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The effects of soil texture and ash thickness on the post-fire hydrological response from ash-covered soils

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SUMMARY

Ash increases the post-fire hydrological response to rainfall in some situations but decreases it in others, and the reasons for this variability are not well defined. We used simulated rainfall experiments to determine whether the varying hydrological effect of ash can be attributed to differences in the underlying soil texture or the ash thickness. We compared the infiltration rates: (1) before and after controlled burns in 0.5 m^2 plots underlain by two sharply contrasting soil textures (sandy loam and gravelly silt loam), and; (2) before and after the addition of 0.5, 2.5 and 5.0 cm of ash to the burned sandy loam plots with the original ash layer removed. The controlled burns left a ~1 cm ash layer comprised mostly of silt and fine sand particles that clogged the largest pores in the sandy loam soil, reducing the final infiltration rate from 91 mm h^{-1} to 35 mm h^{-1}, but had no effect on infiltration in the silt loam plots. Pore clogging also reduced the final infiltration rate by 20 mm h^{-1} (40%) and the total infiltration by 16 mm (24%) when 0.5 cm of ash was added to the sandy loam plots. However, increased storage in the ash layer combined with slight increases in the final infiltration rate (by 5 and 18 mm h^{-1}, respectively), increased the total infiltration by 16 mm (30%) and 18 mm (26%), respectively with the thicker ash addition treatments. Thus, the varying effect of ash on infiltration and runoff can be at least partially attributed to between-site differences in soil texture and ash thickness. A thin ash layer (<1 cm) overlying a coarse or macroporous soil will clog the larger pores, increasing the hydrological response, whereas the same ash overlying a fine or non-macroporous soil will have no effect. With thicker ash layers (2–5 cm) storage effects increasingly delay and reduce the runoff response to the point where no overland flow is produced regardless of any pore clogging effect in the underlying soil.

1. Introduction

Recently burned landscapes are often blanketed by a layer of ash formed by the combustion of vegetation and the litter and duff layers during the fire. The ash thickness and its physical and chemical characteristics depend upon the fuel density, fuel moisture content, type and quantity of fuels present, and the fire severity (Ulery et al., 1993; Neary et al., 2005). While there is a general consensus that ash affects the immediate post-fire hydrological response, the existing literature is somewhat contradictory as to what this effect actually is. The most common view is that ash contributes to the general tendency towards increased runoff after fire by causing surface sealing and by creating a hydraulically smoother surface (Campbell et al., 1977; Wells et al., 1979; Mallik et al., 1984; Etiegni and Campbell, 1991; Neary et al., 2005; Lavee et al., 1995; Onda et al., 2008; Gabet and Sternberg, 2008). Surface sealing may be caused by the deposition of a low conductivity ash layer on the soil surface (Gabet and Sternberg, 2008), post-depositional compaction of the ash by raindrop impacts (Onda et al., 2008), or the clogging of soil pores by ash particles (Mallik et al., 1984). The calcium oxide found in highly combusted ash can swell when wetted, and this may contribute to pore clogging (Etiegni and Campbell, 1991). However, only three studies have documented a reduction in infiltration due to ash with field or laboratory measurements (Mallik et al., 1984; Gabet and Sternberg, 2008; Onda et al., 2008). Most recent field-based studies have found that the ash layer increases infiltration, primarily by intercepting and storing rainfall (Cerda, 1998a; Leighton-Boyce et al., 2007; Cerda and Doerr, 2008; Woods and Balfour, 2008; Larsen et al., 2009; Zavala et al., 2009).

To some extent, the contradictory results of previous studies may reflect differences in methodology, time since burning, or the scale of measurement. However it is highly probable that the effect of ash on infiltration and runoff does vary between sites, and that this reflects differences in site characteristics such as the physical properties of the ash and soil and the ash thickness. For example, surface sealing and a consequent reduction in infiltration should

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be more likely to occur in coarse soils because there is a greater probability that the ash will have a lower hydraulic conductivity than the soil and because the larger pore size in the soil matrix increases the potential for pore clogging. Increasing the ash thickness should add to the available water storage capacity, thus increasing the time to ponding and the total infiltration, and perhaps offsetting any reduction in infiltration capacity due to surface sealing. Such effects are consistent with hydrological theory, but the extent to which they can explain between-site variability in infiltration in ash-covered soils has not been determined. To address this research gap we used two simulated rainfall experiments to address the following three hypotheses: (1) coarser grained soils are more susceptible to surface sealing by ash than finer grained soils; (2) the runoff response from ash-covered soils decreases with increasing ash thickness because of the increased water storage capacity; and (3) the interacting effects of varying soil texture and ash thickness can create complex hydrological responses in ash-covered soils.

2. Methods

2.1. Study sites

The rainfall simulation experiments were conducted at six sites within the 11,000 ha Lubrecht Experimental Forest (LEF), located 80 km east of Missoula, Montana, USA. LEF has a semi-arid montane climate and elevations range from 1200 to 1350 m. The mean annual temperature is 7 °C and the mean annual precipitation is 55 cm, of which almost half falls as snow (Nimlos, 1986). Rain storm intensities in western Montana range from 12 mm h^{-1} for the 1-h, 2-year return period event to 130 mm h^{-1} for the 5-min 100-year return period event. The dominant tree species at LEF are Douglas fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*), with scattered western larch (*Larix occidentalis*) and lodgepole pine (*Pinus contorta*) (Methlen and Fiedler, 2006). Three of the six sites, designated G1, G2 and G3, were located on sandy loam soils formed from quartz monzonite and belonging to the Winkler Soil Series while the other three sites, designated B1, B2 and B3, were located on gravelly silt loam soils formed from metasedimentary rocks of the Pre-Cambrian Belt Supergroup and belonging to the Crow and Courville Soil Series (USDA Soil Survey, 1995).

At each site, four 2 m × 1 m plots (designated A, B, C and D) with similar slope, aspect and ground cover were marked with stakes and divided in half (Fig. 1). The upper half was used for ash and soil sampling. A 0.5 m^2 sub-plot with a 0.15 m high steel perimeter inserted 0.05 m into the mineral soil in the center of the lower half of the plot was used for the rainfall simulations. Soil texture in each plot was verified prior to the experiments by collecting a sample from the 0 to 5 cm depth interval and determining the particle size distribution using laser diffraction (Malvern Mastersizer; Malvern Instruments Ltd., Malvern United Kingdom). Soil texture was classified in accordance with USDA (1994).

2.2. Burning experiment

To determine whether the effect of ash on infiltration depends on the underlying soil texture, we compared the hydrological response to simulated rainfall in the two soil types before and after controlled burns that formed an ash layer on the soil surface. Pre-burn rainfall simulations were conducted in all four plots at each of the six sites in July and August 2006 (see Section 2.4 *for rainfall simulation procedures*). Woody fuel consisting of logs and branches up to 5 cm in diameter from the dominant tree species at LEF (see Section 2.1) was then added to each plot to achieve a fuel loading equivalent to 90 Mg ha^{-1}, which is typical of high severity wildfires within the dry forests of western Montana (*personal communication* Dr. Ron Wakimoto, Wells et al., 1979). The plots were burned over two consecutive days in September 2006. Relative humidity at the time of ignition ranged from 30% to 56% and the ambient air temperature ranged from 17 to 30 °C. The duration of active burning ranged from 30 to 40 min, with maximum flame heights of 1.0–1.3 m.

Soil temperatures during the burns were monitored with thermocouple probes installed at the soil surface and at 0.5 cm intervals to a maximum depth of 2.5 cm in each plot. Due to the possibility that the probes could be deflected by roots and stones during installation, the exact depths were determined by excavating them after the burns. All of the sites were monitored for 72 h after burning had ceased to allow for smoldering and cooling. No rainfall occurred during this period, after which the plots were covered with tarpaulins to prevent wetting by rainfall prior to the first post-fire measurements.

The first set of post-burn rainfall simulations was conducted in plots A and B at the six sites within 2 weeks after the controlled burns. A fine mesh screen was placed over one of the two plots to determine whether surface sealing due to raindrop impacts contributed to any observed reduction in infiltration. A second set of post-burn simulations was conducted in July 2007, approximately 10 months after the plots were burned. In the original study design this second set of post-burn simulations was only to be conducted in plots C and D at each site to avoid the confounding effects of the first set. However, in October 2006 site G3 was seriously damaged by logging equipment so that the second set of post-fire simulations

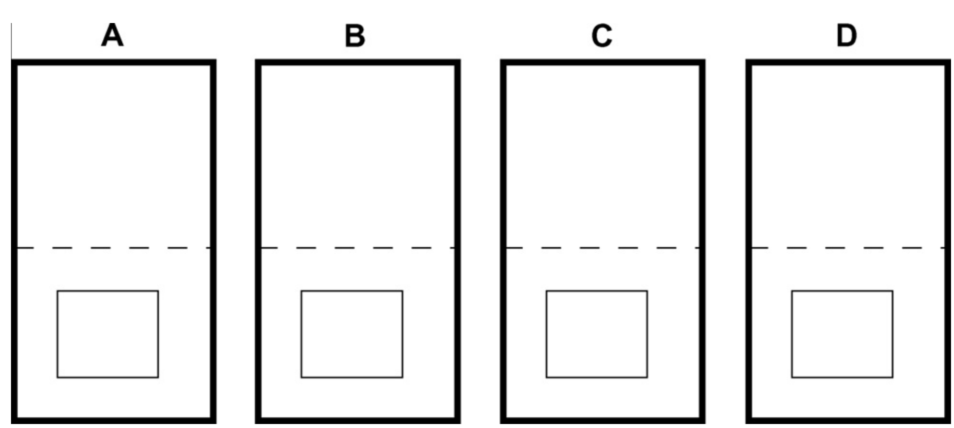

Fig. 1. Layout of plots and sub-plots within each site. Each site had four 2 × 1 m plots (A–D), (indicated by thick outlines), with a 0.5 m^2 sub-plot in the center of the lower half (indicated by thin outlines) for rainfall simulations.