Effects of Pile Burning in the LTB on Soil and Water Quality

SNPLMA 12576 Final Report

Principal Investigators

Ken Hubbert
4050 Harvard Rd., Piedmont, CA 94610
760-953-7456; krhubbert@yahoo.com

Matt Busse (corresponding author)
U.S. Department of Agriculture, Forest Service
Pacific Southwest Research Station
1731 Research Park Dr., Davis, CA 95616
530-759-1721; mbusse@fs.fed.us

Steve Overby
U.S. Department of Agriculture, Forest Service,
Rocky Mountain Research Station, Flagstaff, AZ
928-556-2184; soverby@fs.fed.us

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I. Summary

Recent efforts to restore the structure and composition of many western forests have resulted in an increase in the use of pile burning as a fuel reduction tool. Post-thinning slash piles are often relatively small, hand built, and 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 is restricted (e.g., at the wildland-urban interface) or when ground-based mechanical harvesting is prohibited (e.g., slopes exceeding 30%). The ecological effects of pile burning have not been well understood, however. Whether pile burning results in undesirable changes in soil properties or nutrient runoff has been unclear.

This report presents findings from our three-year study of pile burning in the Lake Tahoe Basin (LTB), completed with funding support from the Southern Nevada Public Lands Management Act (SNPLMA). Our aim was to provide scientifically credible results that would inform land managers and the public about potential impacts of pile burning on soil and water quality. We asked the following questions:

- What is the current condition (pile sizes, fuel types, pile arrangements and densities) of unburned units within the LTB?
- What temperature do soils reach during burning and what repercussion might that have on long-term soil productivity?
- Does the size of individual piles matter to soil or ecosystem function?
- Should large piles be avoided at all cost?
- What on-the-ground burn practices best ensure that any impacts to soil and water quality will be kept to a minimum?
- And does burning in a riparian zone result in unwanted nutrient release to stream water?

These questions formed the guiding principles in the design of our research protocols and experimental methods. From there, we took a deliberate approach by first completing a thorough inventory of burn pile units across the Tahoe Basin, and we used this information to select representative pile sizes, fuel types, and number of piles within a unit for the main study, thus reflecting the array of conditions found within the Tahoe Basin.

The major findings of our work are:

General

- Hand-built pile burn units were scattered across the LTB and ranged widely in size and fuel composition. Burn piles of three kinds were found, often interspersed within a treatment unit:
    - piles dominated by large wood (defined as being greater than 22.5 cm, or 9 inches, in diameter and classed as 10,000-hour fuels) were common,
    - piles containing a mixture of slash sizes and a small amount of large wood (less than 10% of the pile) were also common, and
    - piles containing only small diameter slash only (defined as being less than 7.5 cm, or 3 inches, in diameter and classed as 1-hour, 10-hour, or 100-hour fuels), were less common.

- Average diameter of 781 piles was 3 meters (10 feet), with the maximum diameter approaching 9 meters (30 feet).

- Ground coverage of piles was moderate, averaging 8% of the land surface. Complete conversion of a lodgepole pine stand to burn piles – presumably the upper limit of ground coverage for a pile-and-burn operation – resulted in 15-34% ground coverage.

Soil heating

- Burning of hand-built piles of various sizes and fuel types did not result in extreme soil temperatures unless large wood (10,000-hour fuels) was the dominant fuel type. Even then, extreme heating above 400 ^{o}C was limited to the surface 10-cm (4-inch) soil depth.

- Pile size was of minor importance. The soil heat pulse did not increase significantly for piles ranging from two to seven meters in diameter (6.5 to 23 feet in diameter). Thus, decisions regarding pile size and arrangement can be made based on safety issues and cost effectiveness, not soil heating.

- Soil temperatures declined precipitously from the pile center to the pile edge. Roughly one-half of the ground surface area beneath piles reached maximum heating, whereas the soil on the outer half of the pile perimeter remained considerably cooler.

- Mopping up piles with water was an effective option for limiting soil heating beneath piles that contained a high percentage of large-diameter wood (greater than 22.5 cm [or 9 inch] diameter; classed as 10,000-hour fuels). Waiting for eight hours after ignition before mopping up resulted in near complete fuel combustion and only a minor soil heat pulse.

- Soil heating results and management implications were recently published in peer-reviewed literature:

  Busse, M.D., C.J. Shestak, K.R. Hubbert. 2013. Soil heating during burning of forest slash piles and wood piles. International Journal of Wildland Fire 22, 786-796.

Soil quality

- Soil physical properties were altered moderately (water repellency, porosity) to severely (water infiltration) by pile burning. As a consequence, some localized erosion may be expected in the first few years after burning before surface litter or plant cover return. It is unlikely that this will create erosion problem in the LTB, however, because of the scattered, discontinuous arrangement of pile burn scars across treatment units.

- Burning of wood piles and slash piles did not produce a detrimental change in soil fertility indices (total soil carbon, nitrogen, phosphorus, pH, inorganic nutrients, or visual observations of fine roots production).

- Pile burning did not sterilize the soil. Ample evidence of surviving soil microorganisms was noted regardless of the severity of heating. The results suggest that short-term changes in soil microbial populations and their nutrient cycling processes will not be severe at any soil depth beneath burn piles.

- A strong spike in soil nitrates and sulfates was found within burn scars in the late spring following the initial snowmelt after burning. Consequently, the potential exists for a short-term nutrient pulse in surface and subsurface water following pile burning (see the following water chemistry bullets regarding the significance of this observation).

Downslope water chemistry

- Nitrate concentrations in overland flow were low in 2010 regardless of sample location. Although the concentrations were higher in 2011, they decreased two-fold moving downslope from the pile burn. This reduction in nitrate concentration with distance from the burn piles is attributed to the filtering effect of ground cover. Subsurface flow of nitrates also decreased about two-fold going downslope from burn piles, although the differences were not statistically significant due to high pile-to-pile variability.

- Overland flows in 2010 also exhibited a decrease in phosphate concentration downslope from the burn piles. Interestingly, the phosphate concentrations were substantially lower for burn pile samples, compared to the control samples.

- Phosphate concentrations were higher in surface and subsurface flow in 2011 compared to 2010, and they did not decrease with distance from burn piles. Collectively, the phosphate concentrations ranged from 1 to 4 mg/l, which is below the EPA threshold for water quality.

- Little movement of sulfate in overland flow was detected downslope from the burn piles, as sulfate concentrations at seven meters downslope of the piles were equivalent to, or lower than, at the control sites. Subsurface movement of sulfates also declined with distance from the burn piles.

- We conclude that overland and subsurface movements of nitrates, phosphates, and sulfates were not excessive in 2010 or 2011, and that they may be a minor factor when pile burning in SEZs, particularly when ground cover is present. This raises an interesting point related to current stream buffers (setback requirements) for burn piles in the LTB. Buffer distances of 25 feet for intermittent streams and 50 feet for perennial streams are clearly conservative from a standpoint of nutrient movement based on our finding of inconsequential nutrient transport at 23 feet (7 meters) downslope of burn piles. Additional research may be useful to determine how much smaller the buffers can be and still provide adequate water quality protection.

II. Study Objectives

The risk of large-scale, high severity wildfire in the LTB is unmistakable due to a combination of past fire suppression, drought, logging practices, and urban development. Reducing unhealthy fuel accumulations in the Basin, therefore, is a priority of federal, state, and local fire management agencies. Pile burning offers a rapid and cost-effective method of eliminating fuels and is an important tool for reducing the hazard of high-intensity wildfire. However, there has been little research conducted on how the downward heat pulse during pile burning affects soil physical, chemical, and biological properties in the short- or long-term. Additionally, there is little knowledge of post-fire movement of nutrients in overland or subsurface water flow. A main concern is whether heat-induced soil changes will increase nutrient movement within stream environmental zones (SEZs) and contribute to eutrophication of Basin streams and (ultimately)

Lake Tahoe. With these concerns in mind, we identified a series of study objectives with the overall goal of delivering constructive scientific knowledge of pile burning in the LTB and its effects on soil and water quality. A few of the objectives (inventory analysis; effects of mopping up) were not in the original study plan, but were added once the study began as a logical means to improve the breadth and inference of the results. The specific objectives were to:

- Produce an inventory of current pile conditions in the LTB.
- Determine the soil heat pulse associated with pile burning for the range of pile sizes and fuel types found in the Basin.
- Identify the importance of pile size as a factor controlling soil heating.
- Assess the efficacy of water applications (mopping up) to limit soil heating while allowing for adequate fuel consumption.
- Determine the short-term (2 year) effect of pile burning on soil fertility and soil physical properties associated with erosion potential (water infiltration rate, water repellency, porosity).
- Identify pile conditions (size, fuel type) that lead to soil sterilization.
- Assess nutrient transport toward streams from burn piles located in or near riparian zones.

These objectives were met in four experimental phases:

1. A basin-wide inventory of pre-burn conditions.
2. Measurement of the soil heat pulse beneath a wide variety of burn piles.
3. Post-fire analyses of soil physical, chemical, and biological properties best representative of soil health.
4. Post-fire monitoring of nutrient movement in surface and subsurface water.

III. Findings

A. Pre-burn pile conditions

Before testing the effects of pile burning on soil and water quality, we first ran an inventory analysis of pile sizes, pile densities (number of piles per hectare, or per acre), and ground coverage on federal, state, and private LTB lands. This baseline information was then used to help choose the most common pile types for in-depth study of soil and water quality. Inventory site locations are shown in Figure 1 and site descriptions and photographs are presented in the Appendix. 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). Forest Service units were identified using a corporate database of silviculture activity (Forest Service Activity Tracking System, www.fs.fed.us/r5/rsl/projects/frdb/layers/facts.html) interfaced with GIS software.

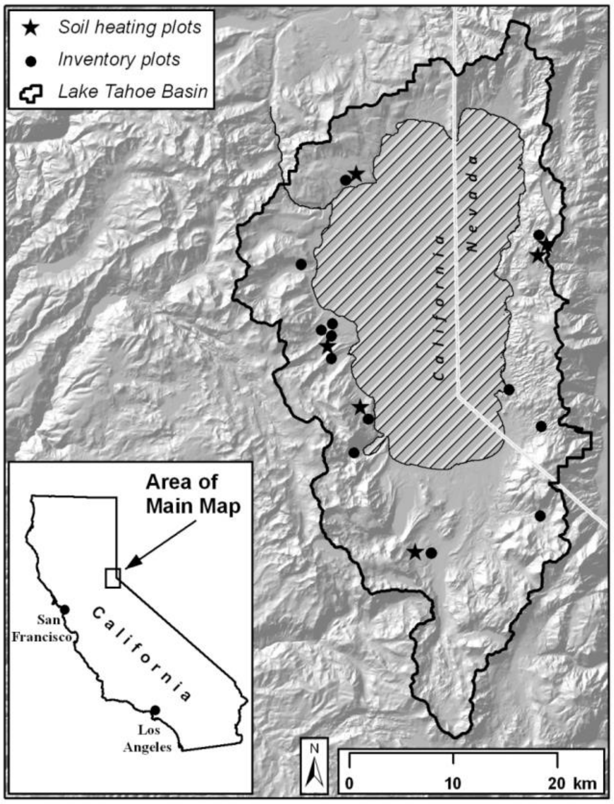


Figure 1. Location of pile burn inventory units within the LTB.

Inventory methods

A systematic grid of 0.1 ha (0.25 acre) plots was installed at each pile burn unit, and mean pile density, size, and dominant fuel type were determined, in the summer of 2009. The plot size was optimized to provide 10 to 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 x width x height x π]/6). Ground coverage occupied by piles (% of treatment area) 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, greater than 22.5 cm diameter (9-inch diameter; classified as 10,000-hour fuels),
2. slash piles, containing a mix of small diameter (less than 7.5 cm or 3-inch diameter; classified as 1-, 10, 100-hour fuels) and medium diameter (7.5 – 22.5 cm; 1,000-hour fuels) woody fuel, with occasional bolts of large wood (usually less than 10% of pile volume), and
3. small-slash piles, comprised of small diameter woody fuel and slash.

Wood piles were found in areas where recent tree mortality was high and were typically intermixed with slash piles within most pile burn units. Examples of the three pile types are shown in Figure 2. *We note that this classification scheme was used to develop a coarse-scale assessment of fuel composition in the LTB and to help select piles for the soil and water quality experiments. A more refined system that accounts for detailed differences in fuel types, or even a photo series similar to those used for natural fuel loads, was beyond the scope of this study yet would be a useful improvement for future applications.*

The cross-sectional area at stump height (analogous to basal area) was determined on all cut trees within a plot. Our intent was to develop a predictive equation of pile ground cover based on thinning intensity, one that might be used as a support tool during the planning of thinning and pile burning operations. Stump area was calculated using the average diameter of two measurements per stump. Total pile ground cover within each treatment unit was then predicted using stump area per unit as the independent variable in regression analysis (statistical analysis was performed using SAS 9.1).

Figure 2. Examples of the three pile types described in this study. Clockwise from upper left: wood pile, slash pile, small-slash pile.

Inventory findings

Pile conditions varied widely throughout the LTB. Among 781 measured piles, there was a six-fold range in pile diameter (1.5 to 9.2 m; 5 to 30 ft) and a 100-fold range in pile volume (0.6 to 55.7 m^3; 21 to 1967 ft^3). Median values were 3.1 m (10.2 ft) and 5.9 m^3 (208 ft^3) for pile diameter and volume, respectively (Figure 3). Fuel composition was primarily wood piles (*n* = 249) and slash piles (*n* = 467) piles. Small-slash piles (*n* = 65) were located commonly at one site

(Old Mill), which received a partial thinning of small understory trees, and infrequently found at the other locations in openings or lightly thinned microsites.

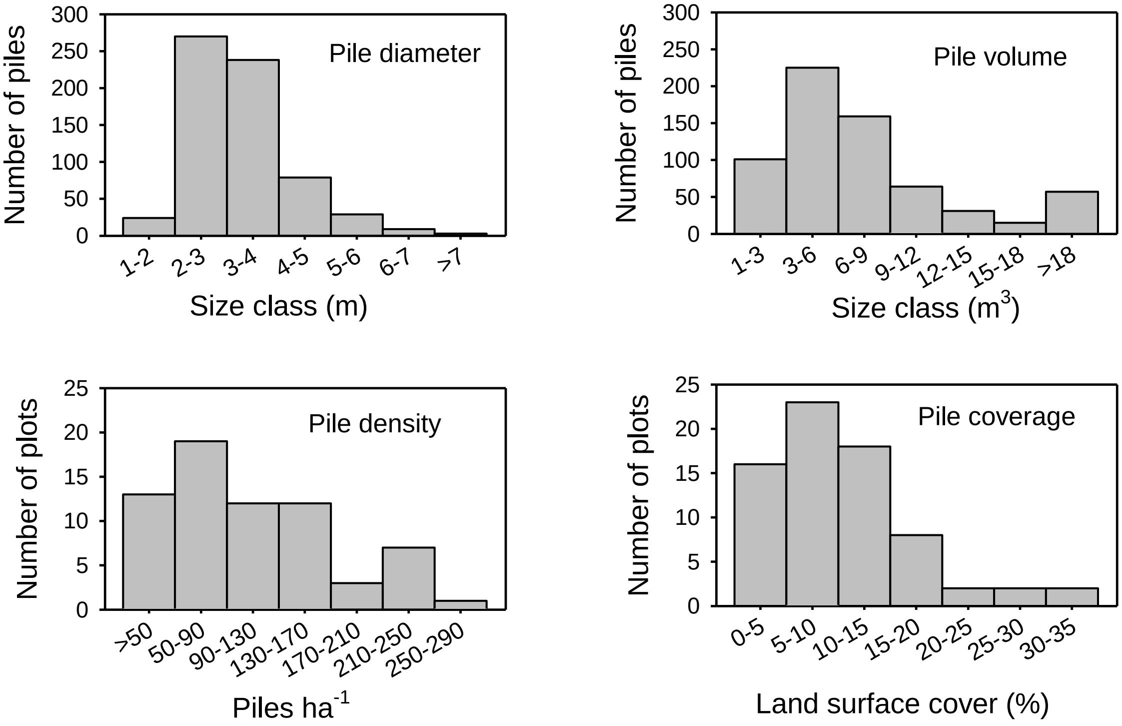


Figure 3. Range in pile diameter and volume, pile density, and pile coverage across 71 inventory plots within the LTB.

Ground coverage occupied by piles ranged from 1% to 34% of the treated area, with a median cover of 8% (Figure 4 shows an example of the range in pile coverage). Coverage was exceedingly high at one site (High Meadows, see Appendix) where a fully-stocked stand of beetle-killed lodgepole pine was converted on site to wood piles. Piles occupied between 15% and 34% of the ground 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 less than 15%.

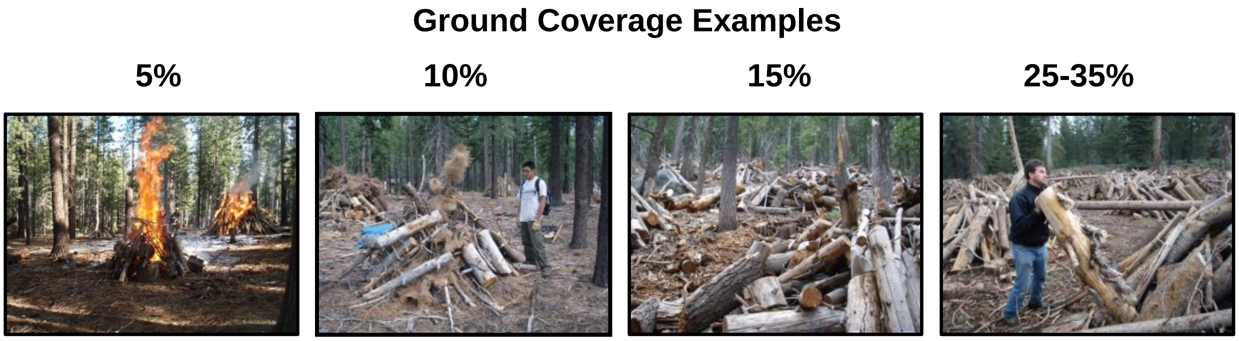


Figure 4. Examples of the range in ground coverage of piles within the LTB. From left to right: Washoe State Park, Bliss State Park, Emerald Bay, High Meadows (see appendix for site descriptions).

A significant relationship between thinning intensity and ground coverage of piles was found for the LTB dataset of 71 plots (ground coverage = 3.75 + 0.223 x stump area, where stump area is in $m^2\ ha^{-1}$; $p < 0.0001$). Using stump area as the sole independent variable accounted for only 31% of the variation in ground cover on the inventory plots, however (Figure 5). Although far from a perfect relationship, this result suggests the potential value of conducting a more detailed, follow-up study to predict pile coverage based on a more common thinning metric such as basal area reduction and using larger plots to avoid the undesired edge effect of small plots.

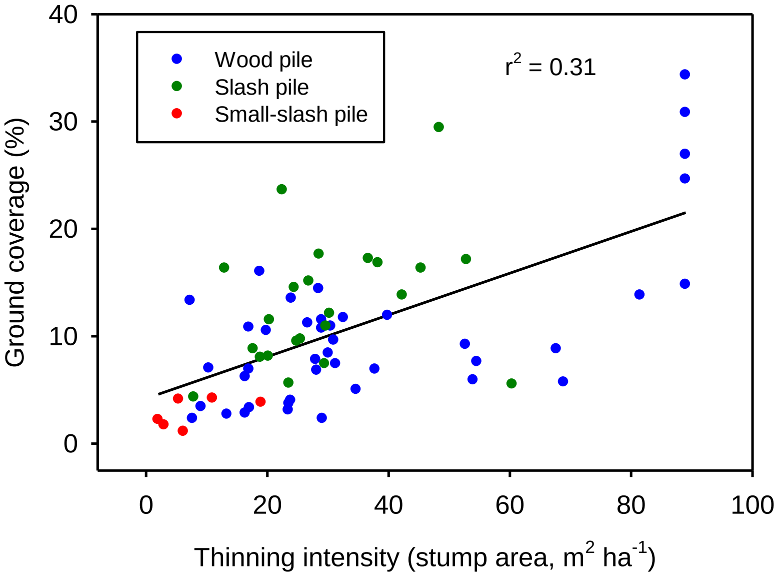


Figure 5. Predicting ground coverage of piles within a treatment unit as a function of thinning intensity.

Inventory summary

- Hand-built pile burn units in 2009 were scattered across the LTB and across land ownerships.
- The range in pile conditions was considerable, from small-diameter piles containing small-diameter fuels to large-diameter wood piles. Most piles were either dominated by large-diameter wood or by a mixture of fuel sizes. These two pile types (wood piles, and slash piles with a mixture of fuel sizes) were typically interspersed within a treatment unit.
- The average pile (*n* = 781) had a diameter of 3.1 meters (10 feet), and the largest pile was 9.2 meters (30 feet) in diameter.
- Ground coverage occupied by piles varied considerably among 71 treatment units, although most units had less than 15% coverage. Complete conversion of a lodgepole pine stand to wood piles at the High Meadows site – presumable the upper limit of ground coverage for a pile-and-burn operation - resulted in 15-34% ground coverage.
- A predictive equation was developed to estimate pile ground cover based on thinning intensity, although it requires further refinement to be useful for planning thinning and pile burning operations.

B. Soil heating during pile burning

Summary

We measured the soil heat pulse beneath hand-built piles ranging in composition from small slash to large wood and in size from 2 to 7 m diameter. Pile specifications were selected based on the inventory analysis of treatment units throughout the LTB, where piles occupied between 1 and 34% of the ground area above sandy-textured soils. The soil heat pulse during burning depended primarily on fuel composition, not on pile size. Piles dominated by large wood (> 22.5 cm diameter) produced temperatures approaching 500^{o}C at 5 cm soil depth and 400^{o}C at 10 cm soil depth, with lethal heating above 100^{o}C lasting up to 3 days. In contrast, soil heating was considerably lower for slash piles that contained a mix of fuel sizes, as maximum temperatures averaged 138 and 86^{o}C at soil depths of 5 cm and 10 cm, respectively. Spatial variability in heating was high beneath all pile types. Soil temperatures were generally greatest near the pile center and decline sharply toward the pile edge. Also, saturating pile burns with water eight hours 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, such as when piles are dominated by large wood and occupy a high percentage of the ground surface and are allowed to burn for extended periods (e.g., no “mopping up” done to quench the burning).

Introduction

Recent efforts to restore the structure and composition of many western 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, following pre-commercial thinning in areas without local bioenergy facilities, or on steep ground. The effects of pile burning are not well understood, however; whether pile burning results in undesirable changes in soil properties or nutrient runoff 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^{o}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^{o}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^{o}C (Badía and Martí 2003; Guerrero *et al.* 2005), while changes in soil mineralogy and other soil physical properties have been noted at temperatures above 500^{o}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^{o}C from 2 minutes to 15 minutes resulted in a six-fold increase in soil inorganic N concentration. Similarly, Galang *et al.* (2010) found that heating a soil to

200^{o}C for 30 minutes produced an equivalent release of labile phosphorous as heating to 500^{o}C for 2.5 minutes. 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-recognized 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^{o}C at a soil depth of 7.5 cm and were below 100^{o}C at 15 cm soil depth beneath a wood and slash pile. Similarly, Massman and Frank (2004) found temperatures above 255^{o}C to a depth of 10 cm beneath a large slash pile. In comparison, temperatures well below 200^{o}C were measured at soil depths ranging from 3 to 6 cm during burning of small-to-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 hypothesized that efforts to limit soil heating would be best met by burning small (but more numerous) piles compared to larger (but fewer) piles due to their relative differences in heat generation and heat transfer within soil. Similarly, we hypothesized that wood piles would generate an intense heat pulse to a considerable depth in the soil profile; whereas, more moderate heat from slash piles would not penetrate far into the soil profile. The study was conducted in the LTB where forest thinning, recent tree mortality and proximity to urban development have resulted in increased use and scheduled planning of pile burning to reduce fuel loadings. We measured the soil heat pulse beneath piles that represented the observed range of sizes and fuel compositions in the Basin.

Methods

Site description

The study was conducted in the lower- to mid-elevation pine and mixed-conifer forests within the LTB (1900 – 2350 m), which straddle 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), 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.

The majority of soils in the LTB are coarse-textured sands. Soils in the northern end of the Basin are very cobbly sandy loams derived from volcanic andesite (US Department of Agriculture, Natural Resources Conservation Service 2007). The remaining soils in the Basin are gravelly loamy sands primarily derived from granodiorite. All soils are relatively infertile, with organic matter content in the surface ten centimeters ranging from 7-11% in volcanic soils and from 2-6% in granitic soils.

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 to 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 standing dead and down wood. Since then, restoration efforts, including the use of pile burning to reduce fuel loading, have been a Basin-wide priority.

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, (3) piles within or adjacent to riparian zones, and (4) piles that were scheduled for burning in 2009 or 2010.

Each pile was measured for volume (length, width, height) prior to burning and fully deconstructed - except for a few exceptions - to determine total mass and to access the pile center for installing soil thermocouples. The field-moist mass of dead foliage and wood was weighed by diameter class to the nearest 29 g using a portable hanging scale (Intercomp, Medina, Minnesota, USA). Fuel moisture content of two samples per diameter class from each site was determined by oven drying (60^{o}C for 95 hours) in order to convert pile mass to a dry-weight basis. Total mass was not measured on four of the 20 piles prior to 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 (ca. 20 cm wide x 30 cm deep) was dug from the pile center to a minimum of 4 m beyond the pile edge for placement of thermocouples and dataloggers (Figures 6 and 7). Thermocouples were inserted horizontally in undisturbed soil below the pile center at 0, 5, 10, and 30 cm depths. High-temperature Type K thermocouples (designed for accurate measurement of temperatures approaching 1200^{o}C, made of 24-gauge wire with ceramic braid insulation) were placed on the mineral soil surface beneath the litter and duff layer. Standard Type K thermocouples (made of 24-gauge wire with glass braid insulation) were used at all other soil depths, where lower soil temperatures were expected. Heavier gauge standard Type K thermocouples (30-gauge wire) were used at the “Old Mill” site for the small-slash piles. Each thermocouple was attached to an Omega OMPL-TC datalogger, which was placed in a water proof case and buried at the far end of the soil trench. Dataloggers were set to record every three minutes beneath small piles and every five minutes beneath large piles. The depth of the litter and duff layer above the surface thermocouples was measured, prior to replacing the soil in each trench and reconstructing the piles.

Figure 6. Deconstructing about one-half of a pile (Sugar Pine #1) and installing thermocouples wires at the pile center. Thermocouples were placed horizontally at specified depths in undisturbed soil (right photo) before reconstructing and burning the pile.

Figure 7. Thermocouple cables were placed in 30 cm-deep trenches (left photo) that extended well beyond the pile edge to avoid heat damage to the dataloggers. The photo on the right shows a completed pile at Washoe State Park, with thermocouples installed and the trench back-filled with soil.

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 center, (2) one to four mid-points between the pile center and the pile edge depending on the pile size and equipment availability, (2) the pile edge, (3) 1 m outside the pile edge (Figure 8). Three wood piles and three slash piles were randomly selected for these tests.

Figure 8. Testing spatial variability in soil heating at the Angora site (pile #1). Pin flags in the photo on left identify the location where heat-sensing thermocouples were installed. Thermocouples attached to datalogger cables (top right photo) were placed horizontally in undisturbed soil at 5- and 10-cm depths before the pile was reconstructed (bottom right photo).

Twenty-seven piles were lit using drip torches between October 29 and December 8, 2009 during the narrow burning window that followed the initial fall precipitation and preceded the winter snow pack. Two additional piles (Angora) were lit on October 15, 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 “chunked” (pushed toward the pile center by field crews to facilitate fuel consumption). Nine piles were “mopped-up” with water within eight to 10 hours of ignition to avoid possible fire escape and, as a result, they were analyzed as a separate experiment. This left 20 “undisturbed” piles (i.e. no mop-up intervention), including a minimum of six of each of the three pile types (large wood piles, slash piles, and small-slash piles).

Soil moisture content at each pile burn site was measured at 5-, 10-, and 30-cm soil depths using ECH2O soil moisture sensors attached to HOBO Micro Station data loggers. 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 (SAS 9.1). Pile diameter was used as the covariate since (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, Studentized residuals (SAS 9.1) were plotted for these two parameters to assess visually if either variable helped explain the data. Statistical significance was considered at $\alpha = 0.05$.

Results

The instrumented piles included a 5- to 10-fold range in pre-burn mass and size (Table 1). Burning in 2009 and 2010 began after the initial fall storms and before the onset of any large winter storms. As a result, soil moisture was low at the time of 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. Pile consumption was 90 to 95% complete at all sites based on visual inspection. The only exception was at Bliss, where ~85% of pile #2 was consumed.

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 (primarily 10,000-hour fuels); S = slash (all fuel sizes); SS = small slash (primarily 1-, 10-, 100-hour fuels).

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

Large differences in maximum temperature and heat duration were measured between pile types, as wood piles generated a substantially greater soil heat pulse than either slash or small-slash piles (examples shown in Figure 9). A standard decline in heat penetration with increasing soil depth was also observed for each pile type.

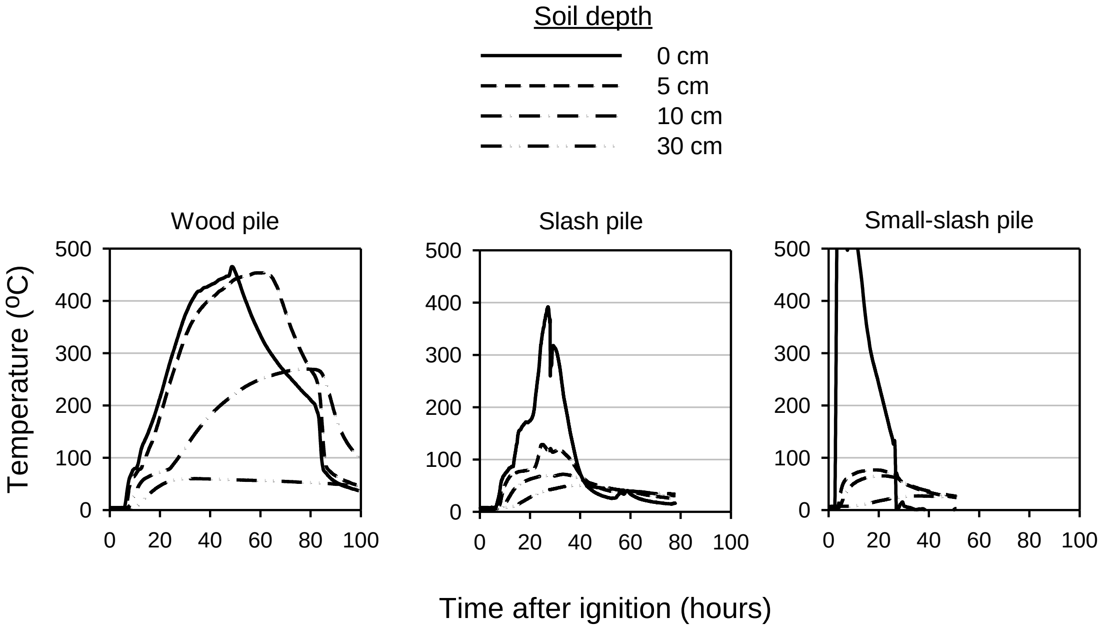


Figure 9. Examples of soil heating profiles during burning of different pile types. The three piles were among the largest within each pile type (wood pile = 2.5 Mg; slash pile = 2.2 Mg; small-slash pile = 1.9 Mg).

Figure 10. Examples of wood pile burning at Spooner Lake and Washoe State Park (bottom right photo). Soil heating beneath the pile in the upper left photo is shown in Figure 9.

Maximum temperatures on the soil surface ranged from 82 to 715°C (Figure 11), 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 statistical 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 200°C was about 2.5 times greater on the soil surface beneath wood piles than either slash or small-slash piles (Figure 12). 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 three pile types (p = 0.848).

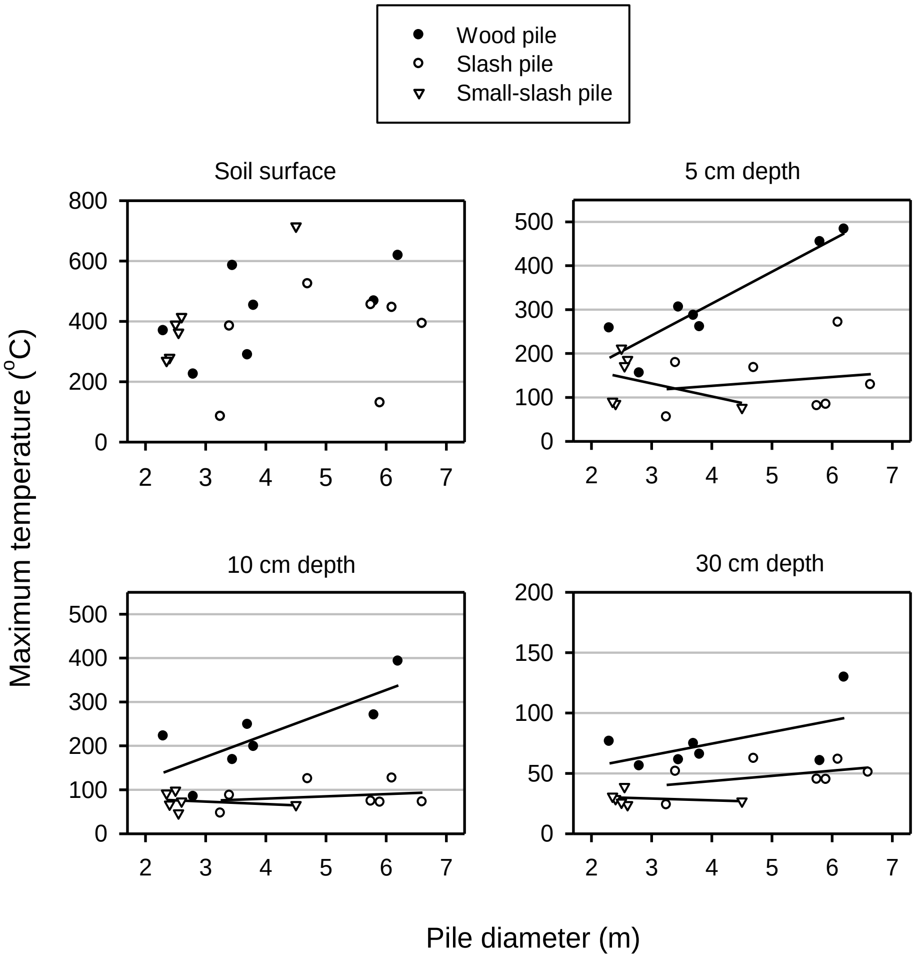


Figure 11. Maximum soil temperatures recorded during pile burning for a range of pile diameters and pile types.

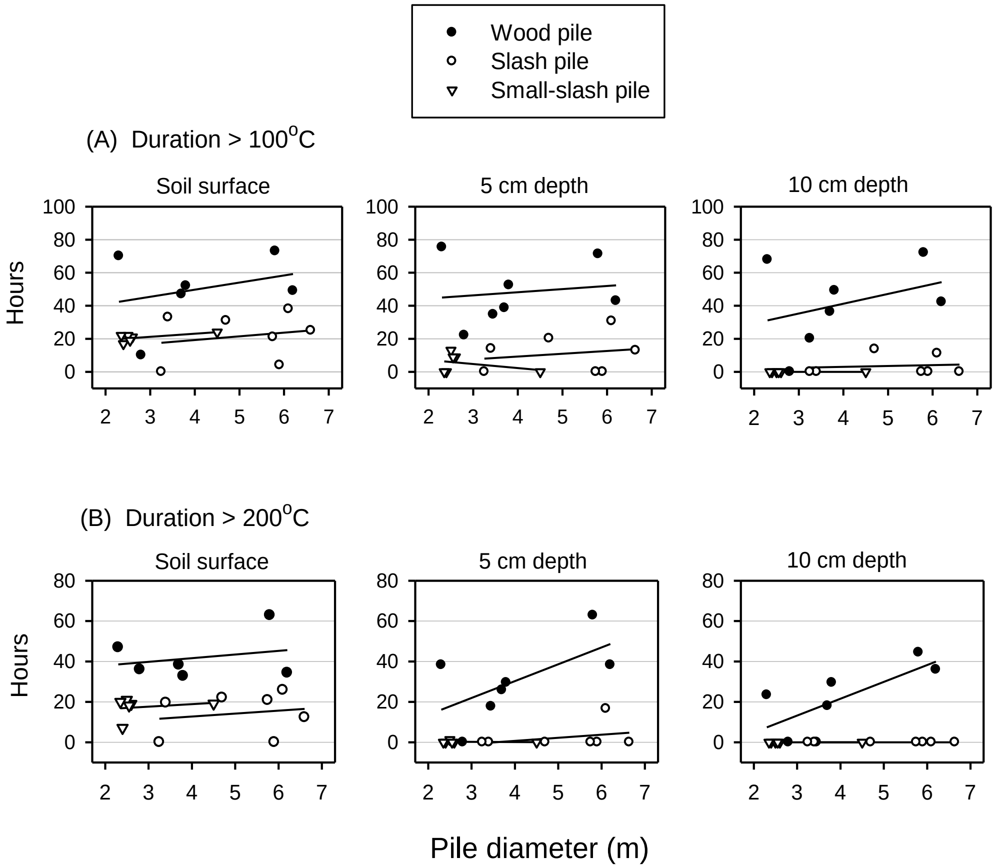


Figure 12. Heat duration above 100 and 200°C during pile burning for a range of pile sizes and pile types.

Differences in heating between pile types were sizable within the soil profile (Figures 11 and 12). At the 5-cm soil depth, the mean maximum temperatures for wood piles was 314 ± 44 °C compared to 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 to 86 ± 11 °C for slash piles and 75 ± 8 °C for small slash piles. Maximum temperatures for wood piles were significantly greater than the other two piles types at soil depths of 5 cm ($p < 0.001$), 10 cm ($p < 0.001$), and 30 cm ($p = 0.005$). Heat duration above 100°C and 200°C was also greater for wood piles than the other pile types (Figure 12). Six out of seven wood piles had soil temperatures above 200°C for 20 to 60 hours at 5 cm depth and for 20 to 40 hours at 10 cm depth. Heat duration above 200°C increased significantly with increasing pile diameter at both 5 and 10 cm 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, Studentized 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 center and declined sharply toward the pile edge (Figure 13). Mean maximum soil temperature was only 48 ^{o}C at the pile edge (5 cm depth) for wood piles and 42 ^{o}C for slash piles. Essentially no heat pulse was registered at ~1 m outside the pile edge at 5 or 10 cm soil depths.

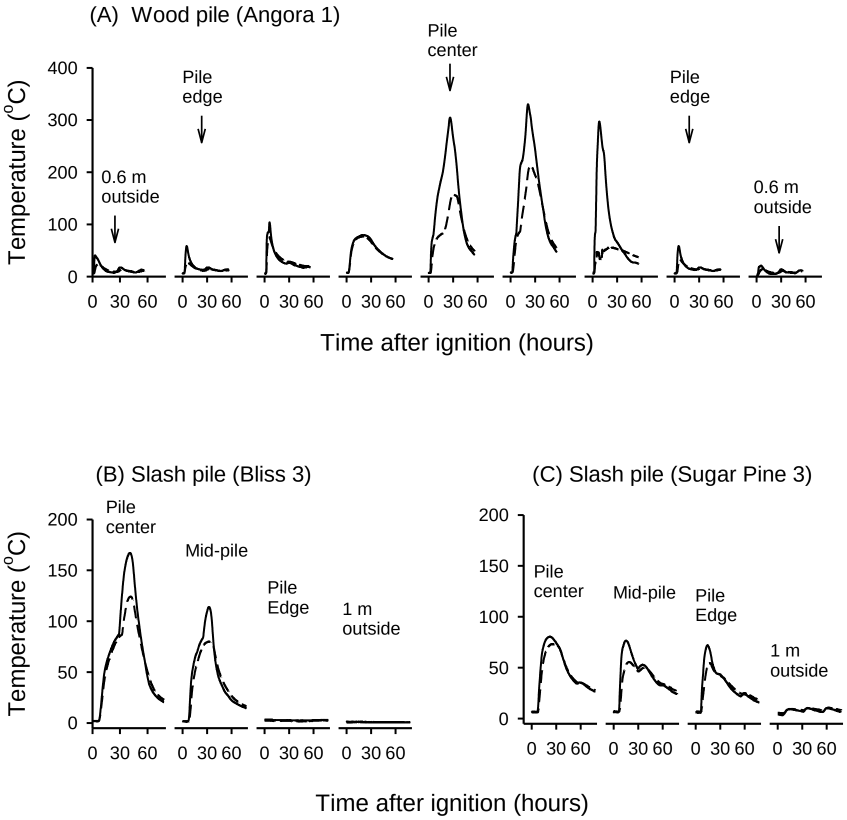


Figure 13. Spatial variability in soil heating at 5 cm (solid line) and 10 cm (dashed line) depths beneath typical pile burns. Thermocouples were located 0.6 m apart along a transect that spanned the diameter of a wood pile (A), and 1 m apart along a transect from the slash pile center to beyond the pile edge (B and C).

The heat pulse beneath the nine instrumented piles that were "mopped up" with water about eight hours after ignition was substantially quenched. Soil temperatures at 5- and 10-cm depths remained well below 100 ^{o}C following ignition, except for a brief period beneath a single wood pile, even though maximum surface temperatures approached 400-500 °C (Figure 14). Fuel consumption was about 90% complete (ocular estimate) prior to applying water (Figure 15).

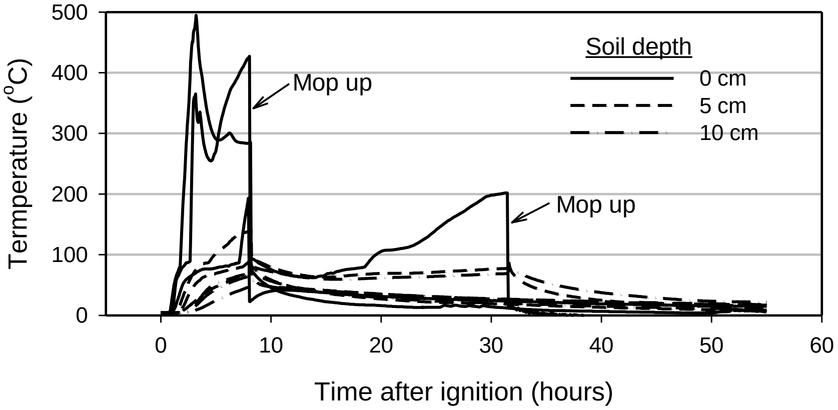


Figure 14. Limited soil heat pulse during burning of wood piles (n = 3) when operationally "mopped-up" (saturated with water) 8 and 32 hours after ignition. Fuel consumption was near complete prior to the initial application of water.

Figure 15. Downloading soil temperature data from the "mopped-up" pile in the background at Washoe State Park. This pile was lit at approximately 0900 and mopped-up at 1700, with ~95% of the pile consumed within 8 hours of ignition. Similar consumption was found for all piles receiving water mop-up.

Discussion

Our intent in this component of the 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; Jimenéz 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 29 piles monitored in our study ranged in size from 2 to 7 m in 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 fall 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 ten centimeter, whereas fairly benign temperatures were detected at 30 cm depth, where mean maximum values were 40 ^{o}C for slash piles and 75 ^{o}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 found only for wood piles at soil depths of five and ten centimeters. We believe this finding 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 smoldering and promote the rapid release of heat to the atmosphere. In this regard, Hungerford (1989) suggested that more than 90% of the heat load during burning rises, leaving a relatively 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 center, which failed to account for possible differences in heat generation near the perimeter of larger piles. Still, our hypothesis that soil heating would increase with slash pile size was not supported, suggesting that a size limit during hand-pile construction may not be necessary for protecting soil.

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 ^{o}C at 5-cm soil depth and from 100 to 400 ^{o}C at 10-cm depth. At a minimum, these temperatures will destroy the seed bank (Beadle 1940), while the upper range is known to volatilize soil carbon and nitrogen, 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-cm and 10-cm soil depths compared to smaller piles.

The heat duration for wood piles was also impressive. Six out of the seven piles produced temperatures above 200 ^{o}C for 20 hours 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 Jimenéz Esquilín *et al.* (2007) have examined soil properties following an extended period of heating (4 hours), and they found substantial changes in soil microbial composition and structure due to pile burning. In comparison, results from our post-fire soil sampling indicated less severe declines in microbial properties beneath wood piles (see *section C. Post-fire changes in soil quality*).

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^{o}C at the 5-cm depth or above 100 ^{o}C at the 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 (Badia and Marti 2003).

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-to-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 vaporize 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 not a sufficient range of conditions to adequately test this premise. All soils were considerably drier (0.03 to 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) despite the common presence of a 1- to 4-cm snow layer at the time of burning. Thus, the conditions in our study represented a worst-case scenario (dry soil). Whether any reductions in soil heating from burning when soils are moist (or covered by a shallow snow layer) would occur are unknown, although we speculate the effects would be relatively inconsequential for those piles of greatest concern (containing a high percentage of large-diameter, 10,000-hour fuels) given their sizeable ability to vaporize soil water.

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. 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 (US Department of Agriculture, 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 one-fourth 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 considered 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 lower 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 center to one meter beyond the pile perimeter. Soil temperature and heat duration declined precipitously from near the pile center to the pile edge for five of six piles, and the sixth pile (Figure 13C) had low temperatures regardless of location. Apparently only one-half or less of the pile area was exceedingly hot beneath the wood piles. This suggests that the 15% cover "threshold" for soil damage may be a conservative underestimation for pile burning, and that coverage near 30% might be more appropriate. In this regard, only one site in the LTB approached 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. Results from our post-fire monitoring (see *section C. Post-fire changes in soil quality*) indicated that soil quality was relatively stable within two years of burning and that long-term or additive soil effects may be a minor issue for pile burning operations in the LTB.

Management Implications

Fuel reduction efforts are a primary consideration in the LTB, as they are in other western forests. Thinning of dense forest stands, urban development, 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 did not reach extreme temperatures in the soil profile unless large wood was a major component. Even then, the extreme heating was limited to the surface ten centimeters. 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 to 280 ^{o}C at a soil depth of five centimeters 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 on the landscape is unknown. Also, the surface soil temperatures during burning were generally above 120 ^{o}C, which is a sufficient temperature to consume the seed bank. Thus, burning in areas with known invasive plant populations may exacerbate their spread. We did not observe the spread of any invasive plant species in two years following burning; still, adopting a more quantitative post-fire monitoring protocol for invasive plants could be considered where appropriate. Finally, the soil heat pulse measured in this study was specific to well cured and reasonably dry fuels (based on the concern in the LTB regarding excess smoke when burning moist, uncured fuels), and may not reflect soil heating dynamics for all fuel conditions. Uncured fuels, when lit, yield a slower heat release and thus can result in an increase in soil heat duration. Again, this is probably only a concern when piles contain large-diameter wood that already burn with a long residence time.

Extreme soil temperatures and long heat durations can be expected when piles contain a high percentage of large wood, clearly a worst-case scenario for soil effects and atypical of many burning operations. Regrettably, we did not identify a threshold for wood content that results in extreme soil heating. The wood piles in our study contained greater than 40% large wood on a mass basis. But how much soil heating occurs when piles contain 10 to 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 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 eight hours 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 of minor importance from a soil heating standpoint. The soil heat pulse did not increase significantly for slash piles ranging from two to seven meters in diameter. Plus, 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 slash piles per treatment unit can be made based on cost effectiveness and safety issues, not soil heating, noting the option of mopping up when large wood is a significant component of the pile.

C. Post-fire changes in soil quality

Summary

A comprehensive suite of soil physical, chemical, and biological properties was measured prior to burning, and then periodically for two years after burning, to assess post-fire soil damage and evaluate the potential for recovery of soil quality. Most properties were sampled at four discrete soil depths (0-5 cm, 5-10 cm, 10-20 cm, 20-30 cm) beneath each of the piles previously identified in the soil heating chapter. The findings included:

- Water repellency was common at the soil surface of burned and unburned soils alike, and increased as the soils dried during the summer months. Burning of wood piles resulted in a large increase in repellency in the surface ten centimeters of the soil profile compared to unburned soil. The effects of slash pile burning on water repellency were less dramatic, however, as changes in repellency were overshadowed by high pile-to-pile variability.

- Porosity was reasonably high in burned and unburned soils (greater than 60%). Burning of wood piles and slash piles reduced soil porosity about 10%, as soil structure and organic matter content were modified. Interestingly, this moderate change in porosity contributed to a large decline in water infiltration rate, particularly for wood pile burns. We assume this decline in infiltration was exacerbated by plugging of soil pores by ash and charcoal particles. Some localized erosion may be expected on steeper ground, therefore, from a combination of increased water repellency and decreased water infiltration rate, particularly in the first few years after burning before the recovery of surface litter or plant cover.

- Total soil carbon and nitrogen, useful indices of soil fertility, increased within the soil profile (0-30 cm) following pile burning. For carbon, the increase resulted from charcoal inputs and was ephemeral in nature – carbon concentrations returned to pre-burn levels by the end of the second year. In comparison, total soil nitrogen concentrations remained elevated for the course of the study. We conclude that burning of wood piles and slash piles did not produce a detrimental change in these soil fertility indices.

- Total phosphorus was unaffected by burning and only a moderate increase in soil pH was found, with all post-fire soils remaining within a near-neutral pH range.

- A strong spike in soil nitrates and sulfates was found 6 months after pile burning (late spring following snowmelt). The response was greatest in the surface 0-10 cm depth. Consequently, the potential exists for nutrient release and movement in surface and subsurface water following pile burning.

- Pile burning did not sterilize the soil. Ample evidence of surviving soil microorganisms was noted regardless of the severity of heating. However, moderate changes in soil microbial populations and their nutrient cycling processes were found in the surface soil layer (0-5 cm depth).

Methods

Soil physical properties

(i) Soil water repellency. Repellency was measured monthly from June through October 2010. Measurements were conducted at the center of each pile using the water drop penetration method (Krammes and DeBano 1965). Repellency was tested at three soil depths (surface, 5 cm, 10 cm). Twenty water drops were placed within a 30-cm square and penetration time was recorded using a stop watch. Water repellency categories included Not Repellent (0-5 second penetration), Slightly Repellent (5-30 seconds), and Moderate to Highly Repellent (greater than 30 seconds) based on the procedure of Hubbert and Oriol (2005).

(ii) Soil porosity. Porosity was determined as the ratio of soil bulk density to particle density. Bulk density of the fine soil fraction was determined using the hollow-core method (Blake and Hartge 1986), with large fragments and rocks (greater than 2 mm) subtracted from the volume and mass of each sample. A particle density of 2.65 g cm^{-3} was assumed for all samples.

(iii) Water infiltration. Infiltration was measured using a minidisc infiltrometer (Decagon Devices, Inc., Pullman, Washington, USA). The infiltration rate was calculated using methods provided in the Mini Disc Infiltrometer User's Manual Version 6.

Soil chemical properties

Soil samples were collected from four depths (0-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm) at each pile prior to burning and at six months and two years after burning. To determine the extent of spatial variability associated with pile burning, we sampled at the pile center (adjacent to thermocouple locations), the mid-point between the pile center and the pile edge, and at the pile edge. An unburned sample was also collected about one meter from the pile edge. All samples were kept at 4 ^{o}C until analyzed, with a small portion of each sample frozen at -20 ^{o}C for analysis of bacterial and fungal biomass.

Chemical measurements included total carbon and nitrogen (dry combustion analysis using a Leco Analyzer), pH (2:1 H_2O to soil), total phosphorous, and water soluble nutrients including nitrate, phosphate, and sulfate.

Soil biological properties

Soil samples collected for chemical analyses were also used for several microbial measurements and determination of nutrient cycling rates. These included: microbial biomass (substrate-induced respiration), basal respiration, bacterial number and biomass (fluorescent microscopy), fungal hyphal length and biomass (fluorescent microscopy), microbial community structure (phospholipid fatty acid analysis), mineralizable nitrogen (30-day incubation), and nitrification (30-day incubation).

Results

Soil physical properties

(i) Soil water repellency. Repellency at the soil surface is a common feature of Tahoe Basin soils. Without burning, the percentage of samples exhibiting moderate to severe repellency ranged from 25% in June when soils were still moist to 60% in late September when soils were dry (Figure 16). Increased repellency as soils become dry is a well-established phenomenon (Doerr and Thomas 2000), and our results indicated a threshold existed near 8% volumetric water content, below which repellency was substantially increased. Burning, particularly of wood piles, increased water repellency at the soil surface compared to unburned soils. However, the amount of pile-to-pile variation in repellency was high and differences between treatments were not significant by late summer ($p = 0.05$). It is unclear why any hydrophobic properties were found at all at the soil surface since the surface temperatures exceeded 300°C for most burns, which is the temperature that water repellency is thought to be destroyed (DeBano 1981).

At five- and ten-centimeter soil depths, water repellence increased progressively with summer drying (Figure 16). This trend was delayed at the ten centimeter depth as the soils remained moist for a longer period of time. Burning of wood piles substantially increased repellency at these depths compared to unburned soil, whereas slash pile burning resulted in greater repellency compared to unburned soil at five centimeter depth and had no effect at the lower depth.

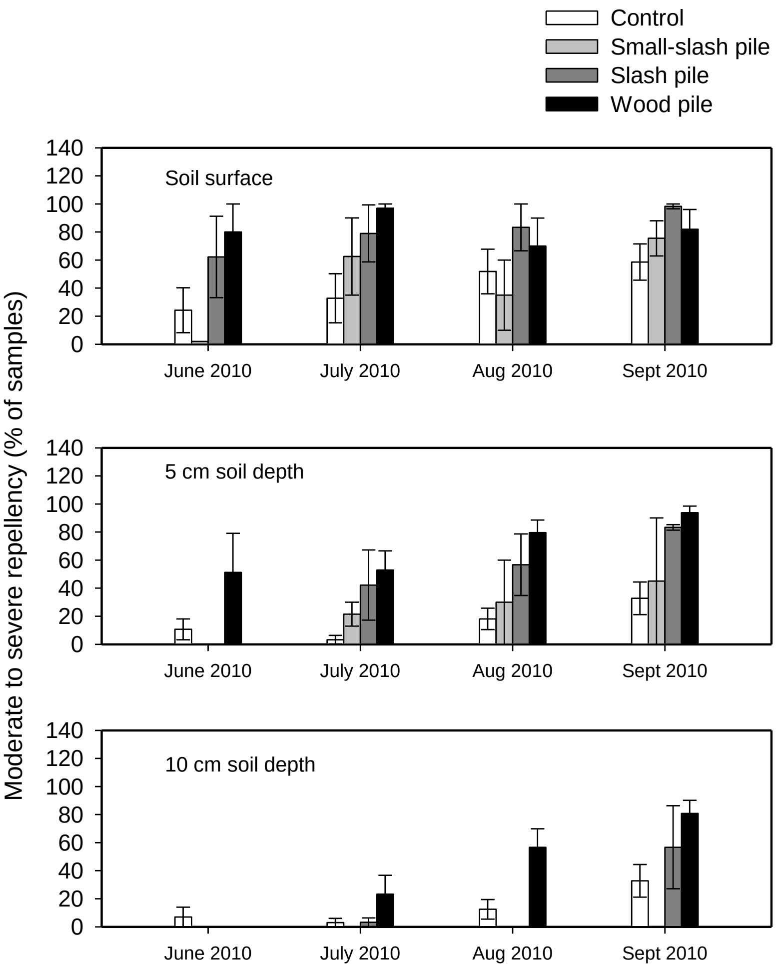


Figure 16. Water repellency at the soil surface and 5- and 10-cm depths during the initial growing season following pile burning. Note the generally high amount of repellency at the soil surface regardless of treatment and the progressive increase in repellency throughout the summer months at 5- and 10-cm soil depths.

ii) Soil porosity. Burning resulted in a 7% decline in porosity in the surface soil beneath slash piles and a 9% decline beneath wood piles (Table 2). This is not an uncommon response to severe fire as soil organic compounds are consumed or altered, resulting in an increase in bulk density and a concomitant decline in total pore space.

Table 2. Effects of pile burning on soil bulk density and total porosity. Porosity was calculated by dividing bulk density by the particle density of mineral soil (2.65 g cm^{-1})

Pile burn	Bulk density (Mg/m3)	Porosity (%)
Slash	1.05 (0.03)	60.4 (1.3)
Control-no burn	0.93 (0.06)	65.0 (2.2)
Wood	0.88 (0.09)	67.0 (3.5)
Control-no burn	0.72 (0.09)	73.0 (3.2)

iii) Water infiltration. The infiltration rate of water was 9-fold slower following slash pile and wood pile burning compared to their respective unburned control soils (Figure 17). Although fire-induced changes in repellency and porosity certainly contributed to this response, it is unlikely (although unproven) that they were solely responsible for the large decline in water infiltration Instead, we suggest that pore plugging on the soil surface by ash, charcoal, and fire-modified minerals played a contributing role. Repeated measurements are recommended to determine the longevity of this alteration to the soil physical quality.

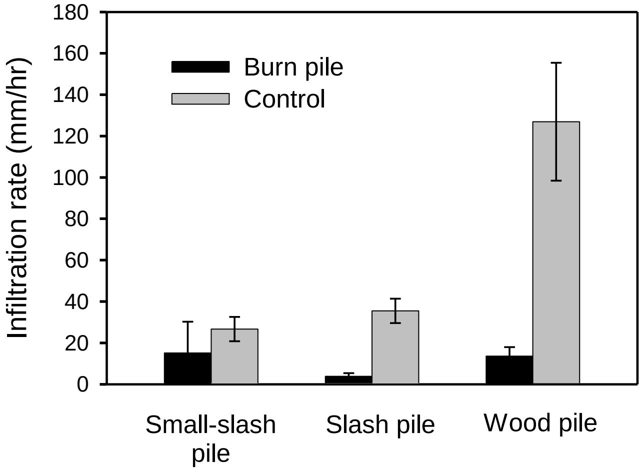


Figure 17. Effect of pile burning on the water infiltration rate at the soil surface.

Summary. Soil physical properties were altered moderately (repellency, porosity) to severely (water infiltration) by pile burning. As a consequence, highly localized erosion may result in the first few years after burning before surface litter or plant cover recover. We do not anticipate this will create a large problem in the LTB, however, as the scattered arrangement of burn scars on the landscape (8% average cover) will limit overland flow and sediment movement during most storms. As noted in the previous section, only in the rare cases where pile burn cover is exceedingly high (e.g., High Meadows site) would this cause some concern. Another factor limiting the erosion potential is that the burn scars were typically pitted or concave shaped following burning, due to the loss of surface organic material, which will help impede downslope sediment movement. Finally, we encourage the periodic re-measurement of water infiltration rates on pile burn scars to determine if and when this important soil physical property recovers.

Soil chemical properties

(i) Total soil carbon. Carbon is the main building block of soil organic matter (SOM) and it is a central measure of soil quality owing to its influence on most soil physical, chemical, and biological properties. Soil porosity, structure, water infiltration, nutrient content and availability, and soil organism abundance, activity, and diversity are all directly linked to the quantity and quality of the soil carbon pool. Consequently, loss of soil carbon during either natural or anthropomorphic disturbance – such as severe fire or climate change – may result in long-term, detrimental changes to a multitude of soil functions. In the case of fire, consumptive loss of soil carbon begins as soil temperatures near 250 ^{o}C, with complete soil carbon loss more typical at extreme values of 500 ^{o}C and higher (Chambers and Attiwell 1994). Published results from pile burning studies have shown a decline in total soil carbon due to burning (Johnson et al. 2011, Korb et al. 2004), although the responses have been inconsistent from site to site. Our soil heating results in this report suggest that many of the pile burns, particularly wood piles that easily surpassed 250 ^{o}C in the upper soil layer, would be expected to lose soil carbon.

Key findings –

- No decline in soil carbon was detected. Instead, there was a two-fold increase in total soil carbon compared to pre-burn values at the first sampling date (Figure 18 and Figure 19). The change was statistically significant to a depth of 30 cm for wood piles and a depth of 20 cm for slash piles. We believe the increase reflects the addition of charcoal and ash to the soil profile (Figure 18).

- Soil carbon levels mostly returned to pre-burn levels by the end of the second year after burning. No statistically significant changes were found relative to pre-burn with the exception of low soil carbon in the 20- to 30-cm depth. Leaching of fine-sized charcoal during snow melt likely accounted for reduction in soil carbon levels.

- There was no clear spatial pattern of soil carbon beneath the piles. Carbon concentrations were statistically similar when sampled along a transect from the pile center to the pile edge (data not shown). This held true for samples collected at six months and two years after burning.

- **Long-term effects of pile burning on soil carbon in the LTB, therefore, are not anticipated.**

(A) Six months after burning

(B) Two years after burning

Figure 18. Examples of charcoal and ash incorporation in the surface mineral soil, at six months and two years after burning. Note the distinct thick band of charcoal-darkened soil prevalent at six months.

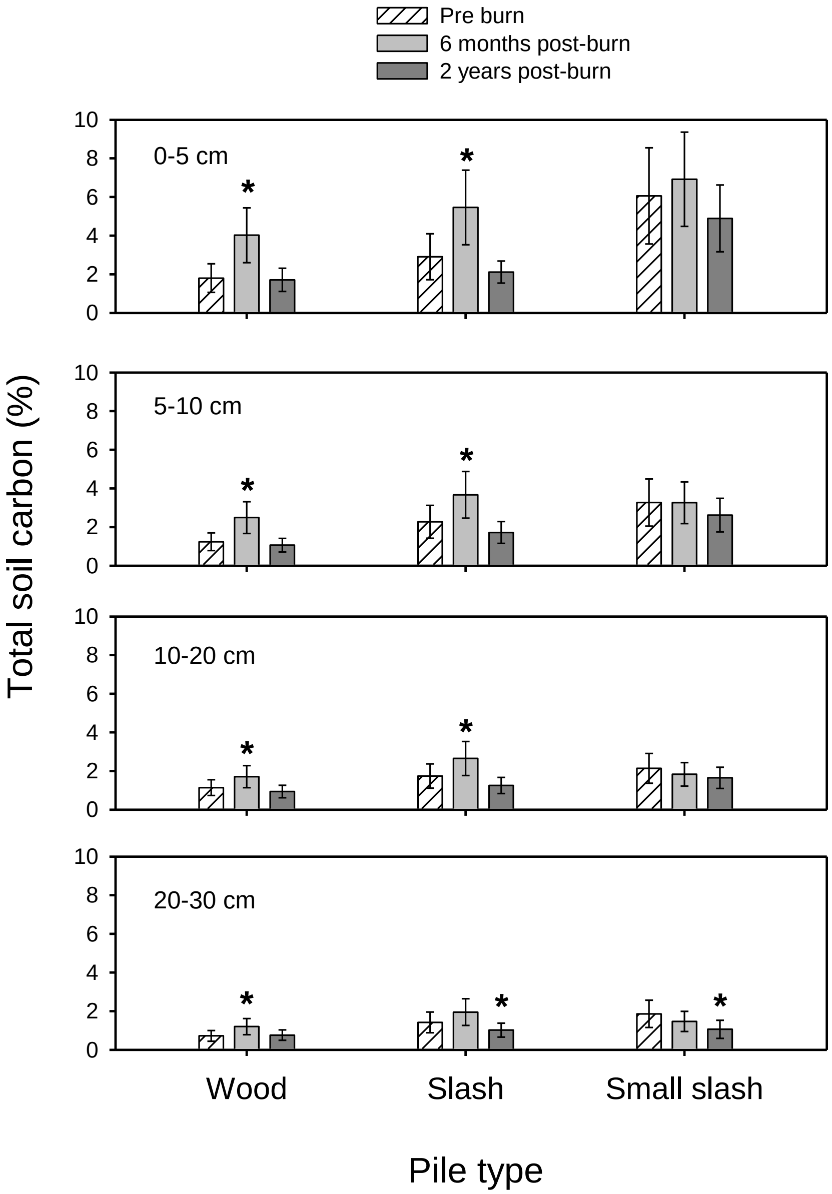


Figure 19. Total soil carbon concentration before and after pile burning. Error bars represent 95% confidence intervals, and asterisks are present if the post-burn value at six months or two years is significantly different (α = 0.05) from the pre-burn value for a given soil depth and pile type.

ii) Total soil nitrogen. Organically bound nitrogen comprises the bulk of the total soil nitrogen pool, yet it is mostly unavailable for plant uptake. Still, it serves a key ecosystem function as the long-term nitrogen reservoir and, as such, is a valued index of soil fertility. The response of soil nitrogen to pile burning followed a similar pattern as was observed for soil carbon (Figure 20).

Key findings –

- No decline in soil nitrogen was detected due to burning. Instead, there was about a two-fold increase in total soil nitrogen compared to pre-burn values for wood piles and slash piles. No statistically significant change was detected for small-slash piles.

- Unlike soil carbon levels, total soil nitrogen remained elevated throughout the two year study. Further testing is needed to help explain this observation.

- There was no clear spatial pattern of soil nitrogen beneath the piles. Nitrogen concentrations were statistically similar when sampled along a transect from the pile center to the pile edge (data not shown). This held true for samples collected at six months and two years after burning.

- **Long-term effects of pile burning on total soil nitrogen, therefore, are not anticipated.**

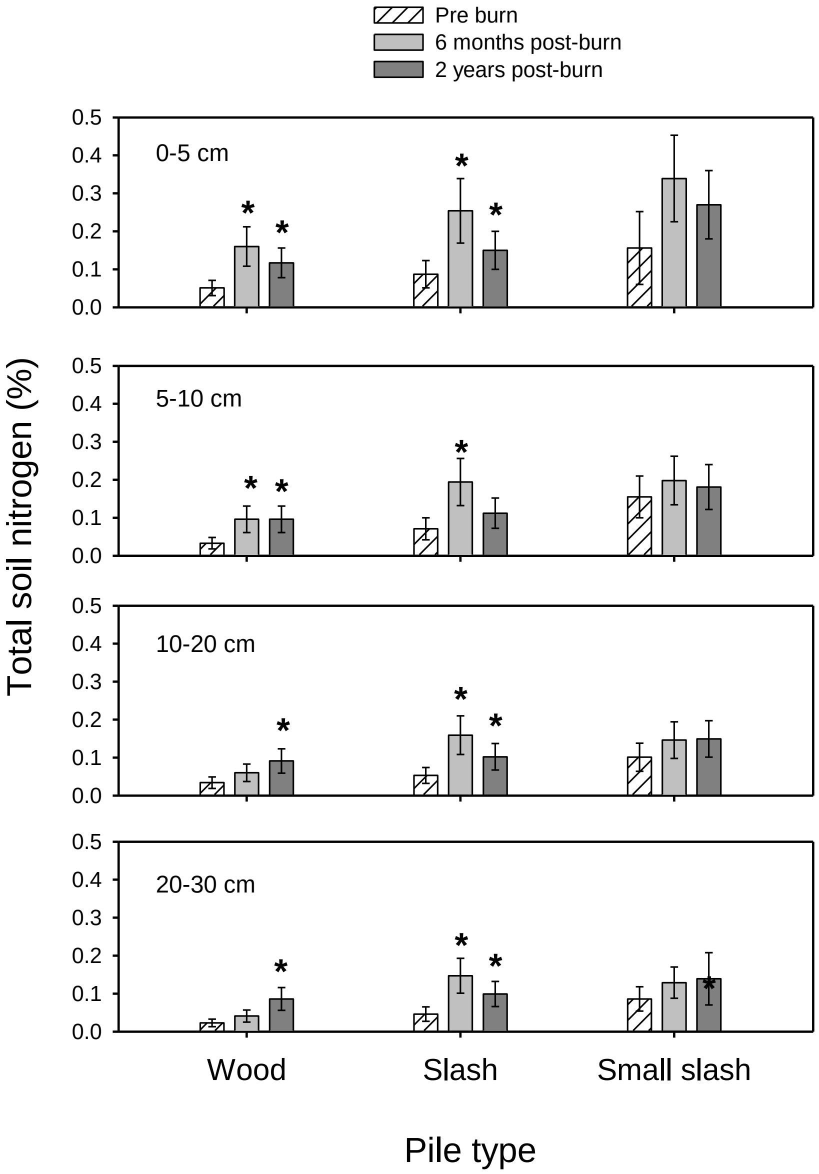


Figure 20. Total soil nitrogen concentration before and after pile burning. Error bars represent 95% confidence intervals, and asterisks are present if the post-burn value at six months or two years is significantly different (α = 0.05) from the pre-burn value for a given soil depth and pile type.

(iii) Total soil phosphorus. No statistically significant differences were seen in total soil phosphorus due to pile burning with the exception of an increase in the surface soil layer (0- to 5-cm depth) two years after burning of wood piles (Figure 21). Therefore, as was the case with total carbon and nitrogen, no long-term effects of burning on total soil phosphorus are anticipated.

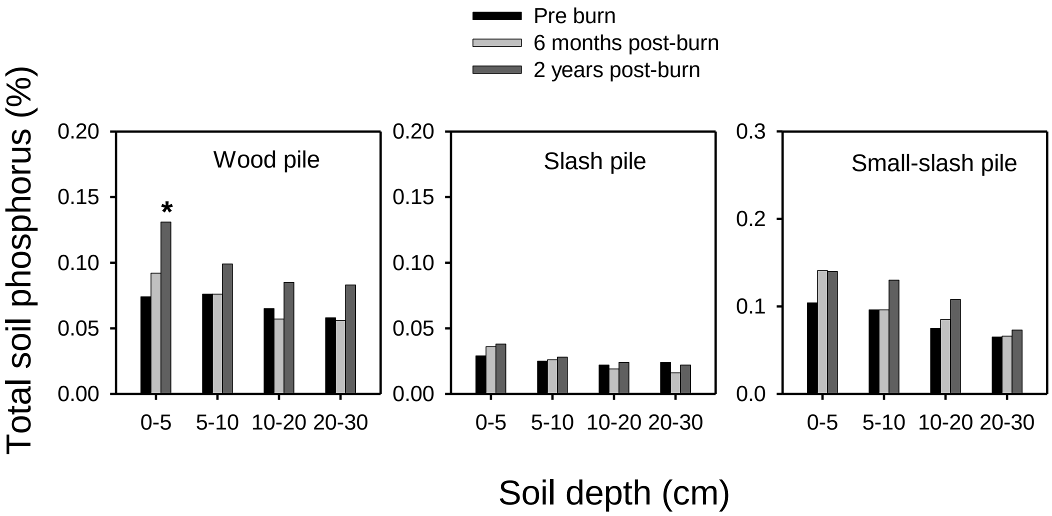


Figure 21. Total soil phosphorous concentration before and after pile burning. Asterisks are present if the post-burn value at six months or two years is significantly different (α = 0.05) from the pre-burn value for a given soil depth and pile type.

iv) Soil pH. The effects of severe burning on soil pH are well established in literature. Moderate increases of 0.5 to 1.5 pH units are often measured as the cation concentration in ash serves to raise the pH. This is almost universally a short-term response, as soil pH typically returns to pre-burn levels within one to two years after burning.

Soil pH measured six months after burning in our study (post snowmelt) was higher for pile burn soils compared to adjacent unburned soils in the upper 0- to 5-cm depth. The increase ranged from 0.3 to 0.7 units (Figure 22), with all sites and treatments maintaining near-neutral pH values (6.2-7.1; *water is neutral if it has a pH of 7*). No differences between burned and unburned soils were found when pH was measured two years after burning (data not shown).

Also, few differences in pH were detected between burned and unburned soil at depths below five centimeters.

Figure 22. Soil pH measured six months after pile burning at the 0- to 5-cm depth. Pile types included wood pile (Spooner 1 and 2), slash pile (Sugar Pine, Bliss), and small-slash pile (Old Mill).

(v) Available nutrients.

(A) Soil ammonium

Key findings –

- Pile burning resulted in a short-term 1.5- to 4-fold increase in ammonium concentration at 0- to 5-cm and 5- to 10-cm soil depths from the release of organically bound nitrogen (Figure 23). However, the ammonium concentrations at the six month date were not particularly high (2-6 mg/kg), especially when compared to other fire effects studies involving severe burning.
- The increase in ammonium concentration was ephemeral. No statistically significant differences between burned and unburned soils were detected at the final sampling date.

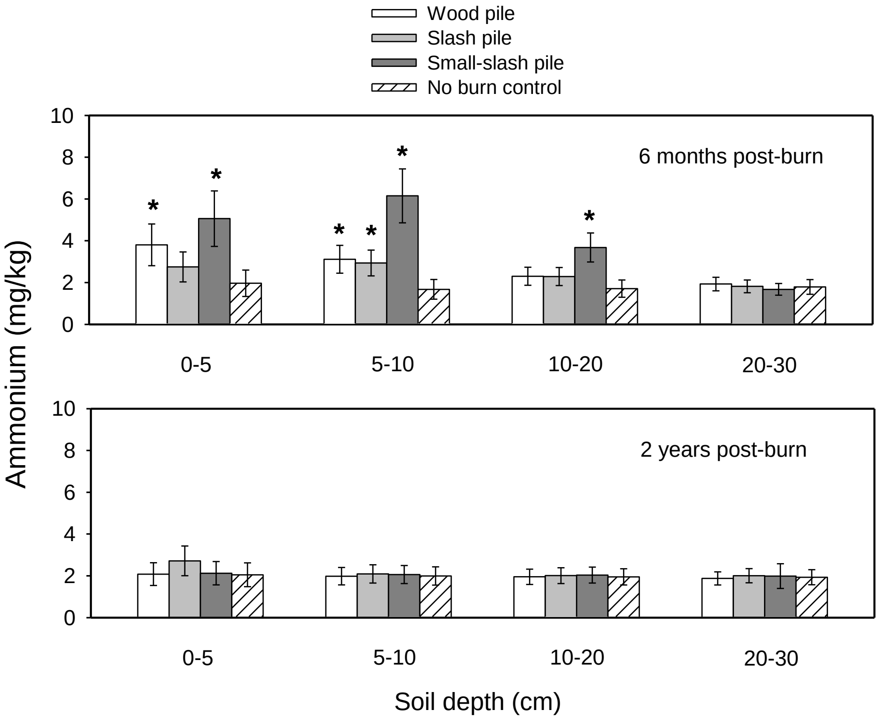


Figure 23. Soil ammonium concentrations six months and two years after pile burning. Asterisks are present if the post-burn value is significantly different (α = 0.05) from the No burn control for a given sample date and soil depth.

(B) Soil nitrate

Key findings –

- A strong spike in soil nitrate was found 6 months after slash pile burning. The response was greatest in the surface 0- to 10-cm depth (Figure 24). Consequently, the potential exists for nitrate release and movement in surface and subsurface water following slash burning.
- Nitrate concentrations remained elevated (in some cases) for two years after burning of slash piles.
- No effect of burning wood piles on nitrate concentrations was observed. Reasons are unclear for the disparate response in nitrate release between burnings of wood piles versus slash piles.

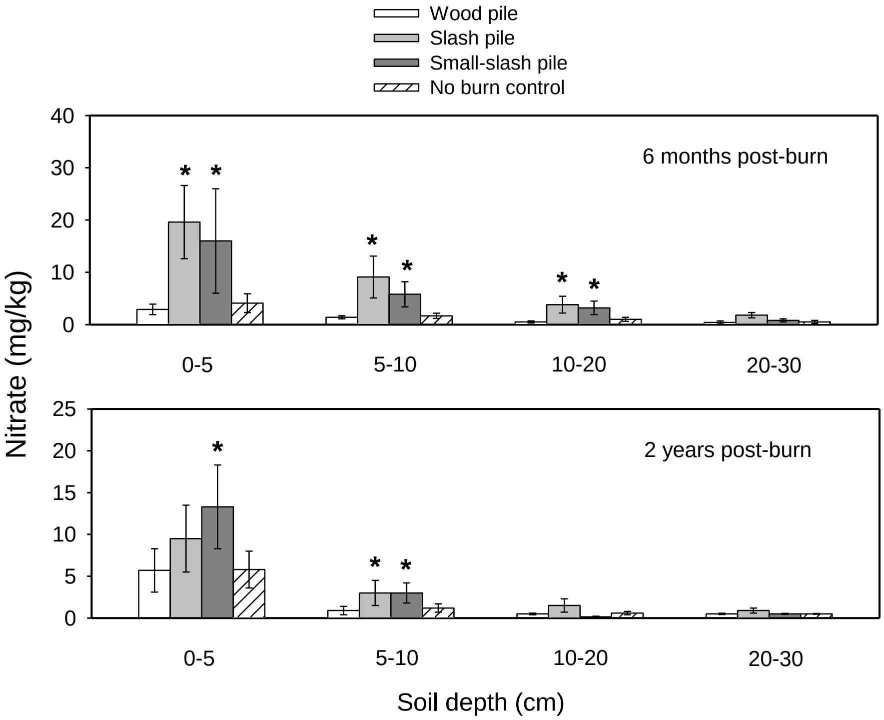


Figure 24. Soil nitrate concentrations six months and two years after pile burning. Asterisks are present if the post-burn value is significantly different (α = 0.05) from the control-unburned for a given sample date and soil depth.

C) Soil phosphate

Key finding –

- Water-extractable phosphate concentrations were unaffected by pile burning.

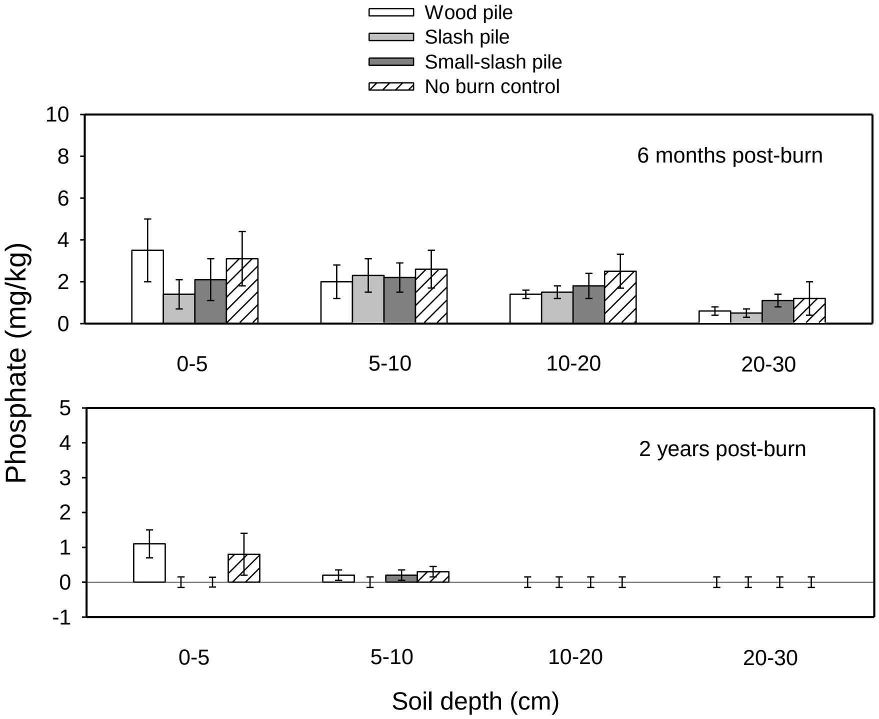


Figure 25. Soil phosphate concentrations six months and two years after pile burning. No statistically significant differences between burned and unburned soils were found for a given sample date and soil depth. Error bars without means at two years post-burn signify phosphate concentrations below the limit of detection.

D) Soil sulfate

Key findings –

- A large spike in water-extractable sulfate was measured at six months following burning of small-slash piles (Old Mill site). The response was noted at all soil depths.
- Burning of slash piles and wood piles also lead to an increase in sulfate concentration throughout the soil profile, albeit of less magnitude compared to small-slash piles.
- Full recovery relative to unburned soil was found within two years.

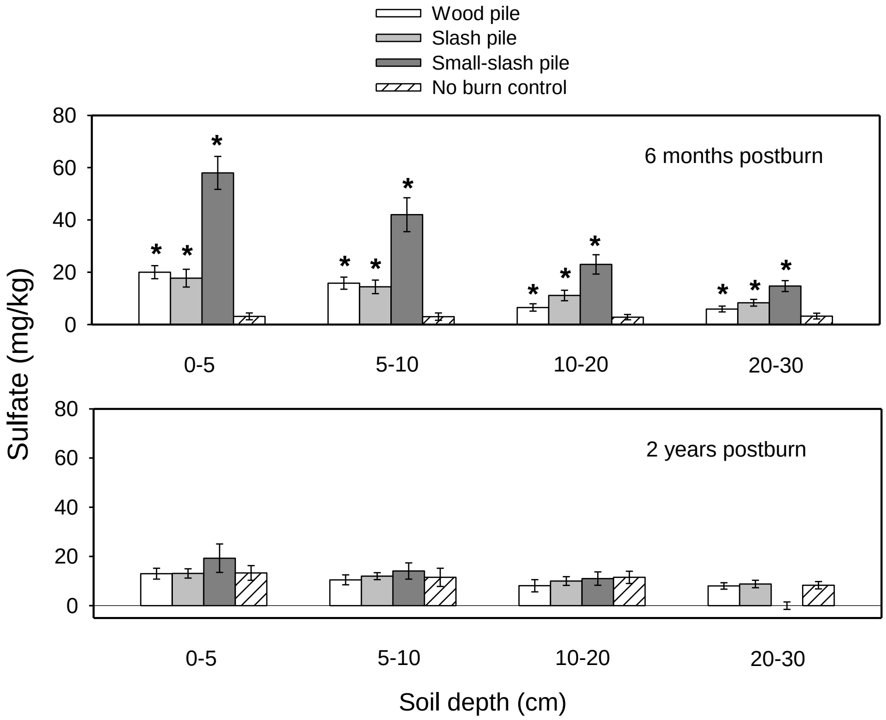


Figure 26. Soil sulfate concentrations six months and two years after pile burning. No statistically significant differences between burned and unburned soils were found for a given sample date and soil depth. Error bars without means at two years post-burn signify phosphate concentrations below the limit of detection.

Soil biological properties.

Soil organisms and their nutrient cycling processes have been shown to respond widely to fire (Chambers and Attiwell 1994, Choromanska and DeLuca 2002). For example, death of bacteria and fungi can occur at relatively low soil temperatures of 100 ^{o}C, which is clearly within the range of temperatures encountered in this study. To kill all soil microorganisms with a single pile burn is unlikely, however, given the heat-resistant structures (e.g. spores) and survival mechanisms displayed by this diverse group of organisms.

We selected a broad suite of microbial properties of general sensitivity to burning. Results are presented in Table 2. Samples were collected from the inner 1/3, middle 1/3, and outer 1/3 of each pile and analyzed separately. However, because there were few differences in microbial properties between the three locations within a pile, the values were averaged and the results reflect the entire pile area.

Table 3. Summary of soil biological responses to pile burning. Data (means and standard errors in parentheses) are for the 0- to 5-cm soil depth at six months after burning.

Microbial property	Wood pile				Slash pile		
	Burn	No burn	Change		Burn	No burn	Change
Total bacteria (number x 10^{9}/g)	4.0 (2.2)	4.5 (1.6)	**-20%**		5.5 (0.7)	7.8 (1.0)	**-29%**
Bacterial biomass (mg/kg)	313 (76)	389 (112)	**-20%**		441 (95)	499 (133)	**-12%**
Fungal hyphae (m/g)	154 (41)	362 (88)	**-57%**		214 (107)	425 (154)	**-50%**
Fungal biomass (mg/kg)	491 (138)	625 (194)	**-21%**		591 (200)	942 (244)	**-37%**
Microbial biomass–SIR (mg/kg)	257 (38)	270 (22)	**-5%**		207 (45)	235(26)	**-12%**
C respiration (µmol/g/h)	0.05 (0.1)	0.03 (0.01)	**+39%**		0.04 (0.01)	0.03 (0.01)	**+37%**
Mineralizable N (mg/kg/30 d)	2.5 (2.2)	2.8 (1.8)	**-10%**		3.1 (2.6)	3.4 (1.9)	**-9%**
Nitrification (mg/kg/30d)	0.11 (0.17)	0.09 (0.11)	**+22%**		1.56 (1.78)	1.18 (0.99)	**+32%**

Key findings –

- Burning of wood piles and slash piles did not sterilize the soil. Table 2 shows a wide range of responses to fire, from a large decline in fungal hyphae to a large increase in microbial respiration, and everything in-between. In general there was a decline in bacteria and fungi population sizes but an increase in some of their functions (C respiration, nitrification).
- These results are a worst-case scenario (surface 0- to 5-cm depth at the first post-fire sampling). Results for lower depths in the soil profile (5-10 cm, 10-20 cm, 20-30 cm) showed fewer differences between burned and unburned soil, as did samples collected two years after burning (data not shown).
- Given the inconsistent response of the suite of microbial community and functional measures to pile burning, our results suggest that the effects of pile burning on soil organisms is not a crucial consideration when selecting preferred forest practices in the LTB.
- Fine-root proliferation was detected in many post-burn soils (Figure 27), providing additional (indirect) evidence of adequate functioning of soil biological properties following burning of hand piles.

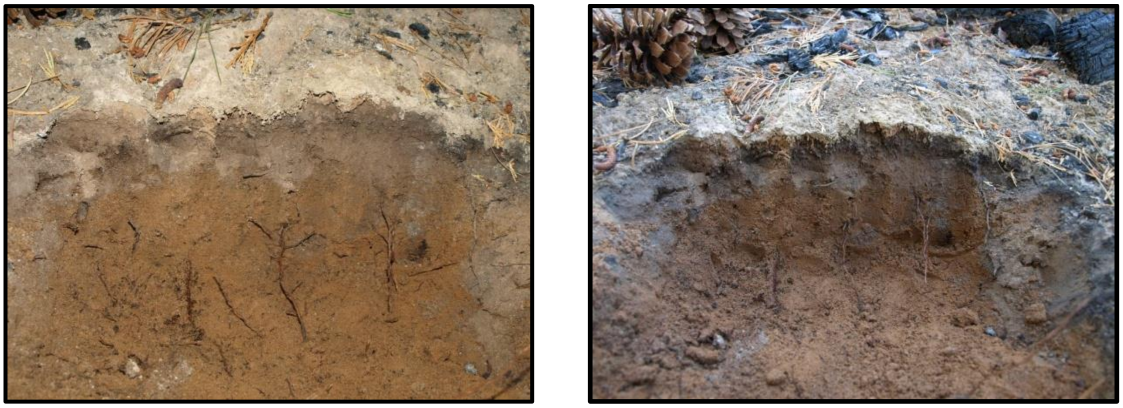


Figure 27. Examples of fine-root growth in the surface soil layer in the first growing season after burning.

D. Pile burning effects on downslope water chemistry

Summary

Pile burning within or near stream environment zones (SEZs) may accentuate the release of nutrients to LTB waters. Our objective was to assess this concern by testing the effects of pile burning on downslope surface and subsurface water chemistry. We suspected that post-fire changes in these properties would ensue, particularly in cases where pile burning resulted in extreme and prolonged soil heating. Twenty-nine burn piles of varying size and fuel composition were selected. Sites occurred on both granitic and volcanic parent materials, as well as glacial outwash. No consistent evidence of increased nutrient movement was detected downslope from burned piles. Overland flow of nitrate, phosphate, and sulfate generally declined with distance away from the pile edge, and there was only a modest, inconsistent change in subsurface nutrient concentrations downslope from piles. The findings suggest that pile burning does not contribute a strong pulse of nutrients to downslope water.

Introduction

The last 150 years of change in the Tahoe Basin forests has culminated in uncharacteristically high tree densities and increased surface and aerial fuels, magnifying the risk of high-severity fire (Weatherspoon et al. 1992). To help remove accumulated forest fuels, pile burning has been adopted as a cost-effective alternative when prescribed underburning or biomass harvesting are impractical. Whether pile burning results in undesirable changes in nutrient runoff is not well established in literature, however. Most evidence suggests that elevated soil temperatures result in direct changes in soil physical properties, destruction of soil organic matter, and a flush of nitrates, phosphates, and sulfates (Frandsen and Ryan 1986, Stephens et al. 2004). Indirectly, soil hydraulic properties such as water repellency and infiltration rate may also be altered, further facilitating nutrient movement in surface and sub-surface flow and resulting in broad implications for lake functions (Stephens et al. 2004).

Between 1968 and 2000, the clarity of Lake Tahoe decreased by 33 feet due to increased nutrient loading from tributary streams, surface runoff, attached sediments, and atmospheric deposition (Reuter and Miller 2000). Nitrogen (N) and phosphorus (P) are the primary nutrients affecting algal growth and lake clarity in this ecosystem. Therefore, a particular concern of fuel reduction projects in the Tahoe Basin is their proximity to SEZs, where there is the potential of burning to increase nutrient and sediment loading of streams. Fire can increase the mobilization of labile nitrogen and phosphate that is then transported off-site during precipitation or snowmelt (Miller et al. 2006). High concentrations of nitrates, ammonium, and phosphates have been identified in the interflow between the mineral soil surface and the decomposing organic litter layer (Miller et al. 2005). The authors suggest that well-developed surface organic layers in fire-suppressed forests are a key source of the high nutrient levels.

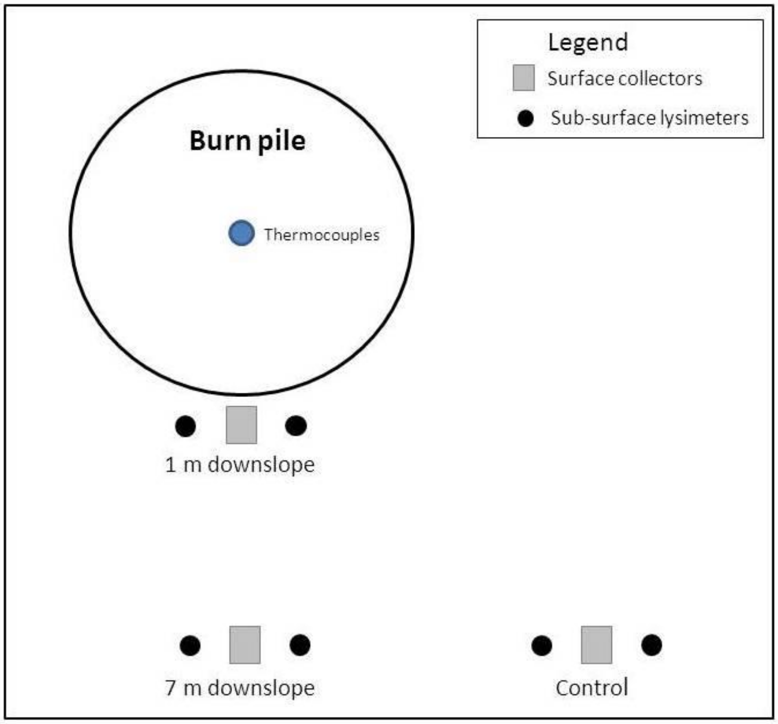
There has been little research conducted on how the heat pulse during pile burning either directly or indirectly affects post-fire movement of nutrients in overland or subsurface flow. Therefore, the objective of this component of our study was to measure post-burn changes water chemistry directly downslope of the burn piles.

Methods

Surface overland flow collectors were installed prior to burning to quantify fire-induced changes in water quality. The collectors were modeled after those designed by Miller et al. (2006), see Figure 28. Zero-tension lysimeters were used for collecting subsurface water samples.

Figure 28. Surface overland flow collector: 2.5 gallon sample collector placed in the soil profile and attached to metal flashing that directs overland flow of water from the mineral soil-duff interface into the reservoir bucket. The metal flashing was covered with a representative litter+duff layer once installed.

The following schematic shows the operational design of the water chemistry study. Surface and subsurface sample collectors were installed at three locations, (1) one meter downslope from each pile, (2) seven meters downslope, and (3) seven meters laterally distant from the downslope influence of each pile (the control point). The average slope of the land on which the burn piles were built was 23%, with a range from 5% to 44%.



Water samples were collected after snowmelt in late spring 2010 and 2011. Soluble anions (nitrate, phosphate, sulfate) were analyzed using ion chromatography (DX500, Dionex Corp., 1228 Sunnyvale, California, USA). Water samples captured by the zero-tension lysimeters and overland flow collectors were filtered using ashless quantitative filter paper (2.5 um pore size; Whatman Inc., Florham Park, New Jersey, USA) prior to analysis. Anion analysis followed U.S. EPA Method 300.0 protocols using a Dionex IonPac AS4A anion exchange column, carbonate/bicarbonate eluent, and suppressed conductivity detection.

Results

Damage to numerous overland flow collectors by local wildlife (presumably bears) reduced the sample size and, ultimately, limited the robust nature of the results. In addition, results for subsurface flow were only available in 2011 due to low snow and rainfall amounts in 2010. Nevertheless, the results offer evidence that nutrient flow following pile burning occurs at low concentrations and declines with distance downslope from burn piles.

Key findings –

- Nitrate concentrations in overland flow were low in 2010 regardless of sample location (Figure 29). Nitrate concentrations were higher in 2011, and they decreased two-fold moving downslope from the pile burn. This reduction in nitrate concentration with distance from the burn piles is attributed to the filtering effect of ground cover. Subsurface movement of nitrates also decreased about two-fold going downslope from the pile (Figure 30), although the differences were not statistically significant due to high pile-to-pile variability.
- Overland flow of phosphates in 2010 also exhibited a decrease in concentration downslope from the burn piles, and, interestingly, the concentration of phosphates was substantially lower for burn pile samples compared to the control samples.
- Phosphate concentrations were higher in surface and subsurface flow in 2011 compared to 2010, and they did not decrease with distance from burn piles. Collectively, the phosphate concentrations ranged from 1 to 4 mg/l, which is below the EPA threshold for water quality.
- Little movement of sulfate in overland flow was detected downslope from the burn piles, as the concentrations at seven meters below the piles were equivalent to or lower than in control samples. Subsurface movement of sulfates also declined with distance from burn piles.
- We conclude that overland and subsurface movements of nitrates, phosphates, and sulfates were not excessive in 2010 or 2011, and that they may be a minor factor when pile burning in SEZs, particularly when ground cover is present. This raises an interesting point related to current stream buffer (or setback requirements) for burn piles in the LTB. Buffer distances of 25 feet for intermittent streams and 50 feet for perennial streams are clearly conservative from a standpoint of nutrient movement based on our finding of inconsequential nutrient transport at 23 feet (7 meters) downslope of burn piles. A small-scale monitoring program of stream water chemistry (e.g. following a single SEZ pile burn project) may be useful in this case, to determine how much smaller the buffers can be and still provide adequate water quality protection.

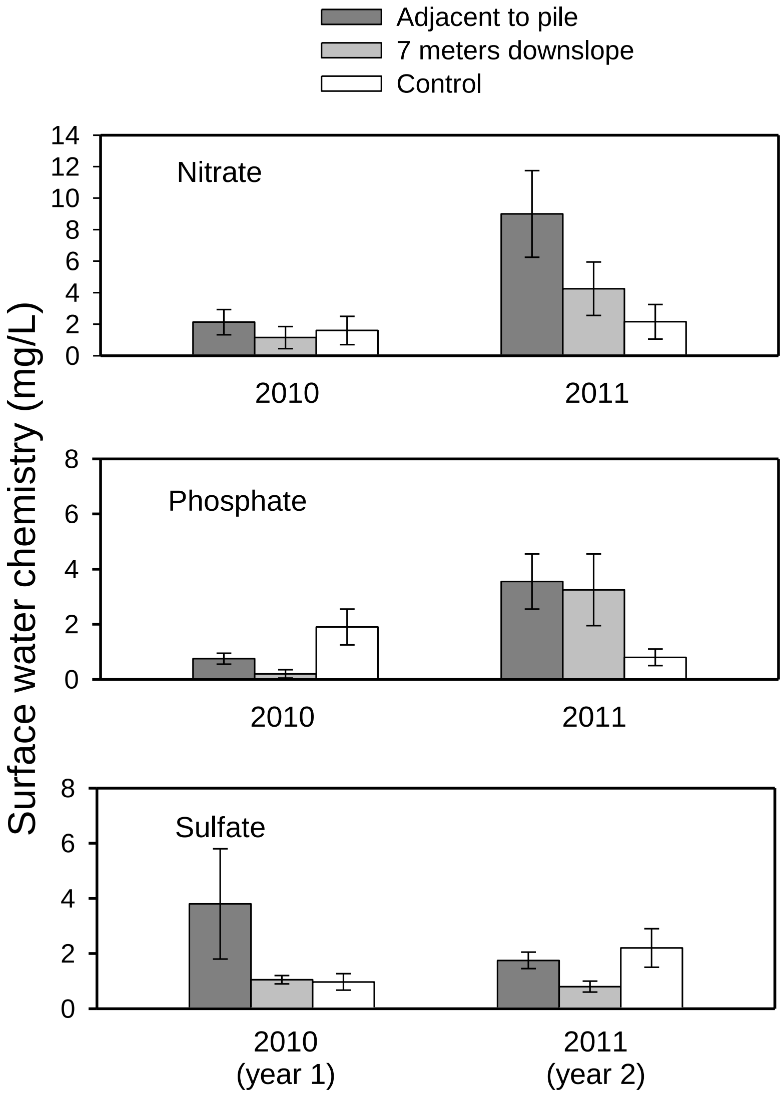


Figure 29. Overland flow of nitrates, phosphates, and sulfates in the first and second year following pile burning.

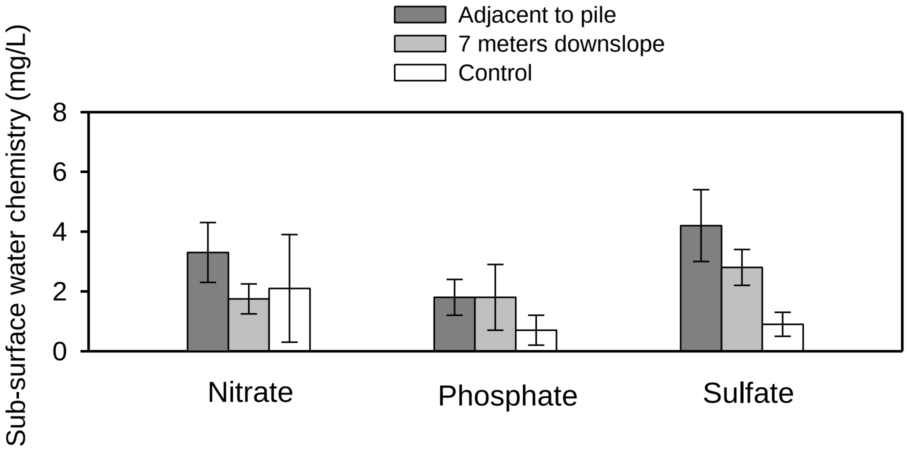


Figure 30. Sub-surface water chemistry in the second year after pile burning.

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V. Appendix.

Inventory summary of pile conditions, site location, and ownership (see Figure 1 for the site map). Systematically-located plots (0.1 ha) were nested within each site to determine pile conditions. Pile types (wood, slash, small-slash) are listed in order from most common to least common at a site.

	**Washoe** Pile type: wood Ave pile diameter: 3.3 m (range = 3.0- 3.4 m) 10.7 ft (range = 10-11 ft) Pile density: 79/ha (32/acre) Ground coverage: 6% (range = 5-6%) Location: Ownership: California State Parks

	**Donut** Pile types: slash; wood Ave pile diameter: 3.5 m (range = 2.1-5.5 m) 11.4 ft (range = 7-18 ft) Pile density: 166/ha (67/acre) Ground coverage: 15% (range = 11-17%) Location: Ownership: Forest Service

	**Meeks** Pile types: slash; wood; small-slash Ave pile diameter: 2.6 m (range = 1.5-3.4 m) 8.5 ft (range = 5-11 ft) Pile density: 183/ha (74/acre) Ground coverage: 10% (range = 6-14%) Location: Ownership: Forest Service

	**Emerald Bay I** Pile types: wood; slash Ave pile diameter: 3.7 m (range = 3.5-4.0 m) 12 ft (range = 12-13 ft) Pile density: 89/ha (36/acre) Ground coverage: 10% (range = 7-15%) Location: Ownership: Forest Service

	**Emerald Bay II** Pile types: wood; slash Ave pile diameter: 3.4 m (range = 3.0-3.5 m) 11 ft (range = 10-12 ft) Pile density: 89/ha (36/acre) Ground coverage: 8% (range = 7-8%) Location: Ownership: Forest Service

Bliss

Pile types: slash; wood

Ave pile diameter: 4.9 m (range = 4.3-6.1 m)
16 ft (range = 14-20 ft)

Pile density: 72/ha (29/acre)

Ground coverage: 15% (range = 8-29%)

Location:

Ownership: California State Parks

Camp Caspian

Pile types: wood; slash; small-slash

Ave pile diameter: 3.7 m (range = 3.0-3.9 m)
12 ft (range = 10-12 ft)

Pile density: 124/ ha (49/acre)

Ground coverage: 12% (range = 6-16%)

Location:

Ownership: Forest Service

Chinkapin

Pile types: slash; wood; small slash

Ave pile diameter: 3.0 m (range = 1.8-4.3 m)
10 ft (range = 6-14 ft)

Pile density: 213/ha (86/acre)

Ground coverage: 15% (range = 12-18%)

Location:

Ownership: Forest Service

	**McKinney** Pile types: slash; wood Ave pile diameter: 2.7 m (range = 1.5-6.4) 9 feet (range = 5-21 ft) Pile density: 126/ha (51/acre) Ground coverage: 8% (range = 2-14%) Location: Ownership: Forest Service

	**High Meadows** Pile type: wood Ave pile diameter: Pile density: Ground coverage: 26% (range = 15-34%) Location: Ownership: Forest Service

	**My Backyard** Pile types: wood; slash; small-slash Ave pile diameter: 4.0 m (range = 3.0-6.4 m) 13 ft (range = 10-21 ft) Pile density: 79/ha (32/acre) Ground coverage: 9% (range = 12-18%) Location: Ownership: Forest Service

Lower Sugar Pine

Pile types: wood; slash; small-slash

Pile density: 151/ha (61/acre)

Ave pile diameter: 3.0 m (range = 2.4-4.0 m)
10 ft (range = 8-13 ft)

Ground coverage: 13% (range = 6-24%)

Location:

Ownership: California State Parks

Spooner Lake

Pile types: wood; slash

Ave pile diameter: 4.0 m (range = 2.1-5.8 m)
13 ft (range = 7-19 ft)

Pile density: 40/ha (16/acre)

Ground coverage: 5% (range = 3-9%)

Location:

Ownership: Nevada State Parks

431

Pile types: slash; wood; small-slash

Ave pile diameter: 2.4 m (range = 1.5-3.4 m)
8 ft (range = 5-11 ft)

Pile density: 62/ha (25/ac)

Ground coverage: 3% (range = 2-3%)

Location:

Ownership: Private

	**Old Mill** Pile types: small-slash; slash; wood Ave pile diameter: 2.4 m (range = 1.8-2.7) 8 ft (range = 6-9 ft) Pile density: 64/ha (26/acre) Ground coverage: 3% (range = 1-4%) Location: Ownership: Private

END OF DOCUMENT:

Effects of Pile Burning in the LTB on Soil and Water Quality

by Hubbert, Busse and Overby

September 30, 2013