneath piles containing a mixture of fuel sizes. Considerable spatial variability was noted, as soil temperatures were generally greatest near pile centres and decline sharply toward the pile edges. Also, saturating pile burns with water 8 h after ignition ('mopping up') effectively quenched the soil heat pulse while allowing near-complete fuel consumption. The findings suggest that burning of hand piles will not result in extreme or extensive soil heating except for uncommon conditions when piles are dominated by large wood and occupy a high percentage of the ground surface.

Additional keywords: forest restoration, fuel reduction, pile burning, prescribed fire, soil temperature.

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Introduction

Recent efforts to restore the structure and composition of many western USA forests have resulted in an increase in the use of pile burning as a fuel reduction tool. Post-thinning slash piles are typically small (2–5-m diameter), often hand built and are more numerous per unit area compared with traditional tractor piling following intensive harvesting. Burning of small piles gives managers a cost-effective alternative for reducing fuel loads when prescribed underburning or biomass harvesting are restricted, such as at the wildland–urban interface or following pre-commercial thinning in areas without local bioenergy facilities. The ecological effects of pile burning are not well understood, however. Whether pile burning results in undesirable changes in soil properties, nutrient runoff or plant composition is unclear.

Soil heating is a particular concern given anticipated changes to soil nutrient content and availability, microbial composition and function, soil C content, soil mineralogy and water repellency and infiltration following severe burning (Neary *et al.* 2005). At lower temperatures (100–125°C), burning can deplete the seed bank (Beadle 1940) and may result in increases in invasive plant cover (Korb *et al.* 2004; Wolfson *et al.* 2005). Results from muffle furnace studies typically show increases in soil nitrogen and phosphorus availability and related decreases in microbial biomass and soil aggregate stability at temperatures between 200 and 400°C (Chambers and Attiwell 1994; Badía and Martí 2003; Guerrero *et al.* 2005; Glass *et al.* 2008). Total C and N remain fairly constant until temperatures exceed 400–500°C (Badía and Martí 2003; Guerrero *et al.* 2005), whereas changes in soil mineralogy and other soil physical properties have been noted at temperatures above 500°C (Chambers and Attiwell 1994).

Along with maximum temperature thresholds, soil heat duration and water content also influence how soil properties respond to burning. For example, Glass *et al.* (2008) found that increasing the heat duration at 300°C from 2 to 15 min resulted in a six-fold increase in soil inorganic N concentration. Similarly, Galang *et al.* (2010) found that heating a soil to 200°C for 30 min produced an equivalent release of labile P as heating to 500°C for 2.5 min. Soil moisture plays a key role in heating dynamics, particularly when burning natural fuels or scattered slash. Heat penetration is substantially lower in moist soil than in dry soil due to the additional energy required to heat water (Busse *et al.* 2010). Because of this, many studies suggest that burning when soils are moist is the most successful means to limit detrimental soil heating (Frandsen and Ryan 1986; Hartford and Frandsen 1992), despite the well recognised potential for biological damage that can result from moist heat (Choromanska and DeLuca 2002).

The response of soils to temperature extremes is fairly well established in controlled experiments. However, few real-time measurements of soil heating during pile burning exist. In an early study of soil heating, Beadle (1940) found temperatures reached 225°C at a soil depth of 7.5 cm and were below 100°C at 15-cm soil depth beneath a wood and slash pile. Similarly, Massman and Frank (2004) found temperatures above 255°C to a depth of 10 cm beneath a large slash pile. In comparison, temperatures well below 200°C were measured at soil depths ranging from 3 to 6 cm during burning of small–moderate sized piles (Meyer 2009).

Our study objective was to determine the soil heat pulse during operational burning of hand piles encompassing a variety of sizes and fuel compositions. We hypothesised that efforts to limit soil heating would be best met by burning small (but more numerous) piles compared with larger (but fewer) piles due to their relative differences in heat generation and heat transfer within soil. The study was conducted in the Lake Tahoe Basin (LTB), where forest thinning, recent tree mortality and proximity to urban development have resulted in increased use of and scheduled planning for pile burning to reduce fuel loadings. We measured the extent of ground coverage by piles and determined the range of pile sizes and fuel compositions in the LTB. Then the soil heat pulse was quantified beneath piles that represented the observed range of sizes and fuel compositions.

Methods

Site description

The study was conducted in the lower–mid-elevation pine and mixed-conifer forests within the LTB (1900–2350 m), which straddles the state borders of California and Nevada in the Sierra Nevada Mountains (38.8–39.2°N, 119.9–120.2°W). The climate is Mediterranean with cold winters and warm, dry summers with infrequent thunderstorms. Annual precipitation at lake level averages 780 mm on the western shore (Tahoe City) and 460 mm on the eastern shore at Glenbrook (www.wrcc.dri.edu, accessed 15 December 2012), falling primarily as snow between November and April. Average maximum air temperature at lake level ranges from 26°C in July to 4°C in January. Average minimum temperatures range from 7°C in July to −7°C in January.

Soils in the northern end of the LTB are fine-loamy, isotic, frigid Ultic Palexeralfs derived from colluvial andesite (USDA Natural Resources Conservation Service 2007). The remaining soils in the LTB are primarily derived from granodiorite and are either mixed, frigid Dystric Xerosamments or sandy-skeletal, mixed, frigid Humic Dystroxerepts. All soils are coarse textured, ranging from very cobbly sandy loams (volcanic) to gravelly loamy coarse sands (granitics), and are fairly infertile with organic matter content in the surface 10-cm depth ranging from 7–11% (volcanic) to 2–6% (granitics).

Changes in forest composition and structure have been considerable in the LTB pine and mixed-conifer forests since the 1850s. Old-growth harvesting, grazing, fire exclusion and suppression, and urban development have resulted in forests with higher stand densities and a greater presence of shade-tolerant, fire-sensitive tree species compared with pre-settlement forests (Taylor 2004). Tree species in the study area now include Jeffrey pine (*Pinus jeffreyi*), white fir (*Abies concolor*), red fir (*A. magnifica*), lodgepole pine (*P. contorta*) and incense cedar (*Calocedrus decerrens*). A drought-induced outbreak of fir engraver beetle (*Scolytus ventralis*) caused extensive tree mortality between 1988 and 1992 (Ferrell *et al.* 1994), leaving many of the forest stands with high levels of dead standing and down wood. Since then, restoration efforts including the use of pile burning to reduce fuel loading have been a Basin-wide priority.

Inventory sites and analyses

We inventoried pile burn units on federal, state and private land throughout the LTB in 2009 to determine existing conditions of pile density (number ha^{-1}), pile size and ground coverage occupied by piles. Only units that had been treated before June 2009 but not yet burned were included in the inventory. Forest Service units, hand piled between 2004 and 2008, were identified using a corporate database of silviculture activity (Forest Service Activity Tracking System, www.fs.usda.gov/main/r5/landmanagement/gis, accessed 7 March 2013) interfaced with GIS software. Pile burn units on California and Nevada State Park lands were identified during site visits with agency foresters (Dan Shaw, California State Parks; Roland Shaw, Nevada State Parks). The inventory was limited to conifer units only; slash piles dominated by woody shrubs were not included. Site locations are shown in Fig. 1.

A systematic grid of 0.1-ha plots was installed at each pile burn unit, and mean pile density, size and dominant fuel type were determined. The plot size was optimised to provide 10–20 piles per plot. Pile length, width and height (slope corrected) were measured to the nearest 0.1 m on all piles. Pile volume was estimated from the dimensional measurements assuming a half ellipsoid shape (volume = [length × width × height × π] ÷ 6). Ground coverage occupied by piles was estimated as the sum of the elliptical area at ground level of all piles within each 0.1-ha plot.

Fuel composition was assessed using a simple (visual) classification scheme that was developed solely for this study. Three pile types were identified: (1) wood piles, comprised primarily of large material >22.5-cm diameter; (2) slash piles, containing a mix of small diameter (<7.5 cm) and medium diameter (7.5–22.5 cm) woody fuel with occasional bolts of large wood (usually <10% of pile volume); (3) small-slash piles, comprised of small diameter woody fuel and slash. Wood piles were found in areas where recent tree mortality was high, whereas slash piles were found in recently thinned stands. Examples of each pile type are shown in Fig. 2.

The cross-sectional area at stump height (analogous to basal area) was measured on all cut trees within a plot to estimate the thinning intensity. These data were used in regression analysis (SAS 9.1) to develop a predictive equation of ground coverage occupied by piles as a function of thinning intensity.

Soil heating experiment

We selected 29 piles out of the 781 inventory piles for intensive soil heating measurements. Pile selection was based on providing (1) representatives of each of the three pile types, (2) a range of pile sizes within each pile type and (3) piles that were scheduled for burning in 2009 or 2010.

Each pile was measured for volume (length, width, height) before burning and deconstructed to determine total mass and to

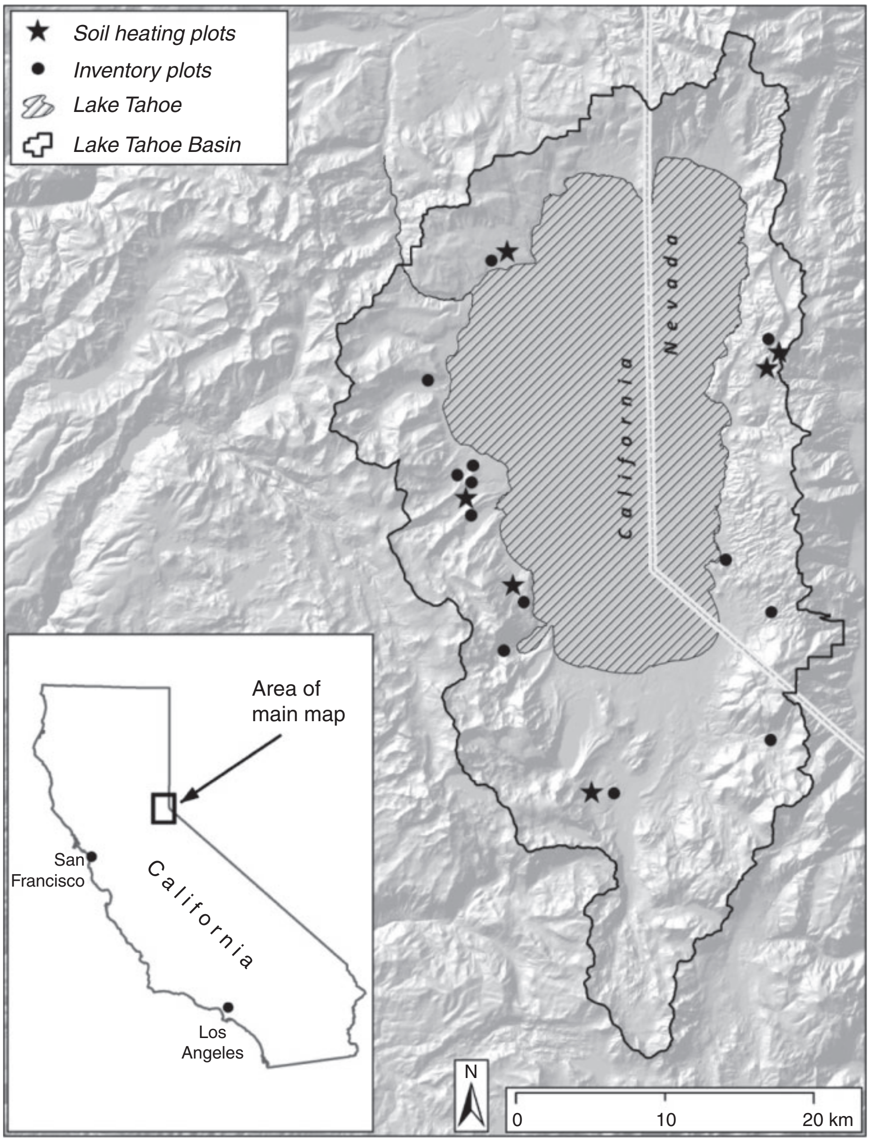

Fig. 1. Location of pile burn inventory plots and soil heating plots within the Lake Tahoe Basin.

access the pile centre for installing soil thermocouples. The field-moist mass of dead foliage and wood was weighed by diameter class to the nearest 20 g using a portable hanging scale (Intercomp, Medina, MN, USA). Fuel moisture content of two samples per diameter class from each site was determined by oven drying (60°C for 95 h) in order to convert pile mass to a dry-weight basis. Total mass was not measured on four of the 20 piles before burning due to time constraints. Instead, their mass was estimated by multiplying their volume times the pile density measured on nearby piles of similar fuel composition.

Once each pile was deconstructed, a narrow soil trench (~20 cm wide × 30 cm deep) was dug from the pile centre to a minimum of 4 m beyond the pile edge for placement of thermocouples and dataloggers. Thermocouples were inserted horizontally in undisturbed soil below the pile centre at 0-, 5-, 10- and 30-cm depths. Type K thermocouples (24-gauge wire, ceramic braid insulation; Omega Engineering, Inc., Stamford, Connecticut, USA) were placed on the mineral soil surface beneath the litter and duff layer. Type K thermocouples (24-gauge wire, glass braid insulation) with 0.3-cm diameter × 15 cm long stainless steel tips were used at all other soil depths. Type K thermocouples (30-gauge wire) were used at the 'Old Mill' site for the small-slash piles. Each thermocouple was attached by a PVC-insulated, type K extension wire to an Omega OMPL-TC datalogger, which was placed in a water proof case (OtterBox, Fort Collins, Colorado, USA) and buried at the far end of the soil trench. Dataloggers were set to record every 3 min beneath small piles and every 5 min beneath large piles. The depth of the litter and duff layer above the surface thermocouples was measured before replacing the soil in each trench and reconstructing the piles.

To estimate the spatial variability in soil heating beneath piles, we placed a series of thermocouples at 5- and 10-cm soil depths below six piles at (1) the pile centre, (2) one to four

Fig. 2. Examples of wood piles, a slash pile, and a small-slash pile (clockwise from upper left). The wood piles in this figure covered 25–34% of the ground area and were the consequence of a complete conversion from a standing-dead lodgepole pine stand.

midpoints between the pile centre and the pile edge depending on the pile size and equipment availability, (3) the pile edge and (4) 1 m outside the pile edge. Three wood piles and three slash piles were randomly selected for these tests.

Twenty-seven piles were lit using drip torches between 29 October and 8 December 2009 during the narrow burning window that followed the initial autumn precipitation and preceded the winter snow pack. Two additional piles (Angora) were lit on 15 October 2010. Once ignited, the piles were allowed to burn undisturbed with the exception that any partially consumed large wood near the pile edge was usually pushed towards the pile centre by field crews to facilitate fuel consumption. Nine piles were 'mopped-up' with water within 8–10 h of ignition to avoid possible fire escape and, as a result, were not included in the main experiment. This left 20 'undisturbed' piles (i.e. no mop-up intervention), including a minimum of six of each pile type.

Soil moisture content at each pile burn site was measured at 5-, 10- and 30-cm soil depths using ECH2O soil moisture sensors (Decagon Devices, Inc., Pullman, WA, USA) attached to HOBO Micro Station data loggers (Onset Computer Corp., Pocasset, MA, USA). The moisture probes were not placed beneath the piles, however, because of potential for heat damage to the sensors. Instead they were placed adjacent to the piles in order to provide a general site assessment of soil moisture content.

Statistical analyses

The effect of pile type on maximum soil temperature and heat duration was tested by analysis of covariance using Proc Mixed procedures (SAS 9.1). Pile diameter was used as the covariate because (1) it showed a strong linear relationship with the other measures of pile size (volume, mass) and (2) it is easily measured and interpreted by field practitioners. Separate ANCOVA analyses were run for each soil depth. Contrast comparisons were used to determine significant differences between pile types, pile diameters and their interactions. The effect of pile diameter on maximum temperature or heat duration was considered significant if the slope (change in maximum temperature or heat duration with increasing pile diameter) was significantly greater than zero. Neither soil moisture content nor forest floor depth were included in the model because of a limited range of soil moisture values and missing forest floor data from two piles. Instead, studentised residuals (SAS 9.1) were plotted for these

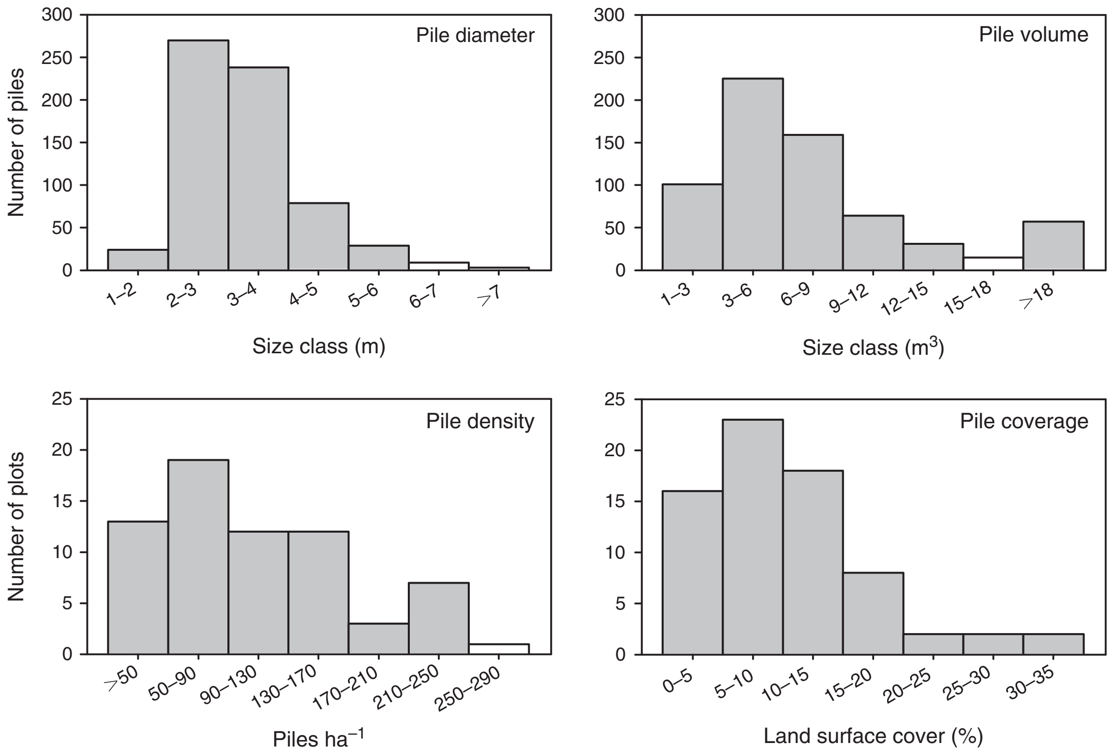

Fig. 3. Hand pile conditions at 71 inventory plots within the Lake Tahoe Basin.

two parameters to assess visually if either variable helped explain the data after accounting for the intercept and slope associated with pile diameter. Statistical significance was considered at $\alpha = 0.05$.

Results

Inventory plots

Pile conditions varied widely throughout the LTB. Among 781 piles, there was a six-fold range in pile diameter (1.5–9.2 m) and a 100-fold range in pile volume (0.6–55.7 m^3). Median values were 3.1 m and 5.9 m^3 for pile diameter and volume (Fig. 3). Fuel composition was primarily wood piles ($n = 249$) and slash piles ($n = 467$) piles. Small-slash piles ($n = 65$) were mainly located at one site (Old Mill), which received a partial thinning of small understorey trees.

Ground coverage occupied by piles ranged from 1 to 34% of the land surface area, with a median cover of 8.0% ($n = 71$ inventory plots). Coverage was exceedingly high at one site (High Meadows, see Fig. 2 – wood piles) where a fully stocked stand of beetle-killed lodgepole pine was converted on site to wood piles. Piles occupied between 25 and 34% of the land surface at High Meadows, which presumably represents the upper limit of coverage for a pile-and-burn operation. The majority of inventory plots (56 out of 71) had ground coverage <15%. Plots with >15% ground coverage were dominated by wood piles ($n = 6$) or slash piles ($n = 9$).

A significant relationship between thinning intensity and ground coverage occupied by piles was found ($P < 0.0001$; percentage ground coverage $= 3.75 + 0.223 \times$ stump area ($m^2\ ha^{-1}$)). However, using stump area as a sole independent variable accounted for only 31% of the variation in ground cover on the inventory plots.

Soil heating during pile burning

The instrumented piles included a 5–10-fold range in pre-burn mass and size (Table 1). Burning in 2009 and 2010 began after the initial autumn storms and before the onset of any large winter storms. Air temperatures ranged from −2 to 8°C at the times of ignition, relative humidity ranged from 40–70% (http://laketahoe.jpl.nasa.gov, accessed 7 March 2013) and a 1–2-cm layer of fresh snow was common at most sites. Soil moisture content was low during burning, ranging across sites from 0.03 to 0.10 $m^3\ m^{-3}$ at 5-cm depth and from 0.02 to 0.12 $m^3\ m^{-3}$ at 10-cm depth (Table 1). Pile consumption was 90–95% complete at all sites based on visual inspection. The only exception was at Bliss where ~85% of pile #2 was consumed.

Large differences in maximum temperature and heat duration were measured between pile types, as wood piles generated a substantially greater soil heat pulse than did either slash or small-slash piles (examples shown in Fig. 4). A standard decline in heat penetration with increasing soil depth was also observed for each pile type.

Maximum temperatures on the soil surface ranged from 82 to 715°C (Fig. 5) with means and standard deviations of 428 ± 54°C for wood piles, 344 ± 64°C for slash piles and 406 ± 66°C for small-slash piles. No significant differences were detected due to pile type ($P = 0.068$) or pile diameter ($P = 0.182$) at the soil surface. However, the heat duration above

Table 1. Pile type, mass, size, underlying forest floor depth and soil moisture content (5-cm depth) at the time of burning for the instrumented piles
Pile type: W, wood; S, slash; SS, small slash

Site (pile number)	Pile type	Mass (Mg)	Diameter (m)	Volume (m^3)	Forest floor depth (cm)	Soil moisture ($cm^3\ cm^{-3}$)
Angora (1)	W	0.91	3.5	12.7	2.0	0.09
Lower Spooner (1)	W	0.24	2.3	2.9	6.0	0.05
Lower Spooner (2)	W	1.38	3.8	16.3	5.0	0.05
Lower Spooner (3)	W	2.53	5.8	30.1	–	0.05
Upper Spooner (1)	W	1.82	6.2	29.7	–	0.03
Upper Spooner (2)	W	1.21	3.7	12.3	13.0	0.03
Upper Spooner (3)	W	0.28	2.8	4.2	2.0	0.03
Angora (2)	S	0.59	3.3	8.5	5.0	0.09
Bliss (1)	S	0.60	3.4	8.8	5.5	0.06
Bliss (2)	S	2.29	5.9	33.7	11.5	0.06
Bliss (3)	S	1.48	4.7	22.3	6.0	0.06
Sugar Pine (1)	S	3.64	6.1	54.6	5.5	0.10
Sugar Pine (2)	S	2.14	6.6	31.4	4.0	0.10
Sugar Pine (3)	S	2.22	5.9	32.8	10.0	0.10
Old Mill (1)	SS	0.21	2.6	5.2	8.5	0.07
Old Mill (2)	SS	0.18	2.4	4.4	7.5	0.07
Old Mill (3)	SS	0.48	2.5	6.2	13.5	0.07
Old Mill (4)	SS	1.90	4.5	23.9	10.0	0.07
Old Mill (5)	SS	0.41	2.5	5.3	10.0	0.07
Old Mill (6)	SS	0.43	2.4	5.6	7.5	0.07

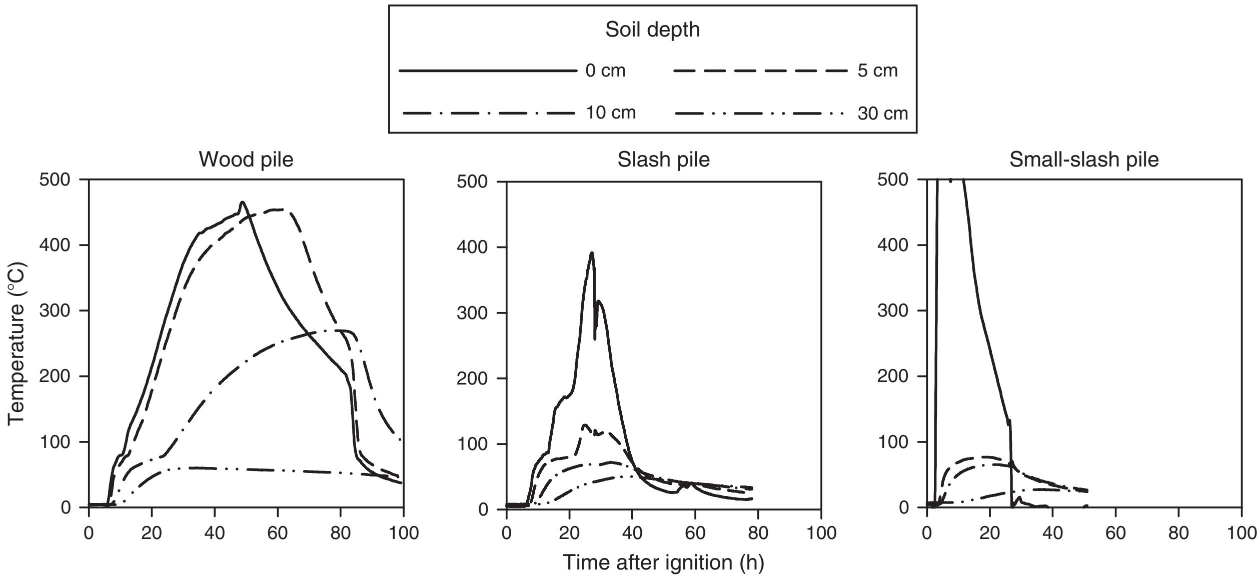

Fig. 4. Examples of soil heating profiles during burning of different pile types. The three piles were among the largest within each pile type (wood pile = 2.5 Mg; slash pile = 2.2 Mg; small-slash pile = 1.9 Mg).

200°C was ~2.5 times greater on the soil surface beneath wood piles than beneath either slash or small-slash piles (Fig. 6). This difference was significant ($P = 0.009$), whereas the effect of pile diameter on heat duration was not significant on the soil surface beneath any of the pile types ($P = 0.848$).

Differences in heating between pile types were sizeable within the soil profile (Figs 5, 6). At 5-cm soil depth, the mean maximum temperatures for wood piles was 314 ± 44°C compared with 138 ± 28°C for slash piles and 137 ± 24°C for small-slash piles. At 10-cm soil depth, the mean maximum temperatures for wood piles was 225 ± 36°C compared with 86 ± 11°C for slash piles and 75 ± 8°C for small slash piles. Maximum temperatures for wood piles were significantly greater than for the other two piles types at soil depths of 5 ($P < 0.001$), 10 ($P < 0.001$) and 30 cm ($P = 0.005$). Heat duration above 100 and 200°C was also greater for wood piles than for the other pile types (Fig. 6). Six out of seven wood piles had soil temperatures above 200°C for 20–60 h at 5-cm depth and for 20–40 h at 10-cm depth. Heat duration above 200°C increased significantly with increasing pile diameter at both 5- and 10-cm

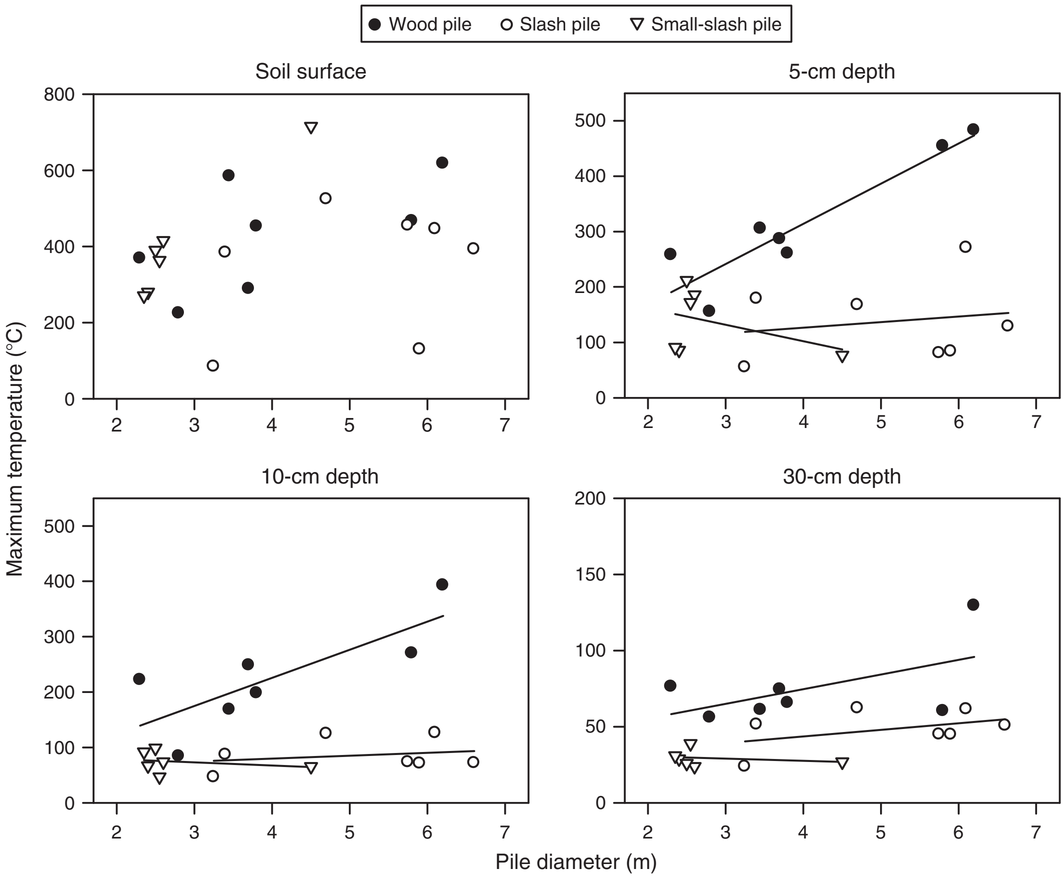

Fig. 5. Maximum soil temperatures recorded during pile burning for a range of pile diameters and pile types.

depths for wood piles only ($P < 0.001$). No significant effect of pile diameter on heat duration above 100°C was found for any of the pile types. Also, studentised residuals showed that soil moisture and forest floor depth were inconsequential in explaining the data variation for maximum temperature or heat duration during burning.

Spatial variation in soil heating was considerable beneath individual burns. In general, the heat pulse was highest at or near the pile centre and declined sharply towards the pile edge (Fig. 7). Mean maximum soil temperature was only 48°C at the pile edge (5-cm depth) for wood piles and 42°C for slash piles. Essentially no heat pulse was registered at ~1 m outside the pile edge at 5- or 10-cm soil depths.

The heat pulse beneath the nine instrumented piles that were 'mopped up' with water ~8 h after ignition was effectively quenched. Soil temperatures at 5- and 10-cm depths remained well below 100°C following ignition, except for a brief period beneath a single wood pile, even though maximum surface temperatures approached 400–500°C (Fig. 8). Fuel consumption was ~90% complete (ocular estimate) before applying water.

Discussion

Our intent in this study was to quantify the magnitude, duration and penetration of the soil heat pulse when burning hand-built piles of various sizes and fuel types. Others have measured the heat pulse beneath a single pile (Massman and Frank 2004; Jiménez Esquilín *et al.* 2007) or multiple piles of uniform size (Meyer 2009) but they have not captured the variety of conditions that can be found during operational burning. The 20 piles monitored in our study ranged in size from 2- to 7-m diameter, in fuel load from 0.2 to 3.6 Mg and in fuel type from thinning slash to large wood, thus representing a wide cross-section of pile conditions. It is also worth noting that the burns were conducted in mid- to late autumn, the preferred season for igniting piles in the LTB, when the underlying soils were at optimal condition (dry) for heat transfer (Busse *et al.* 2010).

Regardless of pile size or fuel composition the soil heat pulse during burning was quenched fairly rapidly with soil depth. The greatest soil heating occurred in the surface 10 cm, whereas fairly benign temperatures were detected at 30-cm depth, where mean maximum values were 40°C for slash piles and 75°C for wood piles. This supports both theory and observation that soil is not a good conductor of heat (Jury *et al.* 1991; Massman and Frank 2004; Busse *et al.* 2010), and that detrimental changes in soil properties when they occur are restricted to surface soil layers. A more unexpected finding was that pile size was not a good predictor of soil heating. Neither maximum temperature nor heat duration varied significantly with slash pile diameter. A positive relationship between soil heating and pile size was

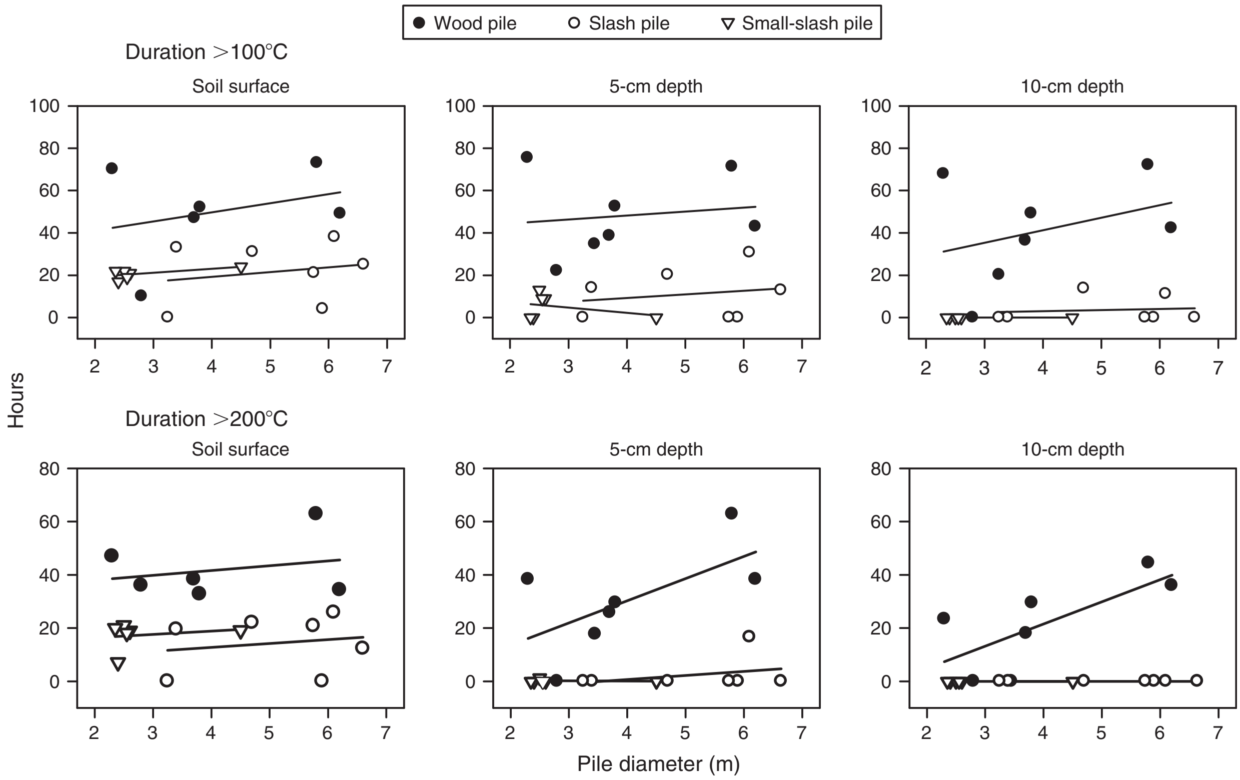

Fig. 6. Heat duration above 100 and 200°C during pile burning for a range of pile sizes and pile types.

found only for wood piles at soil depths of 5 and 10 cm. This finding likely reflects the condition of the fuels at the onset of burning. Most piles contained fuels that were well cured, reasonably dry and free of heat-trapping soil, conditions that limit the amount of smouldering and promote the rapid release of heat to the atmosphere. In this regard, Hungerford *et al.* (1991) suggested that >90% of the heat load during burning rises, leaving a small percentage of the total energy to generate a soil heat pulse. The disconnect between pile size and soil heating may also reflect our experimental protocol of placing most thermocouples beneath the pile centre, which failed to account for possible differences in heat generation near the perimeter of larger piles or identify the exact size of the high temperature zone surrounding the pile centre. Still, our hypothesis that soil heating at the pile centre would increase with slash pile size was not supported, suggesting that a size limit during hand-pile construction is not necessary for avoiding excessive heating. This observation is in contrast to the results of Johnson *et al.* (2011) who found that losses in soil C and N were greater when burning large piles compared with small piles, presumably due to higher soil temperatures beneath large piles.

Unlike pile size the presence of large wood was a primary factor leading to high soil temperatures. Soil heating was severe beneath wood piles, ranging from 155 to 500°C at 5-cm soil depth and from 100 to 400°C at 10-cm depth. At a minimum, these temperatures will destroy the seed bank (Beadle 1940), whereas the upper range is known to volatilise soil C and N, increase soil nutrient availability, reduce microbial biomass and cause detrimental changes to soil physical properties (Chambers and Attiwell 1994; Badía and Martí 2003; Guerrero *et al.* 2005; Glass *et al.* 2008). Thus, substantial changes in soil properties may occur when piles contain a substantial proportion of large wood, analogous to the soil effects noted when large downed wood is consumed by wildfire (Hebel *et al.* 2009). This scenario was particularly relevant for the largest of the wood piles, as they produced higher temperatures at 5- and 10-cm soil depths compared with smaller piles.

The heat duration for wood piles was also impressive. Six out of the seven piles produced temperatures above 200°C for 20 h or more at 10-cm soil depth. What effect this may have on soil is unclear as most controlled-environment studies apply heat for several minutes, not several hours. To our knowledge, only Jiménez Esquilín *et al.* (2007) have examined soil properties following an extended period of heating (4 h), and they found substantial changes in soil microbial composition and structure due to pile burning. In agreement, preliminary results from our post-fire soil sampling indicate sizeable declines in fungal and bacterial biomass beneath wood piles.

In contrast to the wood piles, the slash pile burns resulted in only moderate soil heating. The majority of these piles (11 out of 13) failed to produce a temperature rise above 200°C at 5-cm depth or above 100°C at 10-cm depth in the soil profile. This suggests that burning of hand-built slash piles will not result in major changes in soil physical, chemical or biological functions. Instead, this temperature range will likely lead to ephemeral changes in soil nutrient availability, microbial function and aggregate stability in the upper soil profile (Badía and Martí 2003).

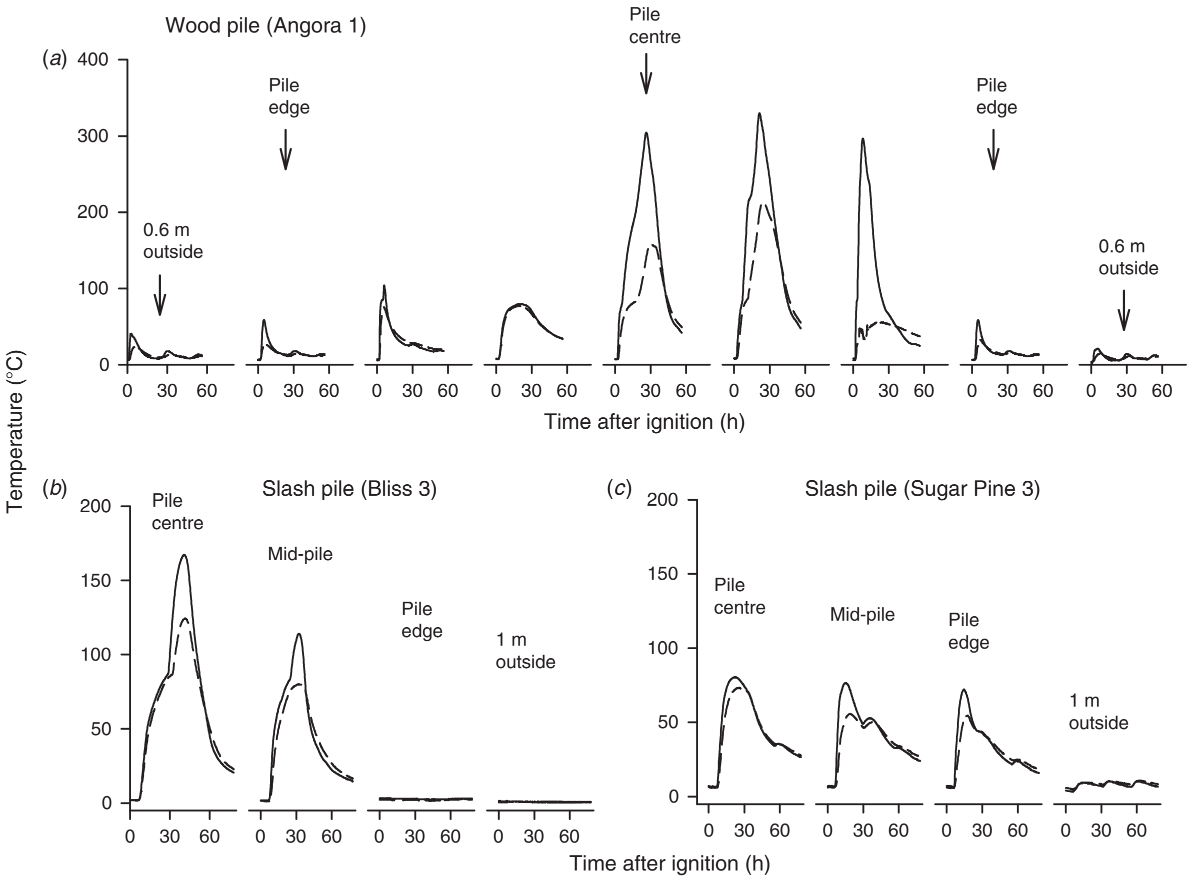

Fig. 7. Spatial variability in soil heating at 5-cm (solid line) and 10-cm (dashed line) depths beneath typical pile burns. Thermocouples were located 0.6 m apart along a transect that spanned the diameter of a wood pile (*a*), and 1 m apart along a transect from the slash pile centre to beyond the pile edge (*b*) and (*c*).

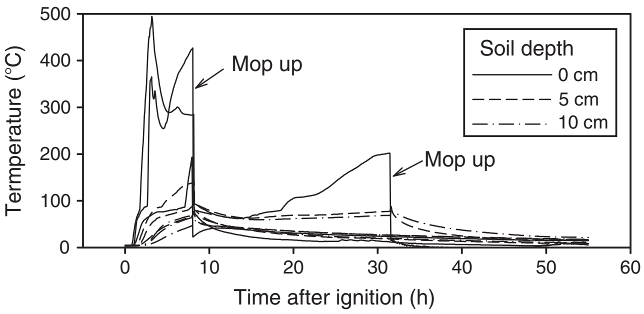

Fig. 8. Limited soil heat pulse during burning of wood piles ($n = 3$) when operationally 'mopped-up' (saturated with water) 8 and 32 h after ignition. Fuel consumption was near complete before the initial application of water.

Previous fire studies have identified the importance of soil moisture content (Frandsen and Ryan 1986; Hartford and Frandsen 1992; Busse *et al.* 2010) and forest floor depth (Knapp *et al.* 2011) in regulating the soil heat pulse during low–moderate severity surface fires. Specifically, moist soils with intact forest floor layers effectively limit heating across a wide range of soil types, textures and clay contents. We questioned whether this principle would hold true for pile burning where concentrated fuel loads may rapidly vaporise soil moisture and consume the forest floor layer. In fact, neither soil moisture content nor forest floor depth accounted for much of the variation in the soil heating data. In the case of soil moisture, however, there was an insufficient range of conditions to adequately test this premise. All soils were considerably drier (0.03–0.10 $cm^3 cm^{-3}$ in the 0–5-cm surface layer) than the recommended moisture threshold of 0.20 $cm^3 cm^{-3}$ for limiting soil heating during surface fires (Busse *et al.* 2010). Thus, the conditions in our study likely represented a worst-case scenario (dry soil), although additional studies are needed to verify whether the inverse relationship between soil moisture and soil heating holds for pile burning.

Whether pile burning results in excessive soil heating depends on the fuel composition, as discussed above, in combination with the extent of ground coverage occupied by piles. Extreme soil temperatures may be of little concern if they occur beneath widely spaced piles within a treatment unit, with sensitive areas such as riparian zones and steep, unstable hillslopes as possible exceptions. Conversely, site and soil damage may occur when temperatures are high and the burn units have a high density of piles. Traditionally, the USDA Forest Service considered detrimental soil damage when ground disturbance exceeded 15% of a treated area (USDA Forest Service 2005). Although the rationale for using this level of disturbance as a 'threshold' was based on professional observation and was never correlated with actual changes in site productivity, it serves as an approximate yardstick for assessing soil disturbance and for recommending mitigation practices. From our inventory, one-fifth of the LTB pile-and-burn plots exceeded 15% ground cover. Another quarter of the plots had 10–15% ground coverage and could run the risk of exceeding this level if retreatment is required.

Two factors are worth considering when evaluating the potential for soil damage in pile burn units that contain a high density of piles per unit area. First, our results suggest that the effective area of soil heating is substantially smaller than the actual ground area occupied by a pile. Spatial variability was tested on a subset of piles by placing thermocouples along a transect from the pile centre to 1 m beyond the pile perimeter. Soil temperature and heat duration declined precipitously from near the pile centre to the pile edge for five of six piles, and the sixth pile (Fig. 7*c*) had low temperatures regardless of location. Although more testing is required to determine a precise estimate of spatial variability, it appears that only half or less of the pile diameter was exceedingly hot beneath the wood piles. This suggests that the 15% cover 'threshold' for soil damage may be a conservative underestimate for pile burning, and that coverage near 30% might be more appropriate. In this regard, only one site in the LTB surpassed 30% pile coverage (High Meadows) as a result of a rare, complete conversion from a standing-dead lodgepole pine stand to wood piles. Second, the length of time required for soils to recover from pile burning needs to be considered, as does the potential need for retreatment as forest stands accrue post-burn fuels. If repeated pile burning occurs before soils adequately recover, then the ground coverage from the two burns is additive. Conversely, if sufficient time is permitted between burning to encourage soil recovery, then the ground coverage is non-additive. Unfortunately, no data are available at present to estimate the soil recovery period following pile burning, although results from our study suggest that slash pile burns may recover fairly rapidly given their modest heat pulse. Recovery following wood pile burning would presumably be long term in cases where organic C and N, and soil physical properties are altered.

Management implications

Fuel reduction efforts are a primary consideration in the LTB, as they are in other western US forests. Thinning of dense forest stands, urban expansion and recent conifer mortality have led to increased use of pile burning to meet LTB fuel reduction needs. Implicit in this restoration effort is the understanding that soil properties and their functions are not detrimentally affected. The findings of our study showed that burning of hand-built piles of a variety of sizes will not reach extreme temperatures (~300–500°C) in the soil profile unless large wood is a major component. Even then the extreme heating will be limited to the surface 10 cm. Thus, we conclude that slash pile burning will have at most a moderate effect on soils, such as altering short-term chemical or biological processes in the surface layer, without causing any major shifts in long-term soil quality.

A few caveats are worth pointing out here. Most important, the moderate temperatures reached beneath the slash pile (60–280°C at a soil depth of 5 cm for slash and small-slash piles) may be sufficient to increase soil nitrate and phosphate concentrations, possibly resulting in unwanted nutrient release to stream waters that flow into Lake Tahoe. Whether this occurs extensively in the landscape is unknown and currently under investigation. Also, the surface soil temperatures during burning were generally above 120°C, which is a sufficient temperature to consume the seed bank. Thus, burning in areas with known invasive plant populations may exacerbate their spread. Finally, the soil heat pulse measured in this study was specific to well cured and reasonably dry fuels and may not reflect soil heating dynamics for other fuel conditions.

Extreme soil temperatures and long heat durations should be expected for piles that contain a high percentage of large wood. Associated changes in core soil properties such as total carbon, nitrogen, physical structure and mineralogy can be expected in this case. Regrettably we did not identify a threshold for wood content that results in extreme soil heating. The wood piles in our study contained >40% large wood on a mass basis, but how much soil heating occurs when piles contain 10–40% large wood was not tested. A conservative approach for managers interested in protecting soil would be to avoid placing many bolts of large wood on piles. However, this may be impractical in situations where tree mortality is great and pile burning is a preferred option for reducing high fuel loads. In this case, a valid precaution would be to ensure that the amount of ground coverage occupied by wood piles is fairly low, as was the circumstance at the LTB sites (both Upper Spooner and Lower Spooner sites had 5.1% ground cover). 'Mopping up' with water is another option that can effectively limit soil heating. Waiting for 8 h after ignition before mopping up resulted in near-complete fuel combustion and only a minor soil heat pulse.

Finally, our study suggests that pile size and the arrangement of piles on the landscape (numerous small piles versus fewer large piles) are inconsequential from a soil heating standpoint unless large wood is a major factor. The soil heat pulse at the pile centre did not increase significantly for slash piles ranging from 2 to 7 m. In addition, the total ground coverage occupied by piles should not differ tremendously for a given fuel load whether all piles are small, medium or large diameter (Busse *et al.*, in press). We estimate that 2-m-diameter piles would occupy 10% of the ground whereas 7-m-diameter piles would occupy 8% of the ground, based on the median fuel volume measured at the inventory sites (750 m^3 ha^{-1}). Thus, decisions regarding the optimal size and number of hand-built slash piles per treatment unit can be made based on factors such as cost effectiveness and safety, with perhaps less attention given to concerns for soil heating.

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