Infiltration Rates After Wildfire in the Bitterroot Valley

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Abstract:

Recent fires have renewed interest in fire's effect on different components of the ecosystem, in particular fire's effects on infiltration and runoff. Forests subjected to high severity burns often develop water repellent soil conditions. Under this condition, the infiltration of water into the soil is lowered and consequently additional runoff occurs. Increased runoff can contribute to surface erosion and lead to sediment deposition in downstream areas.
In this study, a rainfall simulator was used to compare infiltration rates from plots located in high severity burned areas to plots in undisturbed areas on the Sula Ranger District, Bitterroot National Forest in western Montana after the 2000 fire season. Simulated rainfall was applied to 102 0.5 m^2 plots for 60 min at 100 mm hr^{-1}. Bottles collected runoff at 1 and 2-min intervals. There were 15 plots for each of the four burned sites, and 14 plots for the three unburned sites, half of which had their rootmat removed.

Results indicate naturally occurring water repellent soil conditions of the surface on the unburned, rootmat-removed treatment, which had the lowest infiltration rates. The burned plots on the other hand had a water repellent layer centimeters beneath the soil surface. This allowed for some water storage in the surface layer while also maintaining low infiltration rates even below what was expected, especially towards the end of the simulation runs. These results are most likely due to the extremely dry state of the soil and the natural water repellent condition that is common in volcanic ash-cap soils.

Keywords: infiltration, hydrophobicity, rainfall simulator, burn severity, runoff, fires, ash-cap soil

Introduction

Wildfires are naturally occurring events that act as important disturbance mechanisms for ecosystems. Over the last century, land management agencies have intentionally suppressed wildfires under the conjecture that fires are destructive. Fire suppression allows forests to build up biomass, which contributes to the development of high severity fires, particularly across the western United States. When ignited, these large fuel loads may burn at higher intensities and longer durations than under most periodic fire cycles resulting in high severity fires. These fire behavior conditions transfer enormous amounts of heat to the mineral soil (Robichaud at al., 2000). The intense heat can alter the mineral soil structure by closing soil pores (Wells et al., 1979) and destroying fine roots, fire can also reduce soil productivity and increase runoff, thereby causing increased watershed response and downstream sedimentation (Robichaud et al., 2000).

The measurement of fire severity is qualitative and based on the effects the fire has on site resources (Hartford and Frandsen, 1992; Ryan and Noste, 1983). As more forest floor is consumed, more heat is generated, and the degree of burn severity increases. Increased severity gives rise to the potential development of water repellent soil conditions. Water repellency develops when hydrophobic organic matter is vaporized under intense heat from a severe burn and then condenses onto cooler underlying soil layers creating a layer impermeable to water (DeBano, 1966 and 1981; DeBano et al., 1998). The water repellency of soils decreases infiltration rates (Robichaud, 2000) thus leading to an increase in water runoff and downstream sediment yields (Wells et al., 1979). In addition to the water repellency developed in a severe burn, the infiltration rates after wildfires decrease by the sealing of soil pores (Wells et al., 1979), and the exposed soil can be transported easily as sediment (White and Wells, 1982; Giovannini and Lucchesi, 1983; Scott et al.,1998).

Variable degrees of water repellency develop in soils after wildfires. Parameters governing this development are soil texture, antecedent moisture content, fire intensity, and the amount of time following the fire. DeBano (1981) and Robichaud (2000) suggest that infiltration may decrease due to the fire, but will increase with time because the hydrophobic substances responsible for water repellency are slightly water-soluble and slowly dissolve, thereby increasing wettability (Robichaud, 2000). In general, water repellent soil conditions are broken up or washed away within one to two years after the fire (Robichaud, 2000). Studies have also shown that Northern Rocky Mountain forest soils often consist of volcanic ash-cap soils which, when dry and unheated, promote naturally occurring water repellent conditions (Robichaud and Hungerford, 2000).

The objective of this study was to evaluate the effect of high severity fire on infiltration rates into a naturally water repellent ash-cap soil. Our hypothesis was that the severely burned area would have less infiltration due to the water repellent soil condition caused by the fire, but unburned areas would also show traces of pre-existing water repellency.

Methods and Site Description

The study was conducted on the Sula Ranger District of the Bitterroot National Forest in Western Montana during the fall of 2000. Slopes of the plots within the studied areas ranged from 25 to 55 percent with dominantly west-southwestern aspects. The predominant soil is derived from volcanic ash over highly weathered granite and is classified as a sandy skeletal Andic-Dystrocryept. Elevation of the area was approximately 1,950 meters. Vegetation of the area consisted of sub-alpine fir and Menziesia.

The burned study area is located on White Stallion Mountain in the Upper North Fork Rye Creek area. A lightning strike ignited this area and 40 % of the total burned area of 101,000 ha suffered a high severity burn condition as defined by Ryan and Noste (1983). The fire killed all standing trees and consumed all vegetative fuels, leaving the mineral soil covered with ash. Four sites were selected within the study area based on their slope, aspect, proximity to the road, and similar soil and vegetative characteristics. On each of the four sites, 15 0.5 m^2 plots were randomly located. The plots were bordered by 15 cm wide sheet metal inserted vertically 5 cm into the mineral soil.

Three sites were selected in an unburned area located approximately 3 km north of the burned area. These selected sites had slope, aspect, soil type and vegetative characteristics similar to the burned area. On each of the three sites, 14 0.5 m^2 plots were selected. For each site, seven plots had the rootmat removed, leaving the mineral soil exposed, and the other seven plots were not disturbed. The seven undisturbed plots were intended to show the effects organic vegetative matter has on infiltration.

A simulated rainfall event was applied to each of the 102 plots for 60 minutes using the USDA-Forest Service and the USDA-Agricultural Research Service oscillating nozzle rainfall simulators. The mean rainfall intensity was 100 mm hr^{-1}. The rainfall events were conducted on the plots with the existing soil moisture condition. Two soil moisture probes were inserted at 5 and 10 cm below the surface of the plot to monitor changing moisture conditions during the rainfall event. A covered trough at the low end of each plot funneled runoff water and sediment through a valved pipe for timed volume samples. The samples were manually collected in 1000 ml bottles at 1-minute intervals for the first 14 minutes, then at 2-minute intervals for the remainder of the 60-minute run. At the end of each run, any sediment in the trough was washed into a sample bottle. All runoff samples were weighed and oven-dried to determine total runoff volumes and sediment concentrations in order to develop hydrographs and sedigraphs (Robichaud et al., 1994).

Post-burn sampling included the degree of water repellency, depth of water penetration into the soil profile, ash depth, and bulk density. At each plot before simulation began, water repellency was measured using the water drop penetration time (WDPT) method (DeBano, 1981). Eight drops of water were placed in a row on the mineral surface layer next to each plot using an eyedropper. The time the drop remained on the surface in a spherical state was recorded as the penetration time. The maximum time was limited to 5 minutes. If the drop penetrated before 5 minutes then consecutive drops were placed at 1 cm depth increments to a maximum depth of 6 cm. At each increment they were timed for penetration.

Results and Discussion

The average hydrographs for the burned and rootmat-removed treatments showed results that were counter to what was anticipated (Fig.1). The burned plots were expected to produce the highest amount of runoff, but the results showed the unburned plots, with the rootmat-removed, produced the highest amount of runoff.

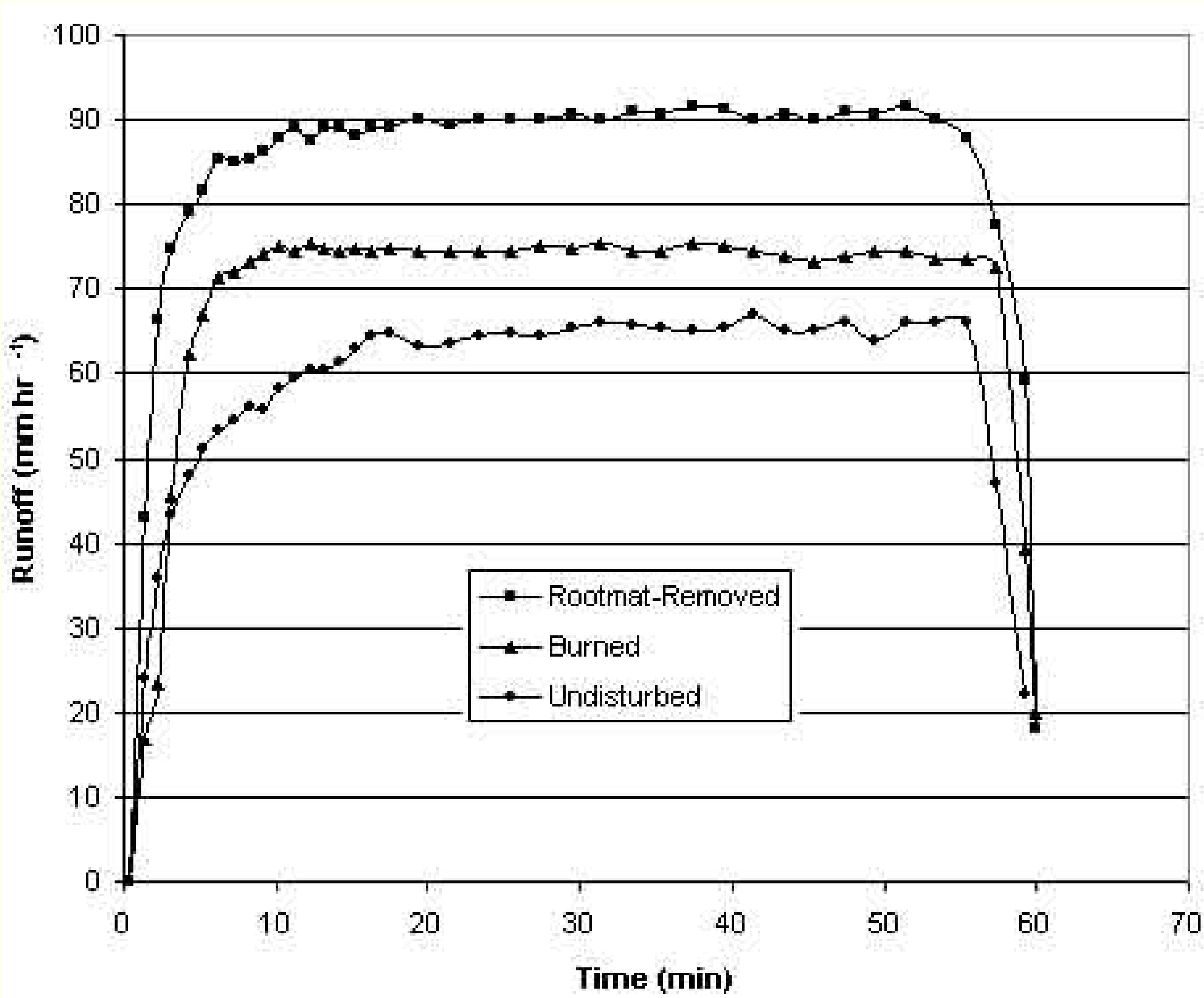


Figure 1. *Average hydrographs from each of the three treatments*

The burned plots averaged approximately 75 mm hr^{-1} while the rootmat-removed averaged approximately 90 mm hr^{-1}. The three plot treatments all produced hydrographs that increased quickly within the first seven minutes, then leveled off and maintained fairly constant runoff rates until the simulated rain event ended at 60 minutes. Robichaud (2000), suggested that under fire-induced water repellent conditions, runoff rates should quickly peak and then begin declining as the hydrophobic substances of the soil are broken down, thus increasing infiltration over time (Fig 2b). He also showed that before a severe burn occurs, little water repellency should exist within the soil (Fig. 2a). The undisturbed hydrograph shows runoff occurring at approximately 13 mm hr^{-1} and no significant detection of a water repellent condition. This is the outcome expected from initially non-water repellent soils in which the organic surface layer absorbs much of the water and slowly allows it to percolate through the soil profile. The hydrograph in figure 2b represents his study for a similar area after a severe burn. Severe water repellent conditions exist, but they decrease as the water soluble hydrophobic substances are broken down and thus the infiltration increases.

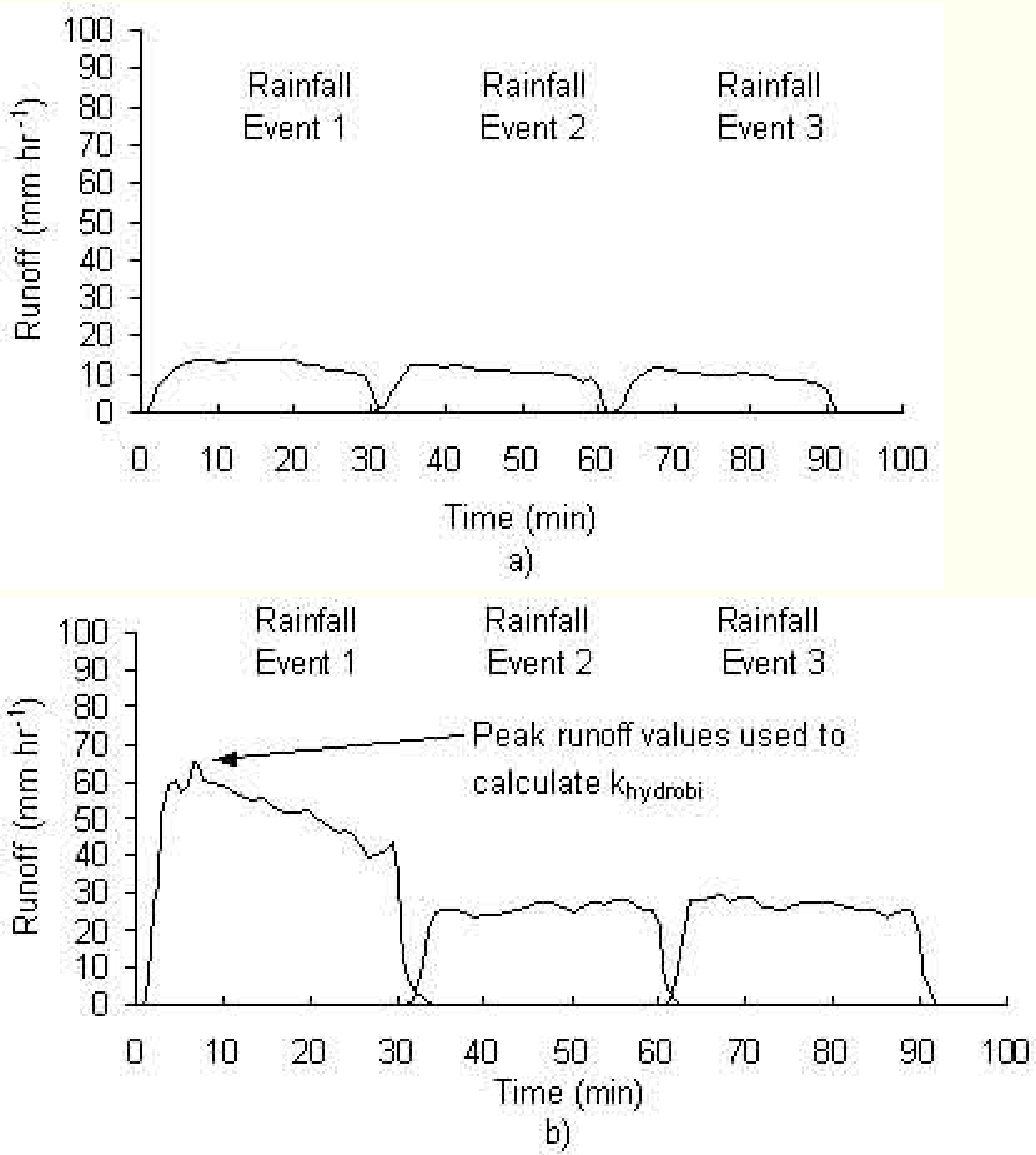


Figure 2. *Hydrographs for a) undisturbed ground cover and b) severe burned, soil type Typic Cryoboralf and Dystric Cryochrept from weathered rhyolite. (Robichaud, 2000, Fig. 2)*

Because the unburned rootmat-removed plots in this study produced more runoff than did the burned plots, the soil must have been naturally water repellent prior to the experiment. To further validate this hypothesis, compare the runoff rates for the undisturbed plots from the two soil types, Figs. 1 and 2a. The naturally repellent soil averages a runoff rate around 65 mm hr^{-1} while the non repellent soil averages around 15 mm hr^{-1}. The studies conducted in this paper and in Robichaud (2000) were within close proximity to one another and used similar procedures. The results suggest that the different soils played a part in infiltration rates. The previous study area involved soil types of Typic Cryoboralf and Dystic Cryochrept, which are both formed from weathered rhyolite. These soils do not exhibit naturally water repellent conditions. Ash-cap soils are especially water repellent when low in moisture and unburned as shown by lab studies conducted by Robichaud et al. (2000) where they simulated burn treatments on different soil types. Additionally, Walsh et al. (1994) and Doerr and Thomas (2000) concluded that soil water repellency is most severe in the dry summer. When the experiments of this study were conducted during the fall of 2000, the area had been suffering from a long drought period and low snowfall from the previous winter.

Total infiltration was calculated through a mass balance equation of rain applied minus the runoff that was captured in the manually gathered samples. Within each treatment, the plots showed no significant difference. T-tests, however, did show significant differences (α =0.05) of the total infiltration values for the three treatments (Fig. 3). The rootmat-removed treatment had the lowest mean infiltration (24 mm) followed by the burned treatment (33 mm) and then the undisturbed treatment (46 mm). These infiltration values correspond to the hydrographs in figure 1.

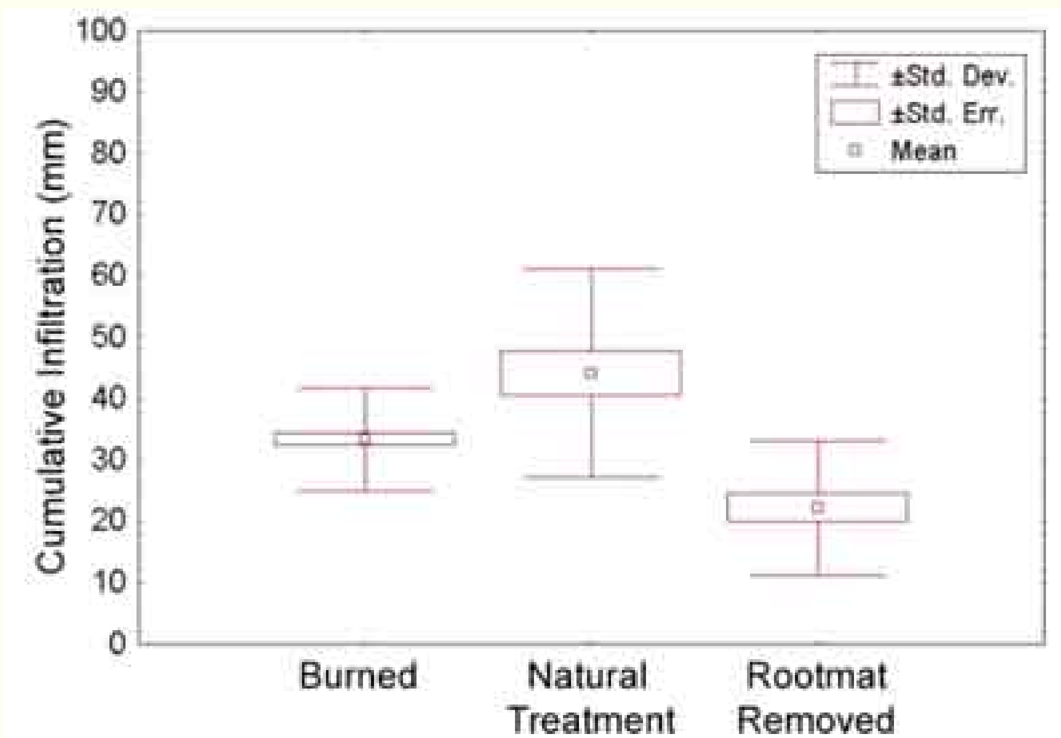


***Figure 3**. Box plot of the cumulative infiltration rates for each treatment. Treatments were significantly different at the α=0.05 level.*

Another factor affecting infiltration is the amount of surface storage that occurs in different capacities for each of these treatments. It is also important to recognize large variability that typically exists with these results due to the inherent difference in site microtopography, fine root distribution, and root holes.

The WDPT tests and soil moisture probes further explain the results that indicate naturally occurring water repellent soil conditions, which affect infiltration and storage. A total of 480 WDPT tests were run on the burned sites and 336 on the unburned sites. Both the rootmat-removed and undisturbed plots are accounted for because the WDPT test is conducted on mineral soil. Therefore, the vegetative cover is removed on all unburned plots for the WDPT tests. The results of the WDPT tests show that for both unburned and burned sites a large percentage of the tests, 77 % and 60 % respectively, detected severe water repellency (>180 sec) within the soil profile (Table 1). Both treatments showed the same percentage of non-repellent soils at approximately 3 %. These percentages are further described in Table 2 in order to show where the water repellency occurred within the soil profile.

Table 1. *Total WDPT tests and their fraction of occurence*

Table 1. Total WDPT tests and their fraction of occurrence

	Burned		Unburned	
Water Repellency Class	# Tests	Occurrence Fraction %	# Tests	Occurrence Fraction %
None (<5 sec)	16	3	11	3
Slight (5-60 sec)	90	19	38	11
Moderate (60-180 sec)	85	18	27	9
Severe (>180 sec)	289	60	260	77
Total # tests	480	100	336	100

Table 2*. Fraction of WDPT tests conducted representing each severity level at different depths of soil.*

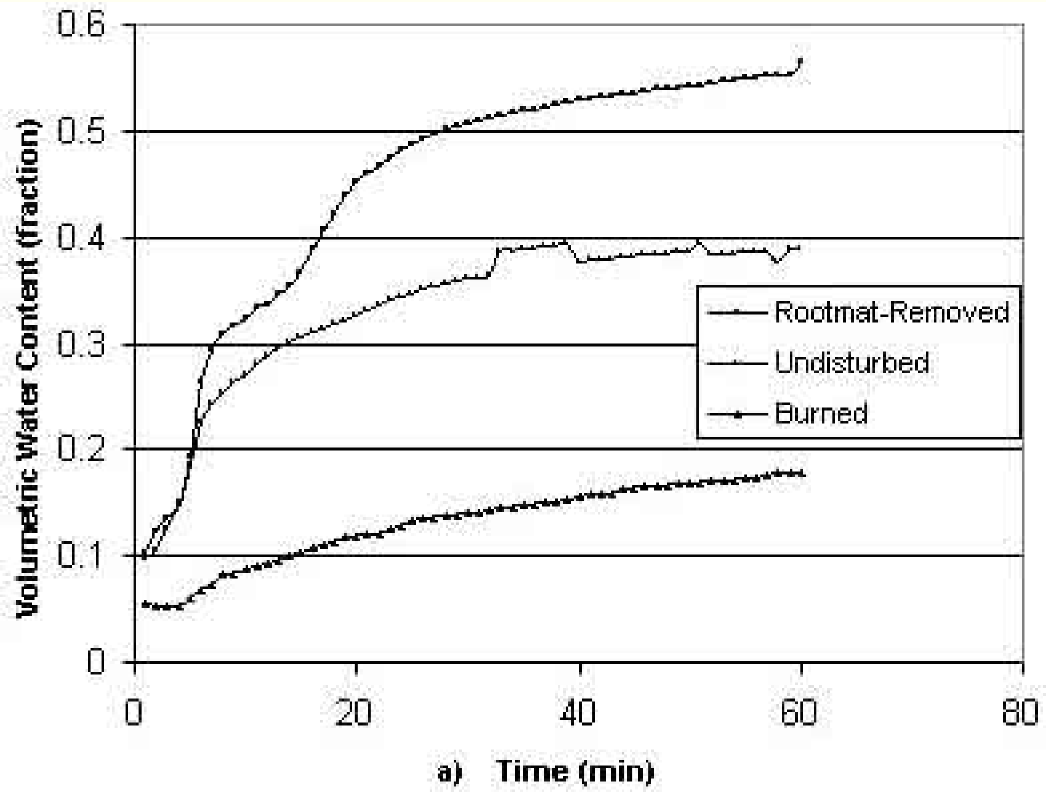
Table 2. Fraction of WDPT tests conducted representing each severity level at different depths of soil

Water Repellency Class	None		Slight		Moderate		Severe	
Depth (cm)	Unburned %	Burned %	Unburned %	Burned %	Unburned %	Burned %	Unburned %	Burned %
surface	18	0	76	2	63	9	80	5
0--1	27	63	16	38	15	38	17	35
1--2	0	0	8	26	11	32	2	42
2--3	0	0	0	16	11	11	1	13
3--4	0	0	0	10	0	7	0	4
4--5	0	0	0	9	0	4	0	1
>5	55	38	0	0	0	0	0	0
N[1]	11	16	38	90	27	85	260	289

1. N represents the total number of tests conducted.

The three classes of water repellency: slight, moderate, and severe, had unique distribution patterns for the two treatments: burned and unburned. When water repellency was detected from the WDPT tests on the unburned plots it occurred on the surface 76, 63, and 80 % of the time for the respective severities of slight, moderate, and severe. It then proceeded to decrease as the depth reached 3 cm. There was no evidence of water repellent soil below a depth of 3 cm on the unburned sites. The burned areas, on the other hand, resulted in few tests (5 % that were severe) which exhibited water repellency on the surface. These results support the fact that natural water repellency is typical of dry soils (DeBano, 1973; Dekker and Ritsema, 1994). The water repellent layer on the burned plots was distributed from just below the surface to 3 cm depth. This provided a thick layer of water repellency within the soil profile. Several tests showed water repellency continuing down to 5 cm on these plots. This indicates the fire causes a redistribution of the hydrophobic substance throughout the soil profile while in the unburned condition it occurs primarily at the surface. As a result, more runoff occurred from the rootmat-removed plots as shown from the hydrographs. Generally these water repellent layers are broken down within 10 to 15 minutes after rain begins (Robichaud, 2000). This did not occur on these plots. The fact that water repellency becomes distributed within the soil profile when a soil is burned explains the results from two soil moisture probes. The probes were placed at approximately 5 and 10 cm depths to monitor the changing moisture conditions of the
soil (Fig 4).

The results from the soil probe data suggest a combined effect of infiltration, runoff, and storage. Both soil probes detected more moisture from the undisturbed and rootmat-removed plots than from the burned plots. This is counter to what would be expected by the results of the runoff hydrograph and cumulative infiltration box plots. A storage layer may account for the difference. The distribution of the water repellent layer when the soil is burned creates a surface that exhibits low water repellency and acts as a small storage reservoir which allows water to accumulate in this layer. When this layer becomes saturated the water continues to run off rather than infiltrate because of the large water repellent region below the surface. This storage capacity is by far smaller than the storage capacity of the organic surface for the undisturbed plots. It is likely that the top organic layer holds a large amount of water before it becomes saturated. At saturation the water hits the water repellent surface of soil, which inhibits water infiltration. The soil moisture probes in the rootmat-removed plots detected the high water content because the top layer is water repellent and has almost no storage; thus a portion of the water did infiltrate causing the higher moisture readings. The percentage of water that infiltrates is higher than the others but low relative to the amount of runoff.



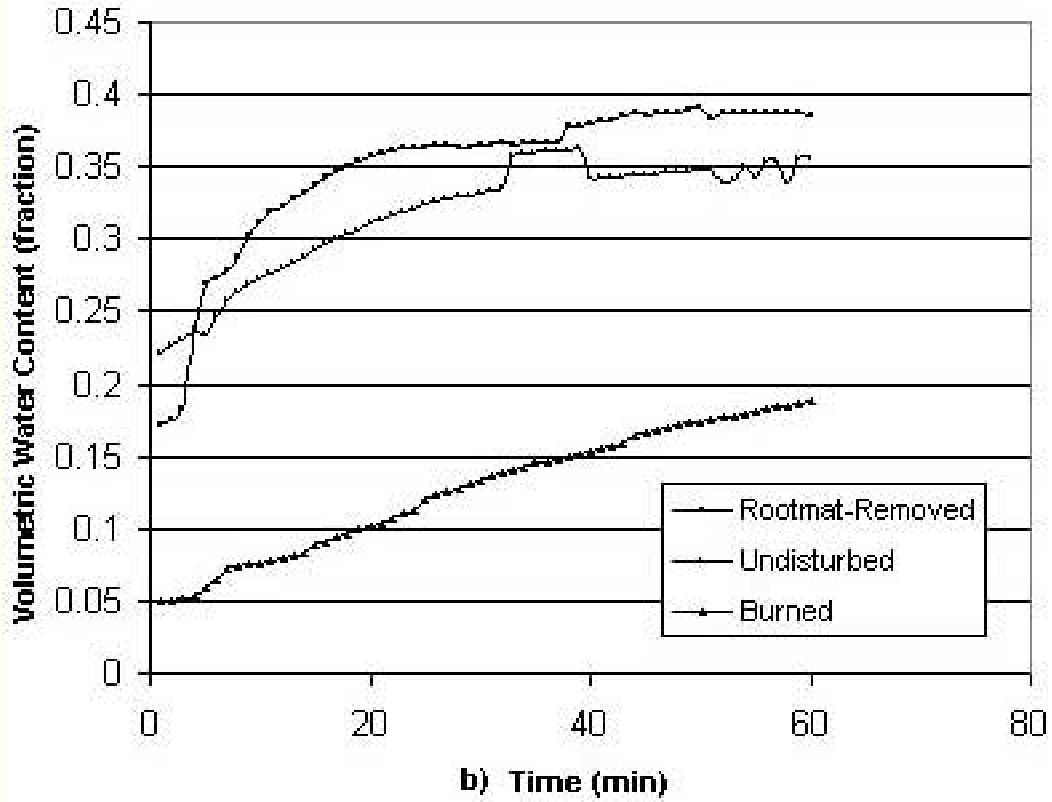


***Figure 4**. Average volumetric water content readings for the three treatments at depths of a) 5 cm and b) 10 cm for the duration of the rainfall simulation.*

Conclusion

This study showed that soil type plays a role in the infiltration and runoff characteristics. Volcanic ash-cap soil have naturally occurring water repellent characteristics, which prior to the fire are concentrated on the surface layer. This was shown by the highest runoff rates from the rootmat-removed sites and the high rate of runoff resulting from the undisturbed vegetated plots. This water repellency diminished quickly with increasing depth.

After a high severity burn, these ash-cap soils no longer had a water repellent layer at the surface, but rather distributed it into a layer between the surface and a 3 cm depth, sometimes extending to 5 cm depth. The top layer of the burned soil exhibited minimal water repellency and thus acted as a small storage space for water while the thick layer of distributed water repellent soil restricts water from infiltrating. The soil moisture detected at depths within the soil profile suggested that the surface storage capacity combined with the amount of runoff influenced infiltration.

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Literature Cited

DeBano, L.F. 1966. Formation of non-wettable soils…involves heat transfer mechanism. Res. Note PSW-132. USDA For. Serv., Pacific Southwest Forest and Range Exp. Sta., Berkeley, Ca. 8pp.

DeBano, L.F. 1973. Water repellent soils: their implications in forestry. Journal of Forestry. 71:220-223.

DeBano, L.F. 1981. Water Repellent Soils: a state of the art. Gen. Tech. Rpt. PSW-46. USDA For. Serv., Pacific Southwest Forest and Range Exp. Sta., Berkeley, Ca. 21pp.

DeBano, L.F., D.G. Neary, and P.F. Ffolliott. 1998. Fire's effect on ecosystems. New York: John Wiley & Sons. 333pp.

Dekker, L.W. and C.J. Ritsema. 1994. How water moves in a water repellent sandy soil 1. Potential and actual water repellency. Water Resour. Res. 30:2507-2517.

Doerr, S.H. and A.D. Thomas. 2000. The role of soil moisture in controlling water repellency: new evidence from forest soils in Portugal. Journal of Hydrology. 231-232: 134-147.

Giovannini, G. and S. Lucchesi. 1983. Effect of fire on hydrophobic and cementing substances of soil aggregates. Soil Science. 136: 231-236.

Hartford, R.A. and W.H. Frandsen. 1992. When it's hot, it's hot--or maybe it's not (surface flaming may not portend extensive soil heating). International Journal of Wildland Fire. 2:139-144.

Robichaud, P.R. 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. Journal of Hydrology. 231-232:220-229.

Robichaud, P.R. and R.D. Hungerford. 2000. Water repellency by laboratory burning of four northern Rocky Mountain forest soils. Journal of Hydrology. 231-232:207-219.

Robichaud, P.R., R.T. Graham, and R.D. Hungerford. 1994. Onsite sediment production and nutrient transport from a low severity burn in the interior northwest. In Proceedings of Interior Cedar-Hemlock-White Pine Forests: Ecology and Management, March 1993, Spokane Wa: Department of Natural Resource Sciences, Washington State University, Pullman, Wa., pp227-232.

Robichaud, P.R., J.L. Beyers, and D.G. Neary. 2000. Evaluating the effectiveness of postfire rehabilitation treatments. Gen. Tech. Rpt. RMRS-GTR-63. pp85.

Ryan, K.C. and N.V. Noste. 1983. Evaluating prescribed fires. In: Lotan, J.E; B.M. Kilgore; W. C. Fischer; and R.W. Mutch (technical coordinators). In: Symposium and Workshop of Wilderness Fire. Gen. Tech. Rpt. INT-182. Ogden, UT. USDA Forest Service, Intermountain Research Station: 230:238.

Scott, D.F., D.B. Versfeld, and W. Lesch. 1998. Erosion and sediment yield in relation to

afforestation and
fire in the mountains of the western Cape Province, South Africa. South African Geographical Journal. 80:52-59.

Shakesby, R.A., S.H. Doerr, and R.P.D. Walsh. 2000. The erosional impact of soil hydrophobicity:
current problems and future research directions. Journal of Hydrology. 231-232:178-191.

Walsh, R.P.D., D. Boakes, C.O.A. Coelho, A.J.B. Gonçalves, R.A. Shakesby, and A.D. Thomas.
1994. Impact of fire-induced hydrophobicity and post-fire forest litter on overland flow in northern
and central Portugal. In: Proceedings of the Second International Conference on Forest Fire Research,
November 1994, Coimbra, Portugal,vol. II, pp1149-1159.

White, W.D., and S.G. Wells. 1982. Forest-fire devegetation and drainage basin adjustments in mountainous
terrain. In: Proceedings of the 10th Geomorphology Symposium, Binghamton, Boston, pp199-223.

Wells, C.G., R.E. Campbell, L.F. DeBano, C.E. Lewis, R.L. Lewis, E.C. Fredricksen, R.C. Franklin,
R.C. Froelich, and P.H. Dunn. 1979. Effects of fire on soil: a state-of-knowledge review. Gen. Tech.
Rpt. WO-7. Washington DC. USDA Forest Service. pp34.

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