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Comparison of soil infiltration rates in burned and unburned mountainous watersheds

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Abstract:

Steady-state infiltration measurements were made at mountainous sites in New Mexico and Colorado, USA, with volcanic and granitic soils after wildfires and at comparable unburned sites. We measured infiltration in the New Mexico volcanic soils under two vegetation types, ponderosa pine and mixed conifer, and in the Colorado granitic soils under ponderosa pine vegetation. These measurements were made within high-severity burn areas using a portable infiltrometer with a 0·017 m^2 infiltration area and artificial rainfall rates ranging from 97 to 440 mm h^{-1}. Steady-state infiltration rates were less at all burned sites relative to unburned sites. The volcanic soil with ponderosa pine vegetation showed the greatest difference in infiltration rates with a ratio of steady-state infiltration rate in burned sites to unburned soils equal to 0·15. Volcanic soils with mixed conifer vegetation had a ratio (burned to unburned soils) of at most 0·38, and granitic soils with ponderosa pine vegetation had a ratio of 0·38. Steady-state infiltration rates on unburned volcanic and granitic soils with ponderosa pine vegetation are not statistically different. We present data on the particle-size distribution at all the study sites and examples of wetting patterns produced during the infiltration experiments. Published in 2001 by John Wiley & Sons, Ltd.

KEY WORDS wildfire; infiltration; New Mexico; Colorado

INTRODUCTION

Wildfires alter the infiltration response of burned watersheds by changing both the physical and chemical characteristics of the watersheds. The most significant effects are evident in watersheds subjected to high-severity burns, characterized by the combustion of all of the organic forest floor material, the presence of a deep ash layer, the alteration of the soil-mineral layer, and charring of the organic matter in the soils (Miller, 1994). The unburned forest floor consists of a litter layer (uppermost layer of the forest floor with recognizable leaves, needles, fine twigs, bark flakes, matted dead grass, mosses and lichens, O1 soil horizon; USFS, 2001) and a duff layer (partially decomposed remnants of the material in the litter layer, O2 soil horizon; Brown and Smith, 2000). These layers absorb most of the rainfall, provide ample storage, and obstruct the flow of water. The combustion process converts the litter and duff layers into ash and charcoal. Ash and small soil particles can seal soil pores (Morin and Benyamini, 1977; Neary *et al.*, 1999), decreasing the infiltration rate (Fuller *et al.*, 1955; Barfield *et al.*, 1981) and increasing potential runoff and erosion. When the charcoal and ash are removed from the hillslope by post-fire runoff or wind, the soil is left bare soil to rain splash and overland flow.

Chemical changes that affect infiltration may be as significant as physical changes. Combustion of organic matter during fire can produce volatile organic gasses that coat soil particles with water-repellant substances, thereby reducing infiltration rates (DeBano, 1981). This effect is thought to be more pronounced in coarser-grained soils where pore sizes are larger than in finer-grained soils (DeBano *et al.*, 1970; Doerr *et al.*, 1996).

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However, laboratory tests have shown that this is not a consistent pattern (Robichaud and Hungerford, 2000). A greater quantity of water-repellent substances may be produced when areas with greater fuel loads are burned or when certain vegetation types, like chaparral, are burned (DeBano, 1981), though naturally occurring water-repellent soil conditions have been observed in unburned soils. Burning reduces soil organic matter, alters the soil pH, and impinges on soil microbiological communities (Clark, 1994), all of which will have an effect on infiltration rates. Heat-induced changes in infiltration rates have been measured in the laboratory (Burgy and Scott, 1952: Robichaud and Hungerford, 2000), after prescribed fire (Arend, 1941; Zwolinski, 1971; Scott, 1993; Robichaud, 2000), and at various times after wildfires (Krammes and DeBano, 1965; Imeson *et al.*, 1992; Pradas *et al.*, 1994; Kutiel *et al.*, 1995; Benavides-Solorio and MacDonald, 2001). Measurements of infiltration rates after wildfire are often limited to rainfall simulations in areas accessible by roads.

In this study we measured infiltration rates using a portable rainfall simulator that allowed us access to remote sites. Our objective was to quantify differences in infiltration rates due to wildfire in two mountainous watersheds with different soil types: a volcanic soil near Los Alamos, New Mexico, burned by the Cerro Grande Fire, and a granitic soil near Pine, Colorado, burned by the Hi Meadow Fire.

Background

The Cerro Grande Fire near Los Alamos, New Mexico (Figure 1), occurred on the eastern flank of the Jemez Mountains and the western side of the Parajito Plateau, and burned nearly 1700 ha in May 2000 (BAER, 2000). Volcanic rocks, either welded or non-welded tuffs or andesite flows, underlie both the Jemez Mountains and the Parajito Plateau (Griggs, 1964). The area is in a semi-arid environment with a summer monsoon wet season from July through September, and covers an elevational range from about 2200 to 3000 m. Los Alamos

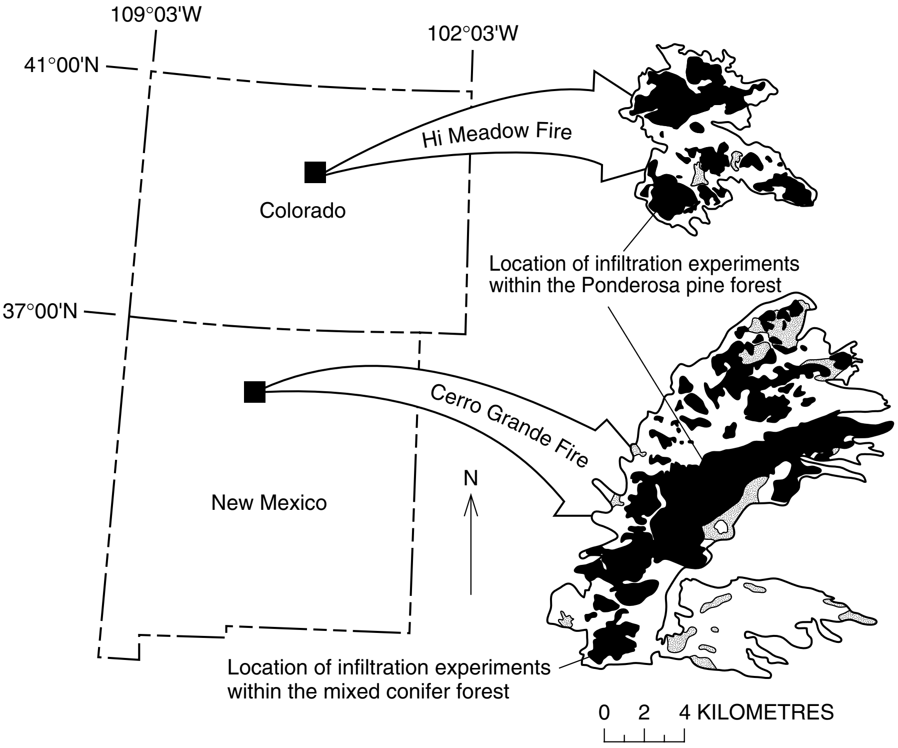

Figure 1. Locations of two wildfires that burned in 2000 and the respective study sites. The black areas were classified as high-burn severity, the crosshatched areas as moderate-burn severity, and the white areas as low-burned severity on the basis of BAER (2000), and Hart (2000)

is at 2259 m and receives 490 mm of mean annual precipitation (Nyhan *et al*., 1978). Three major overstory vegetation types occurred in the burned area: (1) ponderosa pine forest (*Pinus ponderosa*); (2) mixed conifer forest consisting of four species: ponderosa pine (*P. ponderosa*), white fir (*Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*), and aspen (*Populus tremuloides*); and (3) piñon–juniper forest consisting of one-seed juniper (*Juniperus monosperma*) and piñon (*Pinus edulis*) (Balice *et al*., 1997). From visual observations within the Cerro Grande fire perimeter, we estimated that the stem density, a measure of the fuel loading, was about 3000 stems ha^{-1} in the ponderosa pine and mixed conifer forests. These estimates are of the same order of magnitude as measurements in the same area by Balice *et al.* (2000). Before the fire litter and duff layers in these forests were between 0·5 and 3 cm thick.

The Hi Meadow fire near Pine, Colorado, southwest of Denver (Figure 1) burned 450 ha in June 2000 (Hart, 2000). The area is underlain by the Pikes Peak batholith that weathers to grüs or decomposed granite a few centimetres to several metres thick (Moore, 1992). The burned area covers an elevational range of about 2100 to 2700 m and receives about 430 mm of mean annual precipitation (based on data for Bailey, Colorado; Colorado Climate Center, 2001). The predominant overstory vegetation type within the burn perimeter was ponderosa pine forest (*P. ponderosa*). Our visual estimate of the stem density within the Hi Meadow fire area was 400 stems ha^{-1}. The total thickness of the pre-fire litter and duff layers was usually less than 1 cm.

METHODS

We made infiltration measurements in three areas within 1 to 4 months after each wildfire was contained. Burned study areas were selected within the ponderosa pine forest in Rendija Canyon (Cerro Grande fire), the mixed conifer forest in Frijoles Canyon (Cerro Grande fire), and the ponderosa pine forest in Beaver Gulch (Hi Meadow fire). Measurements were also made at the closest unburned sites as a control to determine the effects of wildfire on the infiltration rate. The slopes of the study areas ranged from 6 to 16°. At the Cerro Grande fire, we made infiltration measurements in June 2000 at the severely burned and adjacent unburned sites in both the ponderosa pine and mixed conifer forests, and repeated the measurements at the ponderosa pine forest sites in September 2000. For the Hi Meadow fire, we completed one set of measurements in July 2000.

Equipment

We used a portable rainfall-simulator infiltrometer (McQueen, 1963) for the infiltration measurements (Figure 2). McQueen (1963) lists the main components of the device as (1) a reservoir and control unit, (2) a rainulator, (3) a supporting tripod and wind screen, (4) a base unit containing a splash screen, and (5) a system for measuring runoff water and sediment (a 0·05 m diameter plastic tube with a machined conical tip, calibrated to measure volume in millilitres). We modified the infiltrometer to include an extra strut to stabilize the wind screen further, used silicone cement to seal the cylindrical base unit to the soil (rather than bentonite as specified in the original design), and cut a small notch in the base unit to allow the surface runoff and sediment to drain from the soil *via* a flat metal spout into a container from which we aspirated the runoff into a measuring tube.

The reservoir and control unit permit the application and measurement of controlled volumes of water to the infiltration plot, which is circular in shape and has an area of 0·017 m^2. The rainulator produces raindrops 5·6 mm in diameter. These raindrops, falling the distance from the rainulator to the ground surface (approximately 1·5 m), have an energy value of 0·137 J cm^{-2} cm^{-1} at the normal application rate of about 100 mm h^{-1}. McQueen (1963) estimates that this application rate approximates that of a natural storm with an intensity of about 48 mm h^{-1}.

A major limitation of the McQueen (1963) portable rainfall-simulator infiltrometer is the size of the infiltration plot (0·017 m^2). On the other hand, the size of the equipment and the amount of water needed for the infiltration experiments allowed us to access otherwise inaccessible sites. Issues of scaling up plot-scale

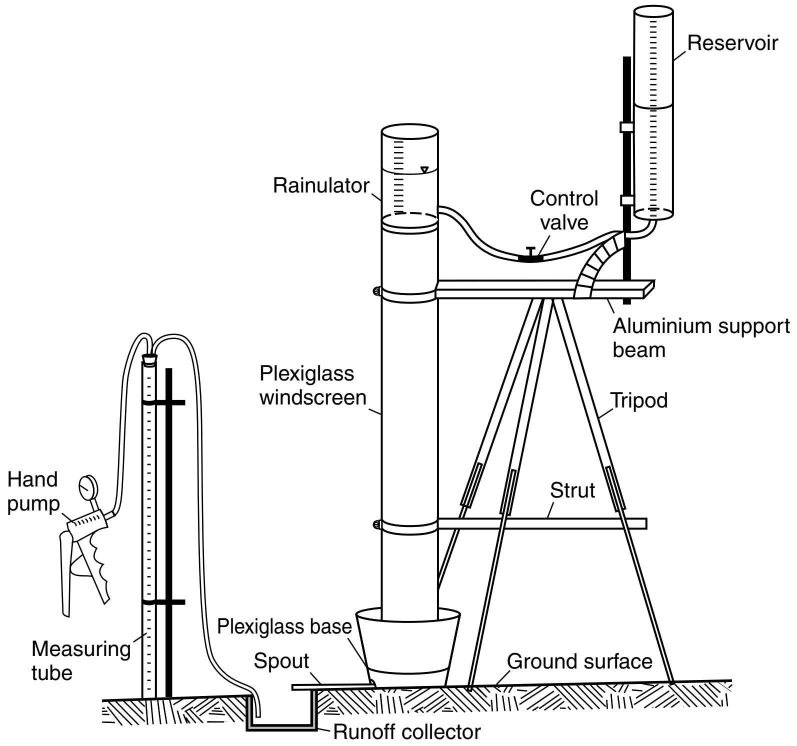

Figure 2. Diagram of the portable rainfall-simulator infiltrometer [modified from McQueen (1963)]

measurements to the watershed scale have been addressed elsewhere, for example by Kirkby *et al.* (1996), Newman *et al.* (1997), and Hendrayanto *et al.* (2000).

The infiltration experiments

We chose study areas to represent the general conditions throughout the rest of the area of interest. At each study area, we selected three to eight replicate sites. An initial infiltration experiment showed that a considerable amount of the applied water was absorbed either by the ash at the burned areas or by the litter and duff in the unburned areas. Therefore, we carefully removed the ash or litter and duff prior to each experiment and collected these materials for further studies. After scraping away the surface material, the base unit and spout were carefully cemented to the ground. While the cement dried we positioned the tripod and windscreen over the infiltration plot and filled both the reservoir and control unit with distilled water. Distilled water was used to minimize variations among experiments due to the chemistry of the local water source. The rain rate from the rainulator was adjusted before the unit was put in place over the windscreen.

Our target was to produce less than 5 mm of runoff per minute once we reached steady-state infiltration rates based on the capacity of the runoff measuring tube, but we did not know *a priori* the steady-state infiltration at a site, nor the variability among replicates. Rainfall rates ranged from 97 to 440 mm h^{-1} in the ponderosa pine forest sites in Rendija Canyon, from 240 to 400 mm h^{-1} in the mixed conifer forest sites in Frijoles Canyon, and from 160 to 300 mm h^{-1} in the ponderosa pine forest sites in Beaver Gulch. We selected rainfall rates iteratively at each site. At the unburned mixed conifer site on volcanic soils we did not produce runoff for two of the replicates because a thick mycorrhizal mat below the soil–duff interface absorbed all of the water applied during our experiment.

Infiltration experiments were conducted for 15 to 20 min, enough time for the infiltration rates to reach steady-state conditions (George Leavesley, USGS, personal communication). We define steady state as that part of the infiltration curve that varies little with time during the experiment. Infiltration rates rapidly decreased to steady-state conditions within 2–3 min. The application rate of the water was adjusted to a steady rate throughout the experiment by modifying the flow rate from the control unit. We recorded the water levels in both the reservoir and control unit. The runoff from the collector draining the infiltration plot was aspirated through an aspiration tube, which was connected through a stopper to the measuring tube. A vacuum was applied to the aspiration tube with a hand pump that was connected to the stopper by a separate tube. The volumes in the measuring tube were also recorded. The data were recorded at 1 min intervals. The temperature of the water was recorded at the beginning and end of the experiment.

The data for the steady-state period were used to calculate an average steady-state infiltration rate for each experiment. Minor variations above and below the steady-state part of the curve reflect the inherent uncertainties in reading the volume marks on the infiltrometer reservoir and control unit. Data for each replicate site were averaged and 95% confidence limits were calculated based on the Student-*t* distribution. Because the infiltration rate is inversely proportional to water viscosity, we adjusted all field measurements made at different temperatures to a constant temperature of 10 °C (CRC, 1987).

Following the experiment, we examined the surface and sub-surface pattern of wetting. The base unit was removed from the plot and measurements of the shape and size of the surface-wetting front were recorded. Starting at the downhill end of the infiltration plot, we excavated vertical slices through the zone wetted by the experiment. Any rocks, roots, or irregularities in the wetting pattern were noted, and a sketch of the pattern at the middle section of the infiltration plot was produced.

Soil characteristics

In order to evaluate the effects of particle-size distribution on infiltration rates, we collected a soil core at each replicate infiltration site. Cores were 0·048 m in diameter and either 0·05 or 0·10 m deep. The soil was dried overnight at 105 °C and the dry sediment sieved by whole ϕ intervals ($\phi = -\log_2$ of the particle size diameter in millimetres; Krumbein, 1934). We averaged the results for each site and calculated D_{16}, D_{50}, D_{84}, and dispersion. Dispersion is a dimensionless number (geometric standard deviation, $\sigma = \sqrt{D_{84}/D_{16}}$, where D_{84} and D_{16} are the diameters at which 84% and 16% of the sediment are finer than the specified diameter; Inman, 1952) that measures the spread of the particle-size distribution and is equal to 1·0 for a distribution with one particle-size class. We created particle-size distribution curves by fitting the data to a third-order polynomial using a cubic spline (Robert Stallard, USGS, personal communication).

RESULTS

Infiltration rates

Steady-state infiltration rates were smaller at all burned sites than at unburned sites (Table I and Figure 3). The volcanic soil in the ponderosa pine forest showed the greatest difference in steady-state infiltration rate. This is highlighted by the ratios of infiltration rates on burned versus unburned soils: 0·15 for ponderosa pine on volcanic soils, at most 0·38 for mixed conifer forest on volcanic soils, and 0·38 for the granitic soil. This ratio provides a relative measure of the effects of burning on infiltration and is useful for comparing disparate sites. Steady-state infiltration rates on unburned volcanic and granitic soils with ponderosa pine forest are not statistically different. The infiltration rate for unburned volcanic soil with mixed conifer forest can only be considered as a lower limit because we were unable to produce runoff at two replicates at this site.

Wetting patterns

Excavation of the infiltration sites indicated a variety of patterns for the wetting profile but, in general, did not indicate any major lateral migration of water. At some infiltration sites, some of the subsurface particles in the volcanic soils were on the order of 10 cm in diameter and represented a significant portion of the infiltration

Table I. Particle-size characteristics and steady-state infiltration rates for volcanic and granitic soils in unburned and burned sites (95% confidence limits are given after the ± symbol)

Location	Forest	Condition	D_{50} (mm)	Dispersion, σ	Bulk density (kg m^{-3})	Number of runs	Infiltration rate at 10 °C (mm h^{-1})
Volcanic soil—Cerro Grande fire							
Rendija Canyon	Ponderosa pine	Unburned	0·73	12·6	1150 ± 160	5	170 ± 80
Rendija Canyon	Ponderosa pine	Burned	0·25	5·6	1010 ± 110	8	26 ± 15
Frijoles Canyon	Mixed conifer	Unburned	0·50	11·2	1000 ± 120	3	>260
Frijoles Canyon	Mixed conifer	Burned	0·75	9·8	960 ± 90	3	97 ± 70
Granitic soil—Hi Meadow fire							
Beaver Gulch	Ponderosa pine	Unburned	1·3	7·7	1210 ± 260	3	120 ± 130
Beaver Gulch	Ponderosa pine	Burned	1·7	8·3	1400 ± 140	3	45 ± 16

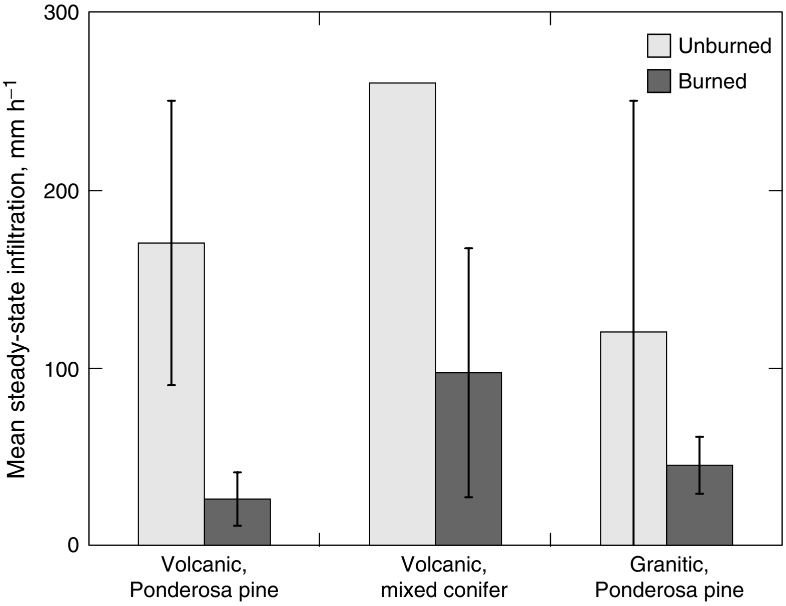

Figure 3. Steady-state infiltration rate in unburned and burned sites

area of 0·017 m^2. These large particles undoubtedly affected the infiltration rate. The wetting profiles often showed pockets of non-wetted soil (Figure 4). Other authors have documented spatial variability of wetting fronts in both unburned and burned soil (Meeuwig, 1971; Imeson *et al.*, 1992, Ritsema *et al.*, 1998).

Surface particle-size distribution

Unburned, volcanic soils were finer (average $D_{50} = 0{\cdot}62$ mm) than unburned, granitic soils ($D_{50} = 1{\cdot}3$ mm) and had a much greater dispersion than the granitic soil (Table I). Both the unburned volcanic soils representing the average of three samples collected from the top 0–0·10 m of soil have a tri-modal distribution with peaks near 0·09 and 1 mm and the largest peak between 8 and 16 mm (Figure 5). The first two peaks of the tri-modal distribution are more pronounced in one sample collected from the top 0–0·05 m and the third peak is much reduced. The differences represent some of the spatial variability of the soils. The 0–0·10 m samples contained soil closer to the weathered bedrock and thus had some larger sizes than the 0–0·05 m sample.

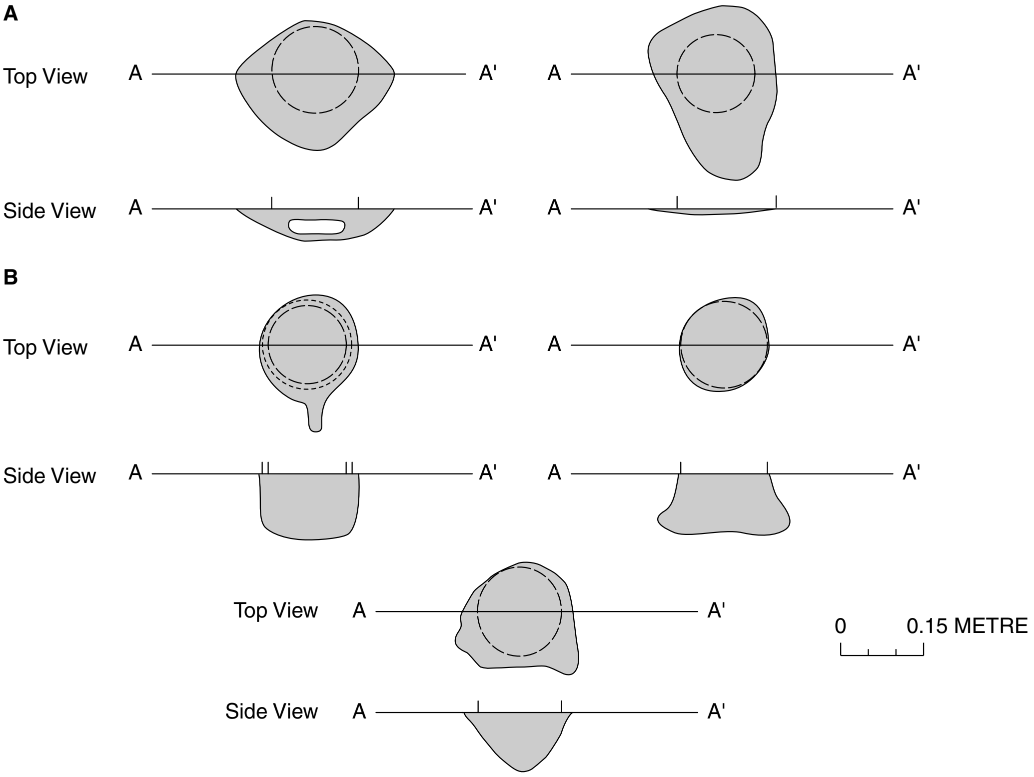

Figure 4. Wetting-front patterns after infiltration measurements. (A) Examples of wetting-front patterns with lateral spreading dominant over vertical penetration. (B) Examples of wetting-front patterns with vertical penetration dominant over lateral spreading. The circles with the dashed line represent the diameter of the rainulator, 15 cm

Unburned granitic soil samples of the top 0–0·10 m were quite different than the volcanic soils and had only one relatively broad peak between 2 and 8 mm (Figure 5B) similar to other unburned granitic soils collected from sites in the adjacent Buffalo Creek fire area (Martin and Moody, 2001; Moody and Martin, 2001). Samples from the top 0–0·05 m were almost identical to the 0–0·10 m samples, and field observations indicated that the weathering profile was thicker on the granitic bedrock than on the volcanic bedrock.

During our infiltration experiments, we observed that surficial ash acts as a storage reservoir for rainfall and initially prevents runoff. Once this storage capacity is exceeded, however, or the ash is washed off, subsequent rainfall may produce runoff. The ash layer often appears black in aerial photographs of burned areas, and a shift toward a lighter colour in subsequent photographs reflects the removal of this ash. The storage effect of the ash was not a factor in the infiltration experiments because we removed it, as well as the litter and duff layer at the unburned sites, so that we only measured the steady-state infiltration rate of the bare soil.

DISCUSSION

Infiltration

Burned volcanic soils with ponderosa pine vegetation show the greatest relative reduction in steady-state infiltration rates. Though we limited our studies to areas classified as high severity (BAER, 2000; Hart, 2000), we think the burn severity of the ponderosa pine site in the Cerro Grande fire was much greater than the burn severity of the mixed conifer volcanic site or granitic site in the Hi Meadow fire as a result of higher

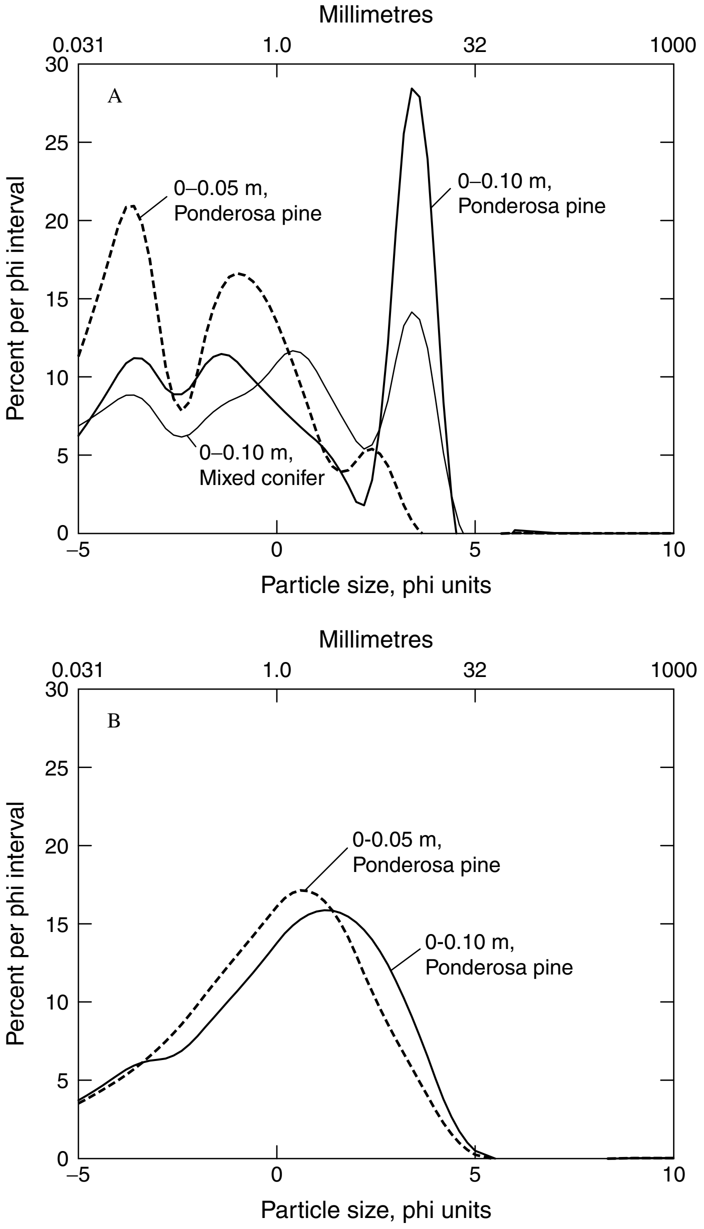

Figure 5. Particle-size distributions for unburned soils. (A) Volcanic soils in two forest types and for 0–0·05 m below the soil surface and 0–0·10 m below the soil surface. (B) Granitic soil for 0–0·05 m below the soil surface and 0–0·10 m below the soil surface

fuel loads. Fuel loadings were higher in the forests burned by the Cerro Grande Fire than those burned by the Hi Meadow fire. The litter and duff layers in the ponderosa pine forest of the Cerro Grande fire were completely combusted, leaving a layer of ash that was white in some locations, indicating hotter temperatures than those areas with black ash (Raison *et al*., 1990). The litter and duff layers in the high-severity sites of the Hi Meadow fire were incompletely combusted, with partially burned needles and no obvious deposits of white ash. Similar observations were noted within the mixed conifer forest site in the Cerro Grande fire and may explain why post-fire steady-state infiltration rates (97 mm h^{-1}) in this area were higher than in the ponderosa pine forest (26 mm h^{-1}). The litter and duff layers in the unburned mixed conifer forest site were thicker (3 cm) than any sites we studied and had a thick mat of mycorrhizal growth below the duff layer. Even the burned soil at the mixed conifer site had the remains of the mycorrhizal mat, which indicated that the heat pulse to the soil was not great enough to combust this organic matter.

Multiple factors bring about the reduction in infiltration rates in burned soils relative to their unburned counterparts. Certainly, fire-induced water repellency is a factor that may contribute to a reduction in infiltration rates, though all of our unburned sites exhibited some naturally occurring water repellency based on water drop penetration tests (Doerr *et al*., 1996). Sealing may also be a factor that reduces surface porosity by the action of raindrop impact on the ash and fine-grained particles. A sealing component was incorporated by Leavesley *et al*. (1989) to model the infiltration rates observed in volcanic soils after the eruption of Mount St Helens in southern Washington, where they measured steady-state infiltration rates of 2 to 5 mm h^{-1}. The sealing process requires a source of fine-grained material. Wildfire produces this in the form of ash, which may swell and clog soil pores (Etiégni and Campbell, 1991). Wildfire may also alter the soil porosity by combusting organic material that binds soil aggregates together (Neary *et al*., 1999).

The particle-size distribution of soil surface layers is a key factor in controlling infiltration rates. The granitic soils were distinctly coarser than the volcanic soils (Table I). Soil water studies on the Pajarito Plateau (Newman *et al*., 1997) indicated that the presence of a homogeneous soil with a well-developed Bt horizon was more important than vegetation type in controlling the flux of water to deeper layers. The effect of wildfire on surface soils with different porosities, organic matter contents, and particle-size distributions is still not well characterized. Discussions by DeBano *et al*. (1970) and Doerr *et al*. (1996) on the one hand, and by Robichaud and Hungerford (2000) on the other hand present conflicting evidence about the magnitude of the effects of wildfire, particularly fire-induced water repellency, on coarse-grained versus finer-grained soils.

Very few measurements of steady-state infiltration rates after a wildfire have been made in mountainous terrain with similar forests. Kutiel *et al*. (1995) measured infiltration rates of 29 mm h^{-1} on burned plots in a pine forest and oak shrubland located in the Mediterranean mountainous region near Haifa, Israel. Imeson *et al*. (1992) measured infiltration rates of 15 to 20 mm h^{-1} in oak forests of northeastern Spain with relatively flat terrain. Both sets of measurements are comparable to those at the burned site of the ponderosa pine forest in the volcanic terrain of Rendija Canyon. The ratio of infiltration rates for burned and unburned sites in the Mediterranean mountains was 0·9, indicating relatively little change, but this ratio ranged from 0·3 to 0·5 for the sites in Spain.

Several experiments have measured effects on infiltration due to prescribed fires. Rates measured on burned and unburned plots in an oak forest in the Missouri Ozarks (Arend, 1941) had a ratio of 0·6. Sites in northern Arizona (Fuller *et al*., 1955) had a ratio of 0·16, which is similar to the ratio for the ponderosa pine site in Rendija Canyon (0·15).

Wetting-front patterns

Wetting-front patterns varied considerably (Figure 4), reflecting both the presence of stones and unwetted zones. Some wetting patterns demonstrated more lateral spreading and had shallow vertical penetration. Others were more confined horizontally with deeper vertical penetration. We were unable to place wetting patterns in generalized categories based on soils, vegetation type, or burn status. By contrast, Meeuwig (1971), while acknowledging that no two wetting patterns were exactly alike, classified wetting-front patterns in granitic soil into eight categories. Imeson *et al*. (1992) nicely depict two examples of complex wetting patterns in 1 m × 0·5 m plots under a burned and unburned soil. Non-continuous zones of water-repellent soil and zones of penetration exist in a complex pattern in response to variations in macropores, vegetation, and both fire-induced and naturally occurring water-repellent soil conditions. Based on the wetting-front patterns we observed after our infiltration experiments, no continuous water-repellent layer was present in the burned soils we studied.

CONCLUSIONS

Our measurements of steady-state infiltration rates after wildfire provide an estimate of the reduction in infiltration compared with rates in adjacent unburned soils. The use of the ratio of steady-state infiltration rates in burned sites to those in comparable unburned soils is an effective method to compare disparate sites. In our studies, volcanic soils with ponderosa pine vegetation showed the greatest reduction in infiltration rates, and this may be a reflection of the burn severity. Qualitatively, we think the New Mexico site with volcanic soils and ponderosa pine vegetation was the most severely burned site we studied, with a ratio of steady-state infiltration rates in burned soils to unburned soils equal to 0·15. The infiltration rates on granitic soils in Colorado with ponderosa pine vegetation were less affected, with a ratio of steady-state infiltration rates in burned soils to unburned soils equal to 0·38. Because the mycorrhizal mat in unburned volcanic soils at the mixed conifer site in New Mexico soaked up all the rainfall we applied, it is difficult to quantify the reduction in infiltration rates, but the ratio is at most 0·38. We measured no statistical differences in infiltration rates on unburned volcanic and granitic soils with ponderosa pine vegetation. Though limited by the small plot size and uncertainties in scaling up from the plot scale to the watershed scale, these ratios provide comparative data that may be useful in empirically based hillslope runoff and erosion models to predict the increase in runoff and erosion as a consequence of wildfires in mountainous terrain.

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