Runoff and Erosion Effects after Prescribed Fire and Wildfire on Volcanic Ash-Cap Soils

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Abstract

After prescribed burns at three locations and one wildfire, rainfall simulations studies were completed to compare postfire runoff rates and sediment yields on ash-cap soil in conifer forest regions of northern Idaho and western Montana. The measured fire effects were differentiated by burn severity (unburned, low, moderate, and high).

Results indicate that this dry, undisturbed ash-cap soil exhibits high runoff rates and is naturally water repellent at the surface. However, the unburned, undisturbed ash-cap soil is not highly erodible due the protective duff layer on the surface. When ash-cap soil was exposed to prolonged soil heating (high severity burn), surface water repellency was destroyed and a strong water repellent layer occurred a few centimeters beneath the soil surface. With the simulated rainfall, the non-water repellent surface layer became saturated; thus making the soil above the water repellent layer highly erodible—especially during high intensity rainfall.

Keywords: water repellent soils, rainfall simulation, burn severity, runoff, erosion.

Introduction

Fire is a natural and an important part of disturbance regime for forest ecosystems and many landscapes are well-adapted to this natural fire cycle. Wildfire suppression has dominated forest management for the past century and has interfered with these natural fire regimes causing unnatural accumulations of forest fuels. Although managed forests burn less frequently than the unmanaged forests, the wildfires that do occur are larger and more severe than in the past, causing more severe and long-lasting effects. Fire effects on forest soil may include fire-induced soil water repellency, reduced infiltration rates, increased overland flow, and increased peak flow, which often result in increased water and sediment yields.

Burn Severity

Burn severity, a qualitative measure of the effects of fire on site resources, is a useful concept for comparing fires (Hartford and Frandsen 1992; Ryan and Noste 1983). A range of fire and postfire conditions, such as fire intensity, fire duration, crown consumption, soil color, and proportion of litter remaining, are typically used to classify burned areas into discrete classes of high, moderate, or low burn severity. Although some aspects of burn severity can be quantified, no single number can be determined to measure 'resource impact'.

The component of burn severity that results in the most damage to soils is fire duration, because duration generally determines the temperature and depth of soil heating. Ryan and Noste (1983) created a burn severity classification system (expanded by Jain (2004)) that estimates the amount of soil heating that likely occurred during the fire based on postfire litter amounts and mineral soil coloration. Because it is specific to soil, the Ryan and Noste (1983) definition of burn severity was used to evaluate burn severity at research sites discussed in this paper.

Water Repellency

Naturally occurring water repellent soils occur in every continent and have different infiltration properties than wettable soils (Letey 2005). Fire creates or enhances water repellency in soils (Doerr and others 2000). As surface vegetation is burned and the soil is heated, organic matter in and on the soil is volatilized, and a significant fraction of these vaporized organic compounds move from the surface into the soil profile (DeBano and others 1976). These aliphatic hydrocarbon vapors condense on soil particles in the cooler layers beneath the surface to form a water repellent layer. This water repellent layer is generally within the top 5 cm of the soil profile, non-continuous, and roughly parallel to the surface (Clothier and others 2000; DeBano 2000). In general, coarse soils (low clay content) are more susceptible to becoming water repellent than finer soils (high clay content) due to the lower specific surface area of coarse soil particles. However, when water repellency is established in fine-grained soils, it can be equally or more severe than in a coarse-textured soil (Doerr and others 2000; Robichaud and Hungerford 2000).

Fire-induced soil water repellency has high temporal and spatial variability (Letey 2005). The degree and depth of postfire water repellency is related to soil heating during the fire, which, because of its dependence on antecedent soil moisture, forest floor thickness, burn duration, postfire smoldering, etc., is highly variable. Fire-induced soil water repellency has been found to vary both in the horizontal and the vertical directions at the 1 cm scale (Hallett and others 2004; Gerke and others 2001). Fire-induced water repellency is most often detected at 1 to 3 cm below the surface (Huffmann and others 2001). In addition, soil water repellency is transient and is related to soil moisture. Generally, both natural and fire-induced soil water repellency is lost during long wet periods and is re-established upon drying, causing short-term or seasonal variations (Robichaud and Hungerford 2000). Fire-induced soil water repellency is temporary because the hydrophobic substances responsible for water repellency are slightly water-soluble and slowly dissolve such that water repellent soil conditions are broken up or washed away within several years after the fire.

Infiltration

In water repellent soils, water may move through a wettable surface layer, and upon reaching a water repellent layer, flow laterally below the surface (DeBano 1981). Given the spatial variability of water repellency, water may flow preferentially, via columns, or 'fingers,' through the less water repellent areas forming an uneven wetting front (Ritsema and Dekker 1994, 1995). Infiltration on water repellent soils is also dependent on the type and distribution of plants over the surface (Shakesby and others 2000). Some plants, such as chaparral, decrease infiltration by adding hydrophobic compounds to the soil directly under the canopy (DeBano 1981). Conversely, infiltration can be enhanced by root channels and macropores (remaining after roots decay or burn) that can act as pathways for infiltrating water through water repellent layers (Meeuwig 1971; Sevink and others 1989; Burch and others 1989; Shakesby and others 2000).

Overland Flow and Erosion

Overland flow and soil erosion rates are dependent on a range of inter-related factors that include rainfall (e.g., amount, intensity, duration), soil (e.g., erodibility, particle size, pore size, bulk density, water repellency), topography (e.g., slope, aspect), and biotic (e.g., vegetation, ground cover, animal use, natural and human disturbances). Because of the reduction in infiltration capacity in water repellent soils, postfire increases in overland flow and erosion are often attributed to fire-induced water repellency (Doerr and others 2000). However, it is difficult to determine the proportion of postfire increased erosion that can be attributed to soil water repellency. Fire can also increase the erodibility of soil through reduction of protective ground cover and soil organic matter, sealing of soil pores, loss of water storage capacity in the litter and duff, loss of soil moisture, break down soil aggregates, and reduction of soil particle size (DeBano and others 1998). Thus, the contribution of soil water repellency on total postfire erosion is often difficult to separate from other fire impacts.

Caution must be used when extrapolating measurements of overland flow from small plots to determine the potential runoff on the hillslope- or catchment-scale where differential flow patterns may have significantly more effect (Shakesby and others 2000; Imeson and others 1992). After a Eucalyptus forest fire in Australia, Prosser and Williams (1998) found that small plots produced greater runoff and sediment transfer than was observed at the hillslope catchment outlet. The lack of spatial contiguity in soil water repellency and the existence of differential infiltration flow patterns may create scattered 'sink' areas across a hillside where water infiltrates and, as a result, does not reach the base of a catchment as overland flow (Imeson and others 1992; Prosser and Williams 1998).

Study Objectives

Small plot rain simulation data from three prescribed burns (northern Idaho) and one wildfire (western Montana) are used to compare fire effects on runoff and erosion of ash-cap soils. The two studies (prescribed fire study and the wildfire study) had common site characteristics (conifer forested environments and ash-cap soil types) and test procedures (rainfall simulation), which facilitated the comparison of first year postfire data from the four fires to: 1) examine fire-induced and natural ash-cap soil water repellency; 2) compare runoff rates; and 3) compare sediment concentrations and sediment yields.

Methods

Prescribed Fire

Site Description—The prescribed fire study was conducted in the Fernan Ranger District, Idaho Panhandle National Forest in the Coeur d'Alene Mountains (48°15′ N, 116°15′ W). Study plots were located between 950 to 1500 m elevation on 14 to 46 percent slopes. The predominant soil type is Typic Vitrandepts, a silt loam derived from volcanic ash-influenced loess 28 to 45 cm thick, over an Eutirc Glossoboralfs, a mixed loamy-skeletal formed from Precambrian Belt rock. Average annual precipitation is 34 inches with about one third of that falling as snow in the winter months (Abramovich and others 1998). Vegetation of the area is typical of the western hemlock/queencup beadlily (*Tsuga heterophylla/Clintonia uniflora*) habitat type (Cooper and others 1991).

Ignition of the first harvested unit was in the spring on April 25 (Bumble Bee). Ignition of the second burn occurred in the fall two years later on September 30 (Buckskin I). The third harvest unit was ignited in the summer on August 25 (Buckskin II). For each of the three prescribed burns, a helitorch-ignited strip headfire was started at the top of the slope with fire strips placed about every 30-40 m down the slope. Ignition was generally very rapid, and the entire unit ignited within 30 min.

Plots—Before each prescribed fire, six paired 1-m^2 plots were systematically selected in the study areas to represent the average fuel condition and average slope, with one plot designated for rainfall simulation and the other for soil temperature measurements. Four steel pins were installed flush with the forest floor surface in each plot to estimate forest floor consumption. In the temperature-measurement plots, these forest floor pins were located near thermocouples. Temperatures during the fire were recorded with eight chromel-alumel thermocouples located at the litter surface, in the humus, at the humus-mineral soil interface, and in the mineral soil at 1, 2, 4, 8, and 10 cm below the interface. Temperatures during the burn were first recorded when the surface temperature reached 80 °C and continued every minute thereafter for 36 h. Immediately before burning, samples of the woody fuels, forest floor, and mineral soil were collected to determine moisture content.

On each of the rainfall simulation plots, a four-sided sheet metal frame was installed. Three frame sides were 15 cm tall and installed with 5 cm inserted into the mineral soil, and the fourth, downslope side of the frame was 5 cm tall and inserted fully into the soil (no extension above the surface of the soil) allowing runoff and sediment to leave the plot.

Rain Simulation—Within days of the prescribed fire, a 30-min rain simulation was conducted at the existing soil moisture condition as determined from a composite soil sample was taken near the edge of the plot frame. The simulated rainfall was applied to each plot using a USDA-Forest Service modified Purdue-type oscillating nozzle rainfall simulator with specifications as described by Meyer and Harmon (1979). The rainfall simulator produced an average rainfall intensity of 38 mm h^{-1} for the Bumble Bee (spring 92) burn site. After the Bumble Bee simulations, the simulated rainfall intensity was increased to ensure that the rainfall rate exceeded the infiltration capacity of the soil. Rainfall intensity was 100 mm h^{-1} for the Buckskin I (autumn 94) and Buckskin II (summer 95) burn sites. Seven rain gauges located around the 1 m^2 plots verified the rainfall amount.

A covered trough at the lower end of each plot conducted runoff (water and sediment) through a pipe fitted with a valve that allowed for timed volume sampling. The samples were manually collected in 1000 ml bottles at 1-min intervals. At the end of the simulation run, any sediment remaining in the trough was washed into a sample bottle. All runoff samples were weighed and oven-dried to determine runoff rates and sediment concentrations.

Wildfire Study

Site Description—The wildfire study was conducted in the Bitterroot National Forest (46°4′ N, 114°0′ W) of western Montana where, in the summer of 2000, lightning strikes ignited the Bitterroot Complex Fires. These fires burned 101,000 ha—40 percent at high burn severity as determined by postfire appearance (USDA 2000). The predominant soil is derived from volcanic ash over highly weathered granite and is classified as a sandy skeletal Andic-Dystrocryept. The mean elevation is approximately 1,950 meters with slopes ranging from 25 to 55 percent and dominantly west-southwestern aspects. Vegetation of the area is typical of the subalpine fir/menziesii (*Abies lasiocarpa/Menziesia ferruginea* h.t.) forest habitat type.

Plots—Within an area of high burn severity, four study sites were selected based on comparable slope, aspect, and ground cover characteristics. On each of the four sites, 15 plots of 0.5 m^2 were randomly located and delineated by a four-sided sheet metal frame as previously described. Approximately 3 km north of the burned study area, three unburned sites were selected such that the slope, aspect, and soil type were comparable to the burned area sites and, in addition, the vegetative characteristics were comparable among the unburned study sites. In each of the three unburned sites, 7 plots of 0.5 m^2 were randomly located and defined by the installation of sheet metal plot frames as described above.

Directly adjacent to each plot frame, water repellency was measured using the water drop penetration time (WDPT) adapted from DeBano (1981). Eight water drops were placed on an exposed surface of the mineral soil and the time to infiltrate into the soil is observed. The degree of water repellency is determined by the length of time the water drop sits on the soil without being absorbed: 0 to 5 sec = none; 6 to 60 sec = slight; 61 to 180 sec = moderate; 181 to 300 or more = severe. The maximum observation time was limited to 5 minutes. If the water drops infiltrated in less than 5 seconds, the test was repeated at 1 cm depth below the surface. This process was repeated at 1 cm increments to a maximum depth of 5 cm.

Near the edge of the plot frame, a composite soil sample was taken to assess soil moisture. Ground cover within each plot was determined.

Rainfall Simulation—Within days after the fire was contained, a simulated rainfall event with a mean rainfall intensity of 100 mm h^{-1} was applied to each of the 102 plots for 60 min using the USDA-Forest Service and the USDA-Agricultural

Research Service oscillating-arm rainfall simulators with specifications as described by Meyer and Harmon (1979). Data from the first 30 minutes of each simulation were used for comparisons and analysis. During the rainfall simulation, samples of runoff and sediment were collected through a covered trough at the downslope edge of each plot as described for the prescribed burns above. The samples were manually collected at 1-min intervals for the first 14 min, then at 2-min intervals for the remainder of the 60-min run. All runoff samples were weighed and oven-dried to determine runoff volume for each interval, total runoff volume, sediment concentrations.

Analytical Methods

The data from the Bumble Bee prescribed fire site were not included in the statistical analysis because the rainfall application rate of 38 mm h^{-1} was much less than 100 mm h^{-1} rainfall application rate applied at all other sites. The total runoff and dry suspended sediment weight were calculated for the first 29 to 30 min of the first simulation for the Buckskin I and II sites and for the first 29 to 31 min of the year 2000 simulations at the Bitterroot sites. Runoff and suspended sediment were normalized by area to account for the different plot sizes. Runoff ratios are total runoff (mm) divided by total rainfall applied (mm) for each simulation; the rainfall is adjusted for the plot size.

Results and Discussion

Burn Severity

Varied antecedent conditions for the three prescribed burns resulted in differential soil heating and a range of fire effects on the soil. Bumble Bee, a spring burn, had the highest pre-fire soil and duff moisture contents (61 to 69 percent and 125 percent, respectively) and the lowest mineral soil temperatures (20 to 80 °C) and proportion of duff consumed (28 percent) during the fire (table 1). Bumble Bee was a low burn severity fire. Buckskin I was burned in the fall with the driest conditions of the three prescribed burns (table 1) and was classified moderate burn severity. Buckskin II, a summer burn, had slightly higher pre-burn fuel and soil moisture conditions than Buckskin I and was also classified moderate burn severity (table 1). The study areas within the Bitterroot Complex Fire area were in unburned and high burn severity areas. These four fires on ash-cap soils provided four burn severity conditions—unburned (Bitterroot), low burn severity (Bumble Bee), moderate burn severity (Buckskin I and II), and high burn severity (Bitterroot).

Moisture Content and Water Repellency

Soil moistures immediately prior to the rainfall simulations were higher in the prescribed fire sites than the wildfire sites (table 2), but probably not high enough to change the soil water repellency response (Robichaud and Hungerford 2000). Soil water repellency was directly assessed in the Bitterroot study, where both burned and unburned soils had strong water repellent responses at different depths. The unburned soil was severely water repellent at the surface while the burned soil

Table 1—Measured conditions before, during, and after three prescribed burns in northern Idaho.

Pre-prescribed Burn			
Fuel and soil moisture contents and weather conditions	**Bumble Bee**	**Buckskin I**	**Buckskin II**
Fine fuels (0-76 mm) (%)	20	9	10
Large fuels (77-300 mm) (%)	41	11	28
Litter (%)	64	13	11
Humus (%)	125	45	48
Soil 0-2 cm (%)	69	40	49
Soil 2-5 cm (%)	61	29	40
Ambient temperature (oC)	22	20	18
Wind speed (kph)	8-15	2-8	0-11
Relative humidity (%)	15	30	57
Prescribed Burn			
Maximum soil temperatures (°C)	**Bumble Bee**	**Buckskin I**	**Buckskin II**
Mineral soil surface	20-80	40-300	90-260
1 cm below min. soil surface	40-70	40-270	70-120
2 cm below min. soil surface	20-60	40-80	60-80
Post-prescribed Burn			
Organic material remaining (%)	**Bumble Bee**	**Buckskin I**	**Buckskin II**
Fine fuels	12	5	0
Duff	72	27	38

Table 2—Pre-rainfall simulation mean ground cover and gravimetric soil moisture content by location.

Locations	**Ground cover**	**Gravimetric soil water content**
	(%)	(%)
Unburned Bitterroot	100	15
Bumble Bee	100	29
Buckskin II	98	25
Buckskin I	70	30
Burned Bitterroot	10	17

had a water repellent layer at 1 to 2 cm below the surface (fig. 1). The creation of a fire-induced water repellent layer has been observed by other researchers (e.g., McNabb and others 1989; Brock and DeBano 1990; Scott and Van Wyk 1990; Doerr and others 2000). However, the high burn severity fire appeared to destroy the natural surface water repellency, and create a water repellent layer at depth. Doerr and others (in press) observed the same affect after wildfires in eucalyptus forests in Australia.

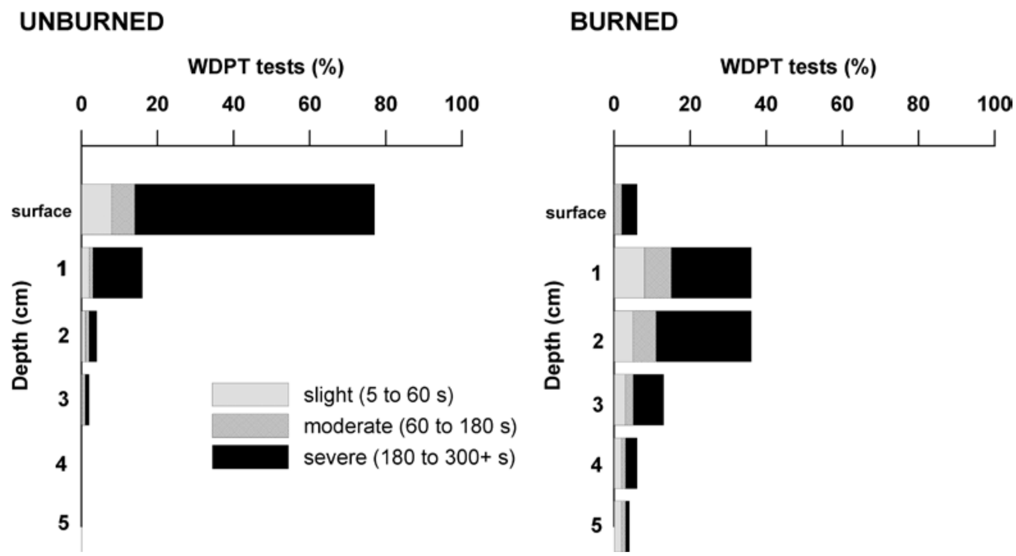

Figure 1—On the Unburned- and Burned-Bitterroot wildfire sites, the portion of water repellent soil, as measured by the Water Drop Penetration Time (WDPT) tests, are indicated for the soil surface and 1, 2, 3, 4, and 5 cm depths. The shading/hatching within each bar indicate the severity of the measured water repellency.

Runoff

The highest runoff ratio rates (fig. 2) and mean runoff amounts (33 and 32 mm) and runoff ratios (0.71 and 0.67) were measured on the high and moderate severity burn sites—Bitterroot-burned and Buckskin I, respectively (table 3). The unburned-Bitterroot sites and the moderate burn severity Buckskin II site had similar runoff ratio rates (fig. 2) and mean runoff amounts (26 and 24 mm) and runoff ratios (0.54 and 0.53) (table 3). This unexpectedly large runoff response in the unburned-Bitterroot sites is likely due to the short time frame of the simulation and the resistance to wetting of the dry organic duff material as well as the naturally water repellent dry surface soil. The Bumble Bee prescribed burn site had low runoff ratio rates (fig. 2) and a low mean runoff amount (4.7 mm) and runoff ratio (0.12) (table 3). However, these data are not directly comparable to the other sites as the lower rainfall application rate may not have exceeded the infiltration capacity of the soil.

Sediment Concentrations and Yields

Sediment concentrations and mean sediment yields generally increased with increasing burn severity (fig. 3 and table 3). Sediment concentrations in the rain simulation runoff tended to peak in the first 5 min, rapidly decrease during the second 5 min, and slowly decrease during the remaining 20 minutes of the simulation (fig. 3). The unburned-Bitterroot sites and the Bumble Bee site (low burn severity) had the lowest concentrations, peaking at 7 and 4 g L^{-1}, respectively and decreasing to less than 1 g L^{-1} at 30 min (fig. 3). These concentrations resulted in mean sediment yields of 0.027 and 0.0091 kg m^{-2}, respectively (table 3). The lower rainfall application rate on the Bumble Bee site probably had little affect on mean sediment yield (table 3) due to the high ground cover remaining after

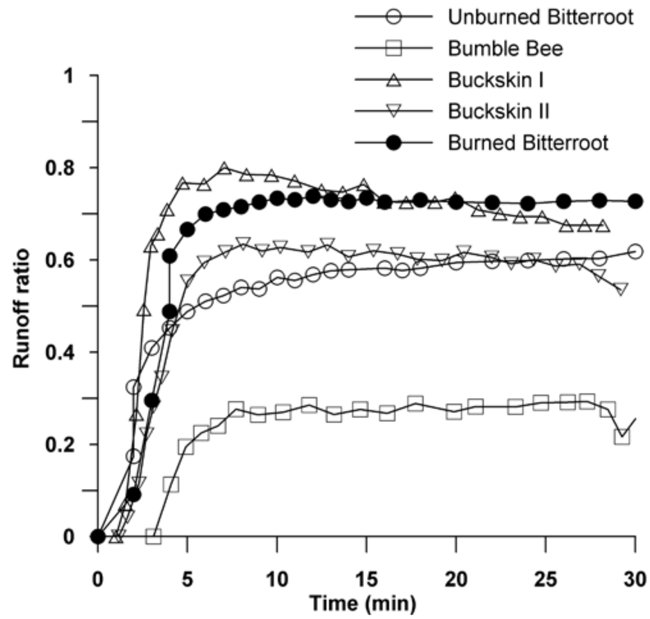

Figure 2—The runoff ratio (runoff / rainfall) rate for all study sites are plotted. The Bumble Bee sites received a lower amount of rainfall as compared to other sites.

Table 3—Mean runoff, runoff ratio, and suspended sediment yield by location. Standard errors are in parentheses. Different letters within a column indicate significant differences at α=0.05. Comparative statistics do not include the Bumble Bee data due to the lower applied rainfall at that site.

Location	Disturbance type	n	Runoff	Runoff ratio	Sediment yield
			(mm)		*(kg m^{-2})*
Unburned-Bitterroot	Undisturbed	21	26 (1.8) a	0.54 (0.032) a	0.027 (0.039) a
Bumble Bee	Prescribed fire	4	4.7 (1.4)	0.26 (0.043)	0.0091 (0.0028)
Buckskin II	Prescribed fire	6	24 (2.5) a	0.53 (0.049) a	0.26 (0.90) ab
Buckskin I	Prescribed fire	6	32 (1.3) ab	0.67 (0.19) ab	0.50 (0.80) ab
Burned-Bitterroot	Wildfire	60	33 (0.60) b	0.71 (0.12) b	0.85 (0.61) b

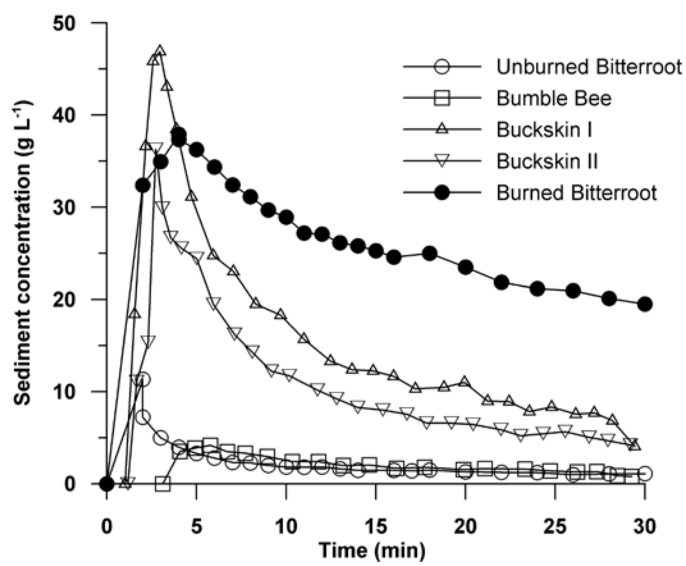

Figure 3—The sediment concentration rate for all study sites are plotted. The Bumble Bee sites received a lower amount of and less intense rainfall as compared to other sites.

the spring burn (table 2). The Buckskin I and II, both moderate burns, peaked at 47 and 36 g L^{-1}, respectively and decreased to about 1 g L^{-1} at 30 min. (fig. 3), resulting in mean sediment yields of 0.50 and 0.26 kg m^{-2}, respectively (table 3). The high severity burned-Bitterroot sites peaked at 38 g L^{-1}, and remained higher than any of the other sites through out most of the 30 min simulation, and decreased to 20 g L^{-1} at 30 min. (fig. 3), resulting in a 0.85 kg m^{-2} mean sediment yield, an order of magnitude greater than the unburned-Bitterroot sites (table 3). The higher sediment yields for the wildfire sites reflect the higher consumption of organic material during a wildfire (longer fire duration and higher soil temperatures) as compared to a prescribed fire. This difference in fires is reflected in the postfire, pre-rainfall mean ground covers, with the Burned-Bitterroot sites having 10 percent ground cover and the Buckskin I and Buckskin II sites having 70 percent and 98 percent, respectively (table 2).

Conclusions

A strong natural soil water repellency was detected at the surface of the mineral soil in the unburned, undisturbed ash-cap soil with low soil moisture content. The high burn severity wildfire appeared to destroy the surface water repellency, and cause a strong water repellent layer to develop 1 to 2 cm below the surface of the mineral soil. Soil water repellency, at the surface or slightly below the surface, increased runoff; however, below-surface water repellency results in a much larger sediment response than surface water repellency. When there is fire-induced, below-surface soil water repellency, rainfall is readily absorbed by the non-repellent surface soil (0 to 1-2 cm) which becomes saturated down to the more resistant water repellent layer. This saturated surface layer is easily detached and entrained within the subsequent overland flow. Additionally, fine roots that bind the surface soil together were likely partially consumed during the fire, making soil particles vulnerable to detachment.

Even in steep forest environments with dry conditions (i.e., severe surface water repellency), the undisturbed, unburned site with its intact duff layer was not highly erodible, despite high runoff rates. During the 30 min of high intensity rainfall, the dry duff did not absorb much water and the rainfall flowed through the duff layer and atop the water repellent mineral soil to the outlet of the plots. Consequently, the runoff rates for the unburned-Bitterroot sites were similar to those found on the moderate burn severity Buckskin II site. However, the sediment concentrations and sediment yields were less than the Buckskin II due to the protective layer of duff material. The Bumble Bee low severity prescribed fire also had minimal sediment response because of the charred, but intact, duff remaining after the fire. The fire effects on sediment concentrations and sediment yields increased with increasing burn severity.

Management Implications

Ash-cap soils are known as highly productive forest soils, and protecting this soil resource is an important land management consideration. Prescribed fires should be ignited when duff moisture content will prevent total consumption of the protective duff layer. Ash-cap soils burned at high severity are highly erodible and postfire rehabilitation decisions should take into account the potential postfire hydrological and sediment response from potential rain events.

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