

RESEARCH ARTICLE

PILE BURNING EFFECTS ON SOIL WATER REPELLENCY, INFILTRATION, AND DOWNSLOPE WATER CHEMISTRY IN THE LAKE TAHOE BASIN, USA

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ABSTRACT

Thinning of conifers followed by pile burning has become a popular treatment to reduce fuel loads in the Lake Tahoe Basin, USA. However, concern has been voiced about burning within or near riparian areas because of the potential effect on nutrient release and, ultimately, lake water quality. Our objective was to quantify the effects of pile burning on soil physical and chemical properties and resulting near-stream surface and sub-surface water chemistry. Twenty-seven hand-built piles of three contrasting fuelbed types (large wood, mixed-diameter slash, small-diameter slash) were burned. Burn sites were located throughout the basin and included both granitic and volcanic parent materials as well as glacial outwash. We suspected that post-fire changes in soil physical and chemical properties would ensue as maximum soil surface temperatures averaged 400 °C for all pile types and exceeded 200 °C for >30 h beneath large-wood piles. Post-fire soil water repellency

RESUMEN

El raleo de coníferas seguido de la quema en pilas se ha convertido en un tratamiento popular para reducir la carga de combustible en la cuenca del lago *Tahoe*, EEUU. Sin embargo, hay una preocupación manifiesta sobre las quemadas dentro o cerca de las áreas riparias, debido al efecto potencial en la liberación de nutrientes y, en última instancia, en la calidad del agua lacustre. Nuestro objetivo fue cuantificar los efectos de la quema en pilas sobre las propiedades físicas y químicas del suelo y sus efectos en la química del agua superficial y sub-superficial. Veintisiete pilas construidas a mano con tres tipos contrastantes de cama de combustibles (troncos grandes, restos de ramas de diámetros variados, restos de ramas de pequeño diámetro), fueron quemadas. Los sitios de quema fueron localizados a través de la cuenca, incluyéndose materiales parentales graníticos y volcánicos, como así también arrastres glaciales. Nosotros suponemos que los cambios post-fuego en las propiedades físicas y químicas del suelo podrían ocurrir con una temperatura máxima en la superficie del suelo de 400 °C en promedio para todos los tipos de pilas, y también de aquellas que, por debajo de las pilas con troncos grandes, excedieron los 200 °C por más de 30 h. La repe-

was greatest for large-wood piles, yet increased for all pile types when soil moisture content fell below a threshold of 7% to 10% during the dry summer season. Soil bulk density increased moderately whereas water infiltration rates decreased more than fourfold after burning of large-wood piles and mixed-slash piles. Surface runoff and subsurface flow concentrations of nitrate, phosphate, and sulfate were measured downslope from the piles at 6 mo and 18 mo after burning. Mean NO_3 , ortho- PO_4 , and SO_4 concentrations were low ($<10 \text{ mg L}^{-1}$) at both sampling dates and typically declined downslope from the pile edge. The results showed that pile burning—regardless of fuel composition—had a limited effect on downslope water quality despite associated changes in soil physicochemical properties.

lencia del agua post-fuego fue mayor para las pilas de troncos grandes, aunque aumentó para todos los tipos de pilas cuando el contenido de la humedad del suelo bajó a un valor límite de 7% a 10% durante la estación seca de verano. La densidad de la masa del suelo se incrementó moderadamente mientras que las tasas de infiltración de agua decrecieron más de cuatro veces después de quemar las pilas de troncos grandes y aquellas con la mezcla de restos de ramas. La escorrentía superficial y las concentraciones del flujo sub-superficial de nitratos, fosfatos y sulfatos fueron medidas desde las pilas y ladera abajo 6 meses y 18 meses después de quemar. Las concentraciones medias de NO_3 , orto- PO_4 , y SO_4 fueron bajas ($<10 \text{ mg L}^{-1}$) en ambas fechas de muestreo y declinaron en forma típica ladera abajo desde el borde de la pila. Los resultados mostraron que, sin tener en cuenta la composición del combustible, las quemas en pilas tuvieron un efecto limitado en la calidad del agua ladera abajo, a pesar de los cambios asociados en las propiedades físico-químicas del suelo.

Keywords: fuel reduction, hydrophobicity, overland flow, pile burning, soil heating, water chemistry

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INTRODUCTION

Suppression of wildfire in the Lake Tahoe Basin (LTB), USA, has resulted in an accumulation of surface and aerial fuels and increased forest density, increasing the risk of high-severity fire (Weatherspoon *et al.* 1992). To help remove accumulated fuels, pile burning of slash and forest residues from thinned conifers and shrubs has been adopted by most agencies and land owners. However, concern has been voiced about pile burning within or near stream environment zones (SEZs). Elevated soil temperatures during burning contribute to the destruction of soil organic matter, degrada-

tion of soil structure and porosity, alteration of hydraulic properties, and changes in nutrient cycling and microbial processes (Frandsen and Ryan 1986, Campbell *et al.* 1995, Certini 2005). Additionally, post-fire soil water repellency can limit infiltration and promote surface erosion (Shakesby *et al.* 2000). Heat-induced changes also affect soil nitrate (NO_3), ortho-phosphate (PO_4), and sulfate (SO_4) status and facilitate their movement in surface overland flow, with potential implications for lake functions and processes (Stephens *et al.* 2004, Miller *et al.* 2006).

Burn piles consisting of large wood generally burn longer and produce more heat than

piles generated from smaller diameter thinning slash (Shea 1993, Busse *et al.* 2013). Busse *et al.* (2013) reported temperatures as high as 600 °C at the soil surface below large-wood piles in the LTB, with soil temperatures remaining above 400 °C for >12 h at the surface and 5 cm depths. Massman and Frank (2004) also found temperatures >400 °C at the soil surface beneath a large slash pile. The potential for considerable changes in soil properties at this temperature range is well established in literature. Soil water loss occurs from 60 °C to 100 °C and nitrifying bacteria are destroyed between 75 °C to 140 °C, limiting the early post-burn release of available NO₃ (DeBano *et al.* 1977, Esquilin *et al.* 2007). Destructive distillation of soil organic matter occurs at 200 °C to 315 °C (Esquilin *et al.* 2007) while nitrogen (N) is volatilized at temperatures ranging from 300 °C to 500 °C (Hungerford *et al.* 1991). Volatilization of sulfur (S) occurs at temperatures of 350 °C to 800 °C (Tiedemann 1987, Neary *et al.* 1999), whereas Raison *et al.* (1985) noted that phosphorous (P) is volatilized at temperatures approaching 775 °C. After severe fire, the consumption of organic bonding agents decreases soil aggregation, resulting in an increase in soil bulk density and reduction in infiltration rates (Giovannini *et al.* 1988, Fernandez *et al.* 1997).

Temperatures approaching 175 °C to 250 °C result in the release of organic volatiles capable of condensing on soil particles and inducing soil water repellency (DeBano *et al.* 1976). When present, near-surface repellency may alter water infiltration and promote overland flow of water and sediments (Wells 1981). The net effect of this process is difficult to predict, however, given the high degree of spatial variability in water repellency commonly found on the landscape (Hubbert *et al.* 2006, Spigel and Robichaud 2007). Doerr *et al.* (2006) also noted that burning can destroy water repellency at the soil surface and significantly increase the persistence of subsurface repellency. In many cases, long periods of hot,

dry weather allow both natural and heat-induced soil water repellency to become reestablished (Crockford *et al.* 1991, Dekker *et al.* 1998, Shakesby *et al.* 2000), particularly as soils dry below a threshold of 10% to 13% water content (Dekker *et al.* 2001, MacDonald and Huffman 2004, Hubbert and Oriol 2005). Fungal hyphae are also well recognized for their contribution to water repellency in the forest floor and mineral soil regardless of soil water content (Savage *et al.* 1969).

Nutrient loading from tributary streams, surface runoff, fine soil particles, atmospheric deposition, and anthropogenic manipulation (such as fire) have contributed to increased algal growth and a 0.3 m yr⁻¹ decline in Lake Tahoe water clarity in recent decades (Reuter and Miller 2000). Nitrogen and P, in particular, are the primary nutrients stimulating algal growth. In this regard, Miller *et al.* (2006) measured sporadic increases in inorganic N and P concentrations in overland flow at the interface between the mineral soil surface and the duff layer after wildfire in the LTB. Miller *et al.* (2005) measured even higher (although also sporadic) surface-flow N and P concentrations at an unburned site outside of the LTB. Therefore, an immediate concern of fuel reduction projects is their proximity to SEZs, where the potential exists to exacerbate nutrient and sediment runoff in streams.

Higher elevations in the Sierra Nevada have warmed approximately 1 °C in the last 30 years, resulting in longer summer droughts, doubling of tree mortality rates, extension of the fire season, and a greater proportion of precipitation falling as rain instead of snow (Stephenson 2008). Given these climatic changes, forest ecosystems in the LTB will increasingly be managed to reduce fire hazards with a continued emphasis on pile burning. Increased winter precipitation falling as rain will accelerate soil saturation, leading to potential increases in overland and subsurface lateral flow of soluble nutrients to tributary streams. The objective of this study was to determine the ef-

fect of pile burning on soil physiochemical properties and nutrient loading in overland and subsurface flow away from burn piles. We compared post-fire changes in soil water repellency, soil bulk density, infiltration, and water chemistry among piles of differing fuel composition. Our research was designed to provide resource managers with knowledge of post-burn soil physical and chemical properties relevant to lake clarity and forest health when treating fuels within SEZs.

METHODS

Site Description

The study was conducted at seven locations distributed around the LTB, California and Nevada, USA (centered at 120°W, 39°N): Spooner Lake State Park (upper and lower sites), Mill Creek, Sugar Pine Point State Park, D.L. Bliss State Park, Washoe Meadow State Park, and the Angora Fire (see Busse *et al.* 2013 for a site map). Elevations ranged from 1905 m at Bliss State Park to 2225 m at Upper Spooner Lake. Climate in the LTB is characterized by cold, wet winters and warm, dry summers. Mean annual precipitation is 78.4 cm with most falling as snow between November and April.

Soils are formed primarily from andesitic volcanic rocks in the northern portion of the LTB and granodiorite in the south. Valley bottoms and lower hill slopes are covered with glacial outwash material derived from the parent rock. All soils are coarse textured (<15% clay), ranging from gravelly loamy coarse sands (granodiorite) to very cobbly sandy loams (volcanic), and are moderately infertile. Organic matter content in the surface 10 cm depth ranges from 2% to 6% for granitic soils and 7% to 11% for volcanic soils. Granitic soils are somewhat excessively drained while volcanic soils are moderately well drained. Rock fragment content is relatively high, ranging from 5% to 30% on granitic soils and

15% to >35% on the volcanic derived soils. Soil available water-holding capacity is low, ranging from 8% to 10% on the granitic soils to 11% to 15% on the volcanic soils. Soils mapped on granitic terrain at Bliss, Sugar Pine, and Spooner Lake state parks are mixed, frigid Dystric Xeropsammets. Soils at the Mill Creek site are derived from andesite and are mapped as fine-loamy, isotic, frigid Ultic Palexeralfs. Soils at Washoe State Park and the Angora Fire site were formed from mixed glacial outwash and are mapped as sandy-skeletal, mixed, frigid Humic Dystroxerepts (USDA Natural Resources Conservation Service 2007).

The LTB landscape is dominated by conifer forests with a mosaic of riparian vegetation and dry and wet meadows. Since the 1850s, wildfire suppression, logging, domestic livestock grazing, and urban expansion have changed the species composition and structure of the conifer forests, resulting in higher stand densities and more shade-tolerant, fire-sensitive tree species (Taylor 2004). Tree species in the study area now include Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.), white fir (*Abies concolor* Lindl.), red fir (*Abies magnifica* Murr.), lodgepole pine (*Pinus contorta* Dougl.), incense cedar (*Calocedrus decurrens* Torr.), and sugar pine (*Pinus lambertiana* Dougl.).

Sampling Design and Field Methods

Seven sites and a total of 27 burn piles were selected. Burns of three pile types were compared: large-wood piles = piles dominated by wood >22.5 cm in diameter; mixed-slash piles = piles containing a mix of small diameter (<7.5 cm) and medium diameter (7.5 cm to 22.5 cm) slash, with occasional bolts of large wood (<10% of pile volume); small-slash piles = piles dominated by small-diameter slash. All piles were hand built from dead and downed materials generated either by insect infestation (Spooner Lake sites only) or during hand-thinning operations (Figure 1a). No me-



Figure 1. Photo sequence showing (a) hand-built large-wood pile, (b) large-wood pile during burning, (c) near-complete fuel consumption of large-wood pile, (d) cross-section of post-fire ash layer with fine roots present in the mineral soil.

chanical equipment was used during thinning or piling operations. Thermocouples attached to data loggers were placed in the soil at 0 cm (surface), 5 cm, 10 cm, and 30 cm depths beneath the pile center (see Busse *et al.* 2013 for details of pile construction and heat pulse measurements). All piles were burned in late fall 2009 with the exception of those at the Angora site, which were burned in fall 2010. Soil moisture content was low at all sites ($0.03 \text{ cm}^3 \text{ cm}^{-3}$ to $0.10 \text{ cm}^3 \text{ cm}^{-3}$) at the time of burning (see Busse *et al.* 2013). Fuel consumption was nearly complete (about 90%) for all piles, with a 3 cm to 15 cm post-fire charcoal and ash layer commonly found (Figure 1b, c, d).

Two overland flow collectors were installed downslope from each pile prior to burn-

ing: one adjacent to the pile edge and the other 7 m distant. The collectors, modeled after those designed by Miller *et al.* (2006), were installed at the interface between the forest floor and mineral soil. A third collector was placed at a cross-slope location not influenced by the pile to serve as a control. Pre-burn samples were collected in October 2009 following a major rain event. Post-burn samples were collected in 2010 and 2011 following spring snowmelt. Animal damage to the collectors and unfavorable (dry) weather prevented sample collection at the Spooner Lake sites in 2010.

Four zero tension lysimeters (ZTL) were positioned downslope from the burn piles: one on either side of each overland collector (pile

edge; 7 m away from pile). The ZTLs were modeled after those developed at Ames Laboratory (Ames Lab Environmental & Protection Sciences Program 2013) and were designed to collect mobile soil water (water that moves under the influence of gravity alone). Additionally, a control ZTL (not influenced by downslope water movement from piles) was placed adjacent to the overland flow control collectors. The top of each ZTL was placed 15 cm below the soil surface. Samples were collected in late spring 2011 following snowmelt. Subsurface flow was not collected in 2010 because below-average precipitation for the 2009 hydrologic water year did not allow soils to reach saturation.

Soil Water Repellency and Soil Moisture Content

Soil water repellency and moisture content (SMC) were measured near the center of each pile in the first year after burning. Sampling commenced on 4 June 2010, six months after burning and shortly after spring snowmelt, and continued monthly through September 2010. Repellency was also measured on unburned soil at each sampling, at a minimum of 3 m from each pile. Using the water drop penetration time method (Krammes and DeBano 1965), 20 water drops were placed within a 30 cm square on the mineral soil surface and at 5 cm and 10 cm depths. Drop penetration time was recorded using a stopwatch. For field collection purposes, we used the following drop penetration time classification scheme: 0 s to 1 s = not repellent, 1 s to 5 s = very low repellency, 5 s to 30 s = slight repellency, 30 s to 180 s = moderate repellency, and >180 s = high repellency (Robichaud 1996). These water repellency indices were further modified by combining 0 s to 1 s and 1 s to 5 s, and 30 s to 180 s and >180 s to give the following classification scheme: 0 s to 5 s = wettable, 5 s to 30 s = slight repellency, and >30 s = moderate and higher repellency (Hubbert and Oriol 2005).

Volumetric soil moisture content was sampled concurrently at the surface and at 5 cm and 10 cm depths using a SM200 Moisture Sensor (Delta-T Devices, Cambridge, England, United Kingdom).

Infiltration and Soil Bulk Density

Hydraulic conductivity (infiltration under a unit hydraulic gradient) was measured using a Mini Disc infiltrometer (MDI; Decagon Devices, Inc., Pullman, Washington, USA) and field methods of Robichaud *et al.* (2008). Three measurements were made within each burn scar in September 2010, about 0.5 m from the water repellency test locations. Post-fire ash layers were carefully removed before infiltration rates were measured on the mineral soil surface. Infiltration was calculated using methods provided in the MDI User's Manual Version 6, with a suction rate of 2 cm for the LTB soils. Soil bulk density was determined using the hollow-core method (Blake and Hartge 1986) on three 0 cm to 5 cm depth samples collected near the center of each pile.

Soil and Water Chemistry

Solution chemistry was measured on soil samples (0 cm to 10 cm depth) collected in early June 2010 from the center of each pile. Samples were sieved to 2 mm, then extracted with deionized water (60 ml water: 20 g soil) for 30 minutes using a wrist-action shaker (Burrell Scientific, Pittsburgh, Pennsylvania, USA), filtered using ashless quantitative filter paper (2.5 μ m pore size; Whatman Inc., Florham Park, New Jersey, USA), and stored at 4°C prior to analysis. Water samples from the ZTL and overland flow collectors were filtered using ashless quantitative filter paper prior to analysis. Soluble anions and cations were analyzed using ion chromatography (DX500; Dionex Corp., Sunnyvale, California, USA). Anion analysis followed US EPA Method 300.0 protocols (EPA 1993) using a Dionex IonPac

AS4A anion exchange column, carbonate-bi-carbonate eluent, and suppressed conductivity detection. Cation analysis was accomplished using a Dionex IonPac CS12A cation exchange column, methanesulfonic acid eluent, and suppressed conductivity detection described in ASTM International (2003).

Unpaired student *t*-test *P* values were calculated comparing controls with post-burn soil bulk density and water infiltration for large-wood, mixed-slash, and small-slash piles. *P* values were calculated comparing soil solution chemistry between the controls and different pile types. In addition, *P* values were determined comparing differences in subsurface and overland flow NO₃⁻, PO₄³⁻, and SO₄²⁻ concentrations between the adjacent and 7 m collectors, and between the 7 m collectors and controls. Values were considered significant at *P* < 0.05.

RESULTS

Soil Heating

The soil heat pulse varied markedly by pile type and soil depth. Similar maximum temperatures were measured on the soil surface for the three pile types, averaging 400 °C (Figure 2). However, the duration of heat above 200 °C was greatly extended for large-wood piles compared to the other pile types. A stair-step decline in heating was found with increasing soil depth, indicative of the fairly poor heat transfer capability of mineral soil. Mean maximum temperature and heat duration were substantially higher for large-wood piles compared to either mixed-slash or small-slash piles at 5 cm and 10 cm depths, whereas limited heating was detected at 30 cm regardless of pile type.

Soil Water Repellency and Soil Moisture Content

Water repellency on the soil surface varied by pile type and time of sampling. Moderate

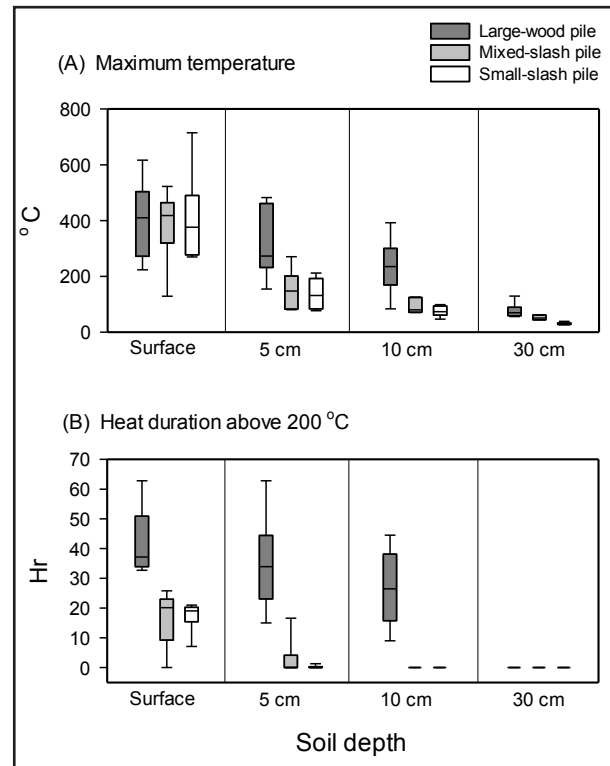


Figure 2. Maximum temperature (A) and heat duration above 200 °C (B) reached during burning at the soil surface and 5 cm, 10 cm, and 30 cm depths for large-wood, mixed-slash, and small-slash piles. Error bars are the 10th and 90th percentiles, the lower and upper edges of each box are 25th and 75th percentiles, respectively, and the horizontal line within each box is the median.

to high repellency beneath small-slash piles increased from 1 % of all samples in June to 79 % in September as SMC declined from 21 % to 4 % (Figure 3). Repellency beneath mixed-slash piles increased from 45 % to 86 % from June to July, and to 96 % in September as SMC dropped from 17 % to 5 %. Repellency below large-wood piles was 75 % in June, then increased to 96 % in July as SMC dropped to 5 %. For unburned control samples, repellency increased from 17 % in June to 59 % in September as SMC decreased from 20 % to 4 %.

At the 5 cm depth, repellency for all pile types showed a steady increase throughout the summer as SMC declined (Figure 3). Repellency beneath small-slash, mixed-slash, and large-wood piles increased from 1 % to 45 %, 1 % to 45 %, and 1 % to 45 %, respectively.

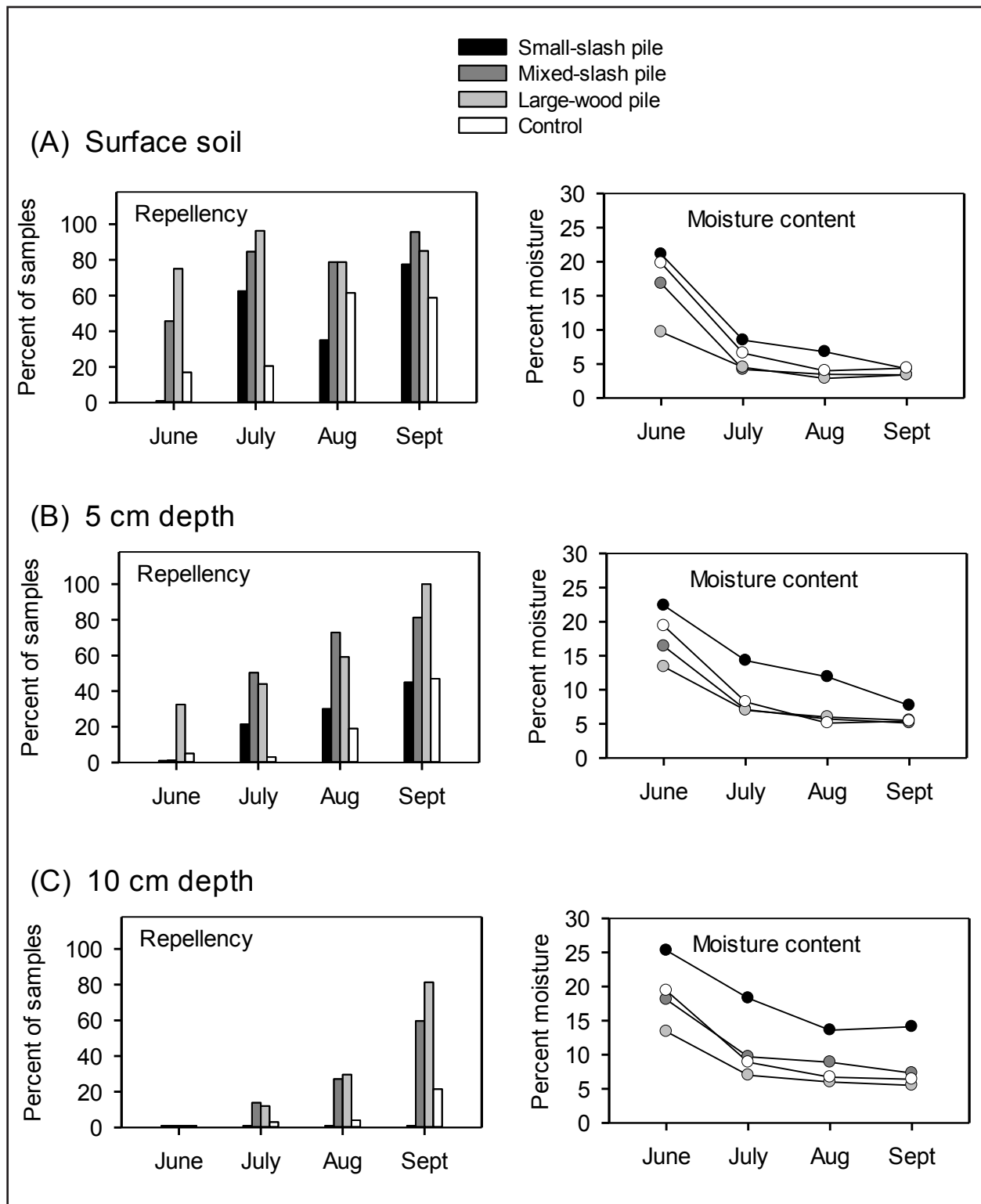


Figure 3. Persistence of soil water repellency in relation to soil moisture content at the (A) surface, (B) 5 cm depth, and (C) 10 cm depth in small-slash, mixed-slash, and large-wood pile scars from June 2010 to September 2010. Water repellency values represent the percentage of samples in the moderate and higher repellency category (water drop penetration time >30 s) for each sampling date and pile type.

1 % to 81 %, and 33 % to 100 %, respectively, between June and September as SMC dropped below 8 %. Repellency beneath the controls increased from 1 % to 47 % as SMC decreased from 19 % to 5 %.

Water repellency was less pronounced at the 10 cm depth, but exhibited a similar increase with declining SMC as found at the 5 cm depth (Figure 3). Repellency beneath mixed-slash piles, large-wood piles, and control sites increased from 1 % to 60 %, 1 % to 81 %, and 1 % to 22 %, respectively, as SMC dropped below 7 %. For small-slash piles, there was no change in repellency throughout the summer (remaining at 1 %) as SMC decreased from 25 % to 14 %.

Bulk Density and Infiltration

Soil bulk density increased moderately for all pile types following burning, whereas water infiltration was reduced below large-wood piles and mixed-slash piles only (Figure 4). Bulk density increased by 21 %, 9 %, and 13 % for large-wood, mixed-slash, and small-slash piles, respectively, although these changes were not statistically significant at $P < 0.05$. Although water infiltration was 4-fold lower beneath large-wood piles compared to adjacent unburned soil, the results were not significant ($P = 0.061$). Water infiltration beneath mixed-slash piles was significantly (6-fold) lower than unburned soil ($P = 0.011$). In contrast, burning resulted in a 2-fold greater infil-

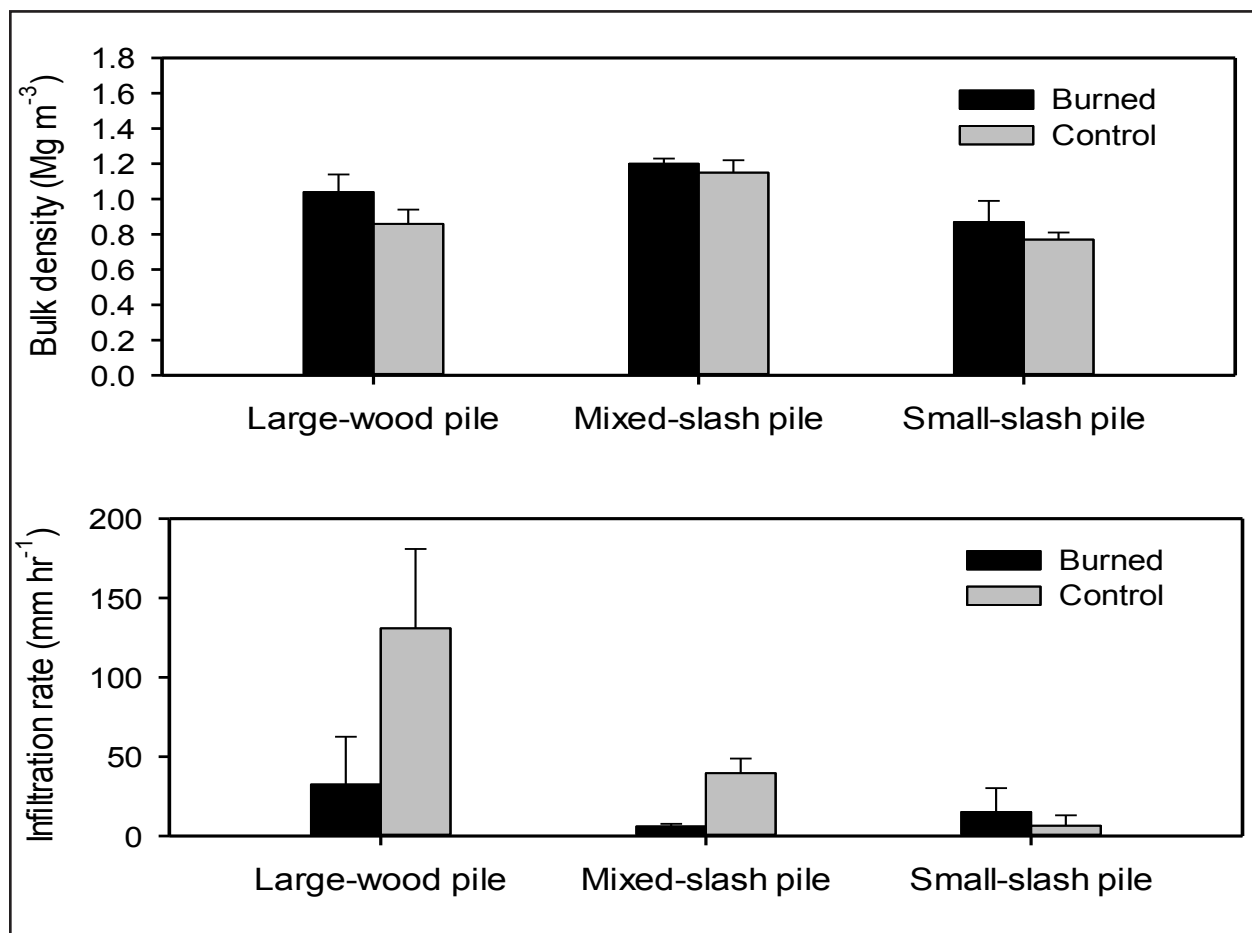


Figure 4. Infiltration rate and soil bulk density compared between burned and control sites for large-wood, mixed-slash, and small-slash piles.

tration rate beneath small-slash piles compared to unburned soil ($P = 0.326$).

Soil Solution, Subsurface, and Overland Flow Chemistry

Post-fire soil solution ammonium (NH_4) concentration (0 cm to 10 cm soil depth) was 1.2 mg kg^{-1} for large-wood piles, and 7.9 mg kg^{-1} and 27.3 mg kg^{-1} for mixed-slash and small-slash piles, respectively (Figure 5). Ammonium concentrations for unburned controls were below 5 mg kg^{-1} for all pile types. Nitrate (NO_3) levels were $<3.0 \text{ mg kg}^{-1}$ for large-wood and small-slash piles. The highest post-burn NO_3 concentration of 14.2 mg kg^{-1} was recorded beneath the mixed-slash piles, but was not significantly different than the control ($P = 0.129$). Phosphate (PO_4) concentrations remained $\leq 4.0 \text{ mg kg}^{-1}$ for all pile types and their respective controls. Post-fire sulfate (SO_4) concentrations were significantly greater than controls, rising to 23.2 mg kg^{-1} ($P = 0.012$), 23.0 mg kg^{-1} ($P = 0.025$), and 67.5 mg kg^{-1} ($P = 0.007$) beneath the large-wood, mixed-slash, and small-slash piles, respectively.

For all sampling events, there were no significant differences in NO_3 , PO_4 , and SO_4 concentrations for either overland or subsurface flow between the adjacent and 7 m collectors, or between the 7 m collectors and controls. Overland flow NO_3 , PO_4 , and SO_4 concentrations were below 4.0 mg L^{-1} for all sample locations and pile types prior to burning (Table 1). Nitrate and PO_4 concentrations at 6 mo post burn remained low for all samples with the exception of the NO_3 concentration adjacent to the small-slash piles (5.4 mg L^{-1}). Sulfate concentrations were elevated adjacent to the mixed-slash and small-slash piles but remained comparable to the unburned controls at the 7 m downslope location.

At 18 mo post burn, NO_3 , PO_4 , and SO_4 concentrations in subsurface flow were moderately low (Table 1). Overland flow NO_3 concentration decreased from 9.2 mg L^{-1} adjacent to the large-wood piles to 1.7 mg L^{-1} downslope (Table 1). A similar decline was found for mixed-slash piles (5.7 mg L^{-1} adjacent to the piles versus 2.8 mg L^{-1} downslope). In contrast, NO_3 increased from 4.9 mg L^{-1} adjacent to the small-slash piles to 8.7 mg L^{-1}

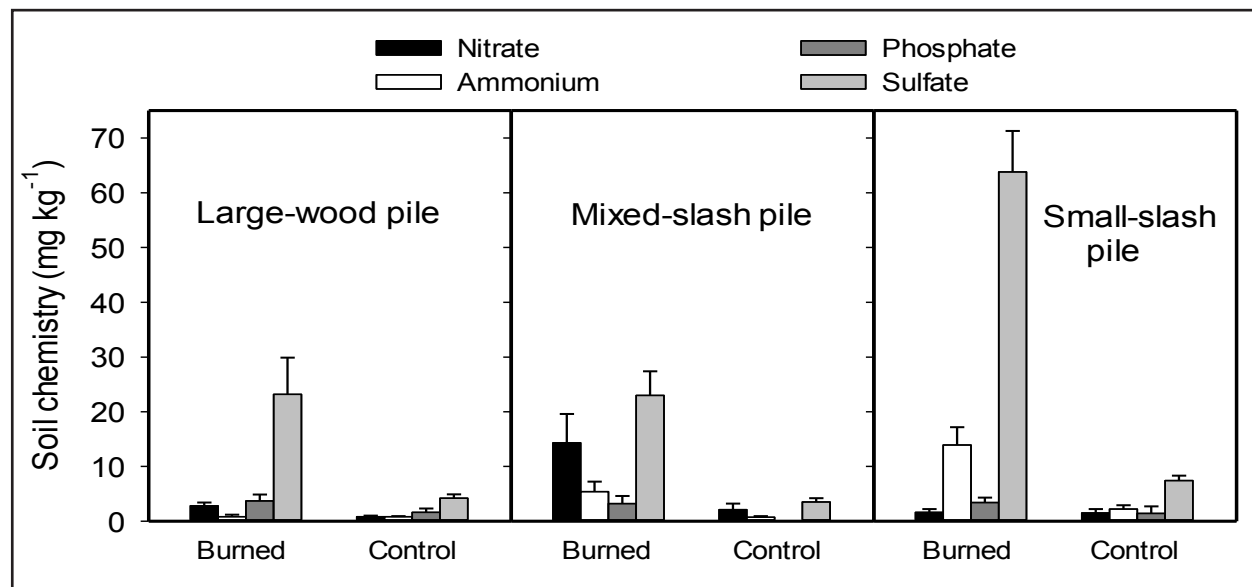


Figure 5. Comparison of soil nitrate, ammonium, phosphate, and sulfate concentrations between burned and control samples (0 cm to 10 cm depth) for large-wood, mixed-slash, and small-slash piles.

Table 1. Means of nitrate, phosphate, and sulfate concentrations in surface and subsurface flow water collected downslope from large-wood, mixed-slash, and small-slash piles. Samples were collected immediately downslope from piles (Adjacent), 7 m downslope (7 m), and in unburned areas not influenced by piles (Control). Collection dates included one month prior to burning (pre-burn), 6 months after burning (2010), and 18 months after burning (2011). Due to damage to collectors in the field, the number of samples at some sites were limited and no SE was calculated.

Pile type	Nitrate (mg L ⁻¹)			Phosphate (mg L ⁻¹)			Sulfate (mg L ⁻¹)		
	Adjacent	7 m	Control	Adjacent	7 m	Control	Adjacent	7 m	Control
Overland flow – pre-burn									
Large wood	1.2 (1.0)	<0.1 ¹	<0.1 ¹	2.3 (1.7)	1.0 (1.6)	<0.1	2.9 (0.9)	1.8 (0.2)	1.2
Mixed slash	1.0 (1.0)	<0.1	<0.1	<0.1	<0.1	<0.1	1.3 (0.2)	1.4 (0.3)	0.3
Small slash	0.6 (0.6)	0.9(0.9)	<0.1	<0.1	<0.1	<0.1	3.5 (1.9)	1.9 (0.5)	0.3
Overland flow – 6 months									
Large wood	ns ²	ns	ns	ns	ns	ns	ns	ns	ns
Mixed slash	0.2 (0.04)	0.3 (0.12)	0.2 (0.0)	1.4 (0.97)	0.1 (0.0)	0.7 (0.0)	5.2 (4.0)	1.1(0.1)	1.2
Small slash	5.4 (0.2)	2.1	0.8	0.4 (0.01)	0.9 (0.8)	0.6	7.1 (5.5)	0.9 (0.2)	1.5
Overland flow – 18 months									
Large wood	9.2 (6.8)	1.7 (5.6)	5.8 (5.0)	4.1 (3.3)	7.4 (2.5)	1.2 (0.03)	2.2 (1.0)	0.5 (0.2)	1.3 (0.6)
Mixed slash	5.7 (3.9)	2.8 (2.5)	1.7 (0.4)	1.5 (0.7)	2.0 (0.1)	1.7 (0.3)	1.1 (0.5)	0.8 (0.3)	0.9 (0.1)
Small slash	4.9 (1.4)	8.7 (7.9)	3.0 (1.4)	1.9 (0.3)	2.7 (1.6)	1.5 (0.2)	1.8 (0.3)	1.2 (0.6)	2.8 (1.6)
Subsurface flow – 18 months									
Large wood	2.4 (1.4)	2.0 (1.1)	<0.1	0.9 (0.4)	1.0 (0.4)	0.5	2.2 (0.5)	2.8 (0.7)	0.4
Mixed slash	1.1 (0.8)	1.5 (0.9)	3.3 (3.1)	3.0 (1.3)	1.0 (0.6)	0.8 (0.8)	5.7 (1.7)	4.2 (0.9)	1.1 (0.6)
Small slash	5.4 (2.3)	0.9 (0.3)	ns	1.7 (0.1)	5.3 (5.4)	ns	8.3 (3.5)	3.1 (1.0)	ns

¹<0.1 below the detection limit

²no sample

downslope. There were few differences in overland flow PO₄ concentrations between the adjacent, 7 m downslope, and control samples, with the exception that PO₄ increased from 4.1 mg L⁻¹ adjacent to the large-wood piles to 7.4 mg L⁻¹ downslope. Sulfate also exhibited little change in concentrations for mixed-slash and small-slash piles, but dropped slightly in concentration at 7 m away from large-wood piles.

DISCUSSION

Effects of Burning and Soil Moisture on Water Repellency

Differences in water repellency among pile types were considerable at the soil surface six

months after burning (large-wood piles > mixed-slash piles > small-slash piles), reflecting the well-known effect of fire on repellency (DeBano 2000). Surface repellency then increased for all treatments during the summer months as the soils dried below about 10% SMC, suggesting a demarcation between water-repellent and non-repellent conditions. Dekker *et al.* (2001) noted that SMC thresholds may resemble a more transitional stage rather than an abrupt change, and a number of studies have shown water repellency to dissipate at a SMC range above 9% to 13% (Dekker *et al.* 2001, MacDonald and Huffman 2004, Hubbert and Oriol 2005). In this study, repellency increased as SMC dropped below a range of about 7% to 10%, which may be

problematic from a standpoint of potential downslope sediment and nutrient movement given that high intensity summer storms are not uncommon in the LTB.

Water repellency steadily increased at soil depths of 5 cm and 10 cm from June to September as SMC decreased. This progression was also noted, although to a lesser extent, for unburned soil. Many studies have reported that summer drying allows water repellency to return (Dekker *et al.* 1998, Shakesby *et al.* 2000). Crockford *et al.* (1991) noted that soil repellency required only six to nine hot, dry days to become reestablished in a sclerophyllous forest in Australia. In our study, however, it appeared that both soil drying and pile burning contributed to water repellency, as noted by the higher level of repellency beneath large-wood piles and mixed-slash piles compared to unburned soil despite similar SMC levels (Figure 3). In contrast, Pierson *et al.* (2008) found that dry-season variability had a greater impact on soil water repellency than fire itself. We believe that the coarse-textured soils in the LTB were a contributing factor to the trends in water repellency based on the observation of Crockford *et al.* (1991) that coarse particles are more prone to coating of hydrophobic compounds than finer particles due to their low surface area per unit volume.

The exact origin of the hydrophobic compounds is unclear. Repellency is intensified at temperatures of 175°C to 200°C (DeBano 2000), yet is thought to be destroyed at temperatures above 270°C (Savage 1974, DeBano *et al.* 1976). From these literature standards, we assumed that most or all hydrophobic compounds would be destroyed during the peak heating phase of the pile burns, which reached 400°C (Figure 2). However, it is likely that residual charred wood contributed hydrophobic compounds to the soil as the burns cooled below the threshold of 270°C. In addition, some hydrophobic compounds were probably volatilized and translocated downward through the soil profile along a

temperature gradient, condensing at cooler temperatures below 5 cm depth (DeBano *et al.* 1976). We also recognize that temperature guidelines for repellency formation or destruction are not definitive since they were developed using artificial soil conditions (disturbed sands) and controlled heat sources—conditions that may not reflect the natural variation in fuel loading or soil properties common to field settings. In contrast to the burned soils, repellency of the control soils was attributed to fungal mycelia that were prevalent at the mineral soil-duff interface at the time of sampling. Hubbert *et al.* (2006) found soils with fungal mycelial mats highly repellent regardless of SMC, even during extended rain events.

Soil Bulk Density and Water Infiltration

Pile burning resulted in a moderate, non-significant increase in soil bulk density for all pile types, equivalent to a decline in total porosity of 5% to 10% (assuming a particle density of 2.65 g cm⁻³). Seymour and Teale (2004) found even smaller changes in soil bulk density and total porosity following pile burning in soils with fairly high clay content and initial bulk densities. Others, however, have noted sharp increases in bulk density following prescribed burning, which were attributed to the loss of soil aggregation caused by the destruction of organic glues and fungal mycelia (Giovannini *et al.* 1988, Hubbert *et al.* 2006). In some cases, aggregation of fine particles into larger silt-sized particles during extreme heating has resulted in a reduction of the clay fraction (Ulery and Graham 1993) and, presumably, a corresponding increase in bulk density.

A four- to six-fold decline in water infiltration was found following burning of large-wood piles and mixed-slash piles, which can only be partially attributed to the moderate reduction in total porosity. This is not too surprising given the assortment of soil phys-

iochemical factors that influence water infiltration (Larsen *et al.* 2009). We suggest that a combination of water repellency and pore plugging complemented the effect of reduced porosity, leading to the post-fire changes in infiltration. Interestingly, all infiltration measurements were made in September when the soils were dry and water repellency was high for burned and unburned soils alike (Figure 3). This suggests that repellency may not have been a primary factor explaining the differences in infiltration between burned and unburned soil. Alternatively, unbound particles at the soil surface (mainly ash mixed with fine mineral soil) are easily mobilized and transported into soil pores after fire and can effectively clog or seal the soil surface (Larsen *et al.* 2009). We found layers of white ash, from 20 mm to 80 mm thick, covering the soil following burning (Figure 1). The ability of ash layers to plug soil pores is not well understood, however. Post-burn ash is generally considered hydrophilic (Cerdeña 1998) and may even raise surface hydraulic pressure, allowing for greater preferential flow in soil (Bodi 2012). In fact, Larsen *et al.* (2009) observed very little clogging of pores when the post-fire ash and mineral soil mixture was comprised of mostly sand-sized particles like those of LTB soils. Clearly, further research is needed to understand the driving forces that limit water infiltration following pile burning.

Unlike the hotter burns, there was slightly greater water infiltration beneath the small-slash piles compared to unburned soil. Repellent mats of fungal mycelia were noted at the mineral soil-duff interface below the small-slash piles prior to burning, and we believe it was the consumption of these mats that allowed for increased infiltration. Rice and Grismer (2010) also noted a widespread presence of hydrophobic fungal mats between the mineral soil and duff layer in unburned LTB soils that acted to restrict water infiltration.

Soil Solution, Subsurface, and Overland Flow Chemistry

Ammonium concentrations normally increase following moderate to severe fire (Certini 2005), although excessive N loss can occur if temperatures approach 600 °C (Kutiel and Shaviv 1989). More often, burning leads to incomplete organic matter combustion, increased protein denaturation, and, as a consequence, increased soil NH_4 availability (Certini 2005, Johnson *et al.* 2011). Accordingly, a flush of NH_4 was noted for the mixed-slash and small-slash piles in which concentrations were five to ten times greater than those of unburned soil. No spike in NH_4 was detected beneath the large-wood piles, however, which likely reflected the more extreme soil temperature, heat duration, and, presumably, N volatilization loss compared to the other pile types.

Post-fire conversion of NH_4 to NO_3 by nitrifying bacteria is one of several crucial steps leading to off-site transport of inorganic N. Nitrate is negatively charged, poorly adsorbed to soil colloids, and thus highly mobile in soil solution (Johnson *et al.* 2011). After burning, NO_3 leaching losses are usually nominal for several months as the conversion of NH_4 to NO_3 is constrained by the temporary reduction of nitrifying bacteria. A spike in NO_3 availability and movement is then common once the nitrifying population recovers (Johnson *et al.* 2011). In our study, soil NO_3 concentrations were low beneath large-wood piles and small-slash piles in spring 2010 (6 mo after burning). This reflected the impact that heating has on nitrifying bacteria and, in the case of large-wood piles, the low post-fire concentration of NH_4 substrate (Figure 5). As a consequence, the initial NO_3 concentrations in the overland flow collectors were far below the EPA standard threshold of 10 mg L^{-1} . Esquilin *et al.* (2007) also found that pile burning immediately reduced the bacterial community size and resulted in low soil NO_3 levels. Low NO_3 concentrations were also reported beneath

upland and meadow slash piles immediately after burning (Johnson *et al.* 2011).

Higher NO_3 runoff levels were measured following the 2011 winter, 18 months after burning, compared to the initial post-fire samples. This observation agrees with the conclusion of Certini (2005) that a NO_3 pulse can appear in runoff well after a fire event, concomitant with the reestablishment of nitrifying bacteria. Nevertheless, the higher NO_3 concentrations at 18 months remained below the EPA threshold of 10 mg L^{-1} for the protection of aquatic ecosystems (United States Environmental Protection Agency 2013) and were within the range of concentrations reported by Miller *et al.* (2006) for surface runoff from wildfire-burned and unburned plots in the LTB ($<0.5 \text{ mg L}^{-1}$ to 8 mg L^{-1}). With respect to the potential for post-fire NO_3 transport to Lake Tahoe waters, we note that not only were the surface flow NO_3 levels low (in agreement with Miller *et al.* 2006), but they additionally declined from the pile edge to 7 m downslope in most cases. We surmise that the downslope dilution of surface NO_3 was due to a combination of percolation, root and microbial uptake, and the natural filtering ability of litter and duff layers. Allowing fire to creep between piles may exacerbate NO_3 movement in SEZs due to the loss of plant and litter cover. Larsen *et al.* (2009) noted that loss of plant and litter cover is a primary factor affecting post-burn hydrologic response.

There was little subsurface movement of NO_3 away from the pile scars at 18 months, as NO_3 concentrations were well below EPA water standards for all pile types. We did observe greater nutrient flow on volcanic parent material (small-slash piles) as compared to the granitic parent material (large-wood piles and mixed-slash piles), but these increases were not statistically significant. This may be a function of the inherent capacity of volcanic soils to maintain continuous preferential flow paths for nutrient transport as compared to coarse-textured granitic soils for which prefer-

ential flow is rapidly dissipated (Burcar *et al.* 1994).

Soil solution SO_4 was greater for burned compared to unburned soil across all pile types (Figure 5). This was not unexpected since (1) the largest portion of S in forest soils is found in litter and duff (Mitchell *et al.* 1989), (2) S is not volatilized at the temperatures measured in our burns, and, instead, (3) SO_4 sulfur is primarily mineralized (released in available form) during the consumption of large woody material and soil organic matter (Chorover *et al.* 1994, Murphy *et al.* 2006). Lower SO_4 concentrations were found in surface and subsurface water samples compared to the soil directly below the pile center. We attribute this dilution to post-fire SO_4 leaching beneath the pile scars (Johnson *et al.* 2011) and uptake by plant growth bordering the piles. From an ecological standpoint, sulfates are not considered damaging to plants or animals at concentrations ranging between about 2 mg L^{-1} and 30 mg L^{-1} (United States Environmental Protection Agency 2013). In our study, neither runoff nor subsurface concentrations of SO_4 were above 10 mg L^{-1} (Table 1).

As with NO_3 and SO_4 , there was no significant increase in post-burn PO_4 runoff, nor was there any significant change in subsurface flow of PO_4 . Our results for pile burning support the observations made by Murphy *et al.* (2006) that showed no significant effects of broadcast prescribed fire on soil solution PO_4 or on the cumulative leaching of PO_4 .

CONCLUSIONS

Soil temperatures averaged 400°C at the soil surface for all pile types and remained above 200°C for >30 hr at the surface beneath the large-wood piles. Persistence of moderate and higher soil water repellency was greatest below large-wood piles, and increased beneath all pile types as the soil dried below about 7% to 10% SMC through the summer season. Water repellency and reduced soil porosity

contributed to a considerable decline in water infiltration rate. Despite post-fire increases in repellency and decreases in surface water infiltration, runoff and subsurface flow concentrations of NO_3 , PO_4 , and SO_4 exhibited little change from the pile edge to 7 m downslope for the three pile types. It appeared that litter and plant cover surrounding the piles were important in taking up and filtering out nutrients

as they moved downslope from the burn pile. In all cases, runoff and subsurface flow concentrations of NO_3 and PO_4 remained below EPA water quality standards for lakes and rivers. Our study findings apply to (1) hand-built piles ranging in fuel composition from small-diameter slash to mostly large-diameter wood, and (2) the coarse-textured, relatively low fertility soils of the LTB.

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