HYDROLOGICAL PROCESSES
Hydrol. Process. **15**, 2905–2916 (2001)
DOI: 10.1002/hyp.381

Spatial and temporal effects of wildfire on the hydrology of a steep rangeland watershed

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Abstract:

Wildfire is a major ecological process and management issue on western rangelands. The impacts of wildfire on hydrologic processes such as infiltration, runoff, and erosion are not well understood. Small-plot rainfall simulation methods were applied in a rangeland wildfire setting to determine post-fire hydrologic response. Infiltration and interrill erosion processes were measured immediately post-fire and one year following the 1999 34 400 ha Denio fire in northwestern Nevada. Plot-scale spatial and temporal variability in fire impacts was compared with adjacent unburned areas. An index of water repellency was derived and used to quantify the influence of water-repellent soil conditions on infiltration. Results indicate the impact of the fire on infiltration was localized primarily on coppice microsites directly under shrubs characterized by high surface litter accumulations. Coppice microsites had very uniform fire-induced soil water repellency with 29 of 30 plots exhibiting at least a 10% reduction in initial infiltration with an average 28% reduction. Cumulative erosion was nearly four times higher on burned coppices compared with unburned coppices. The impact of the fire on infiltration and erosion was reduced, but still evident, 1 year after fire. Significant temporal variability in infiltration between years was observed on both burned and unburned areas, complicating the interpretation of fire impacts and hydrologic recovery following wildfire. Published in 2001 by John Wiley & Sons, Ltd.

KEY WORDS rangeland; fire; infiltration; runoff; erosion; water-repellent; rainfall simulation

INTRODUCTION

Fire is a natural component of sagebrush-steppe ecosystems (Wright and Bailey, 1982) with a return period of 25 to 100 years, depending on community type and natural fuel load and distribution. However, fire suppression activities in the past century have increased the number and severity of wildfires, resulting in increased soil erosion and decreased water quality. Increased runoff and erosion can lead to loss of soil productivity, flooding and increased risk to human life and property. This increased risk of runoff and erosion following wildfire continues to generate concern at the expanding urban–wildland interface throughout the western USA.

The hydrological consequences of fire have been widely examined in forest ecosystems (Meeuwig, 1971; DeBano, 1981; Robichaud, 2000a,b), but few studies have examined wildfire impacts on rangeland hydrology. Most studies have shown an increase in runoff and erosion rates immediately following fire, with recovery to pre-fire rates generally within 5 years (Wright and Bailey 1982). Timing and extent of hydrologic recovery is correlated to vegetation recovery and is highly dependent on slope, soil characteristics and vegetation type (Branson *et al*., 1981; Wright *et al*., 1982; Knight *et al*., 1983; Wilcox *et al*., 1988).

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Received 1 April 2001
Accepted 9 July 2001

Wildfires have often been associated with the formation of water-repellent soil conditions thought to decrease infiltration and increase soil erosion (DeBano *et al.*, 1998). Fire vaporizes organic compounds on the soil surface and distills the rest downwards, concentrating the hydrophobic substances within the upper soil layers. Degree and longevity of water-repellent soil conditions are dependent on the compounds present and the intensity and duration of fire (Wright and Bailey, 1982). Water-repellent soil conditions can also occur in many unburned rangeland plant communities (DeBano and Rice, 1973), but litter and vegetation cover protect the soil and enhance infiltration (Rauzi *et al.* 1968; Blackburn *et al.* 1986). Fire removes this protective covering, exposing the soil to raindrop impact and removing barriers to overland flow. Fire can also reduce the organic matter content in the upper soil layers, thus reducing infiltration (Wright and Bailey, 1982).

It is poorly documented how hydrologic processes including infiltration, runoff and interrill erosion in rangeland watersheds respond to altered vegetation and soil conditions after wildfire. In this study, simulated rainfall was used to examine the impact of high-severity wildfire on infiltration and interrill erosion rates on steep coarse-textured sagebrush-dominated hillslopes.

METHODS

Study area

The study was conducted on a portion of the 34 400 ha Denio fire, which burned in late July, 1999, approximately 24 km southwest of Denio, Nevada, in the Pine Forest Range. The Mean elevation of the research area is 2050 m. The Average annual precipitation is 350–400 mm and the mean annual air temperature is 5·5 to 7·0° C. The study area is located in Major Land Resource Area 23 (Malheur High Plateau) (USDA-SCS, 1981) on the Ola bouldery sandy loam series, which consists of moderately deep soils formed in residuum from granite on mountain sideslopes. A typical profile has three main parts: (1) dark greyish brown very bouldery sandy loam about 18 cm thick; (2) brown coarse sandy loam about 35 cm thick; and (3) greyish brown gravelly coarse sandy loam about 35 cm thick. Depth to unweathered granite is 88 cm. The Ola soil classification is coarse-loamy, mixed, frigid Pachic Haploxerolls (USDA–NCRS, 2001).

Study sites were chosen on north-facing hillslopes (35–40% slope angle) where the vegetation was dominated by mountain big sagebrush [*Artemisia tridentata* ssp. *vaseyana* (Rydb.) Beetle], Idaho fescue [*Festuca idahoensis* var. *roemeri* Pavlick] and bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) A. Love] (USDA–NRCS, 1990). Subdominant grasses were Sandberg bluegrass (*Poa secunda* J. Presl), bottlebrush squirreltail [*Elymus elymoides* (Raf.) Swezey], California brome (*Bromus carinatus* Hook & Arn.), basin wildrye [*Leymus cinereus* (Scribn. & Merr.) A. Love], and Columbia needlegrass [*Achnatherum nelsonii* (Scribn) Barkworth]. Subdominant shrubs were common snowberry [*Symphoricarpos albus* (L.) Blake], and green rabbitbrush [*Chrysothamnus viscidiflorus* (Hook.) Nutt.]. The major forb species were lupine (*Lupinus* spp.), longleaf hawksbeard (*Crepis acuminata* Nutt.), Indian paintbrush (*Castilleja* spp.), rosy pussytoes (*Antennaria rosea* Greene) and low scorpionweed (*Phacelia humilis* Torr & Gray).

Rainfall simulation

Rainfall simulations were conducted immediately following and 1 year after wildfire under antecedent conditions. Four portable oscillating-arm rainfall simulators with specifications as described by Meyer and Harmon (1979) were used to apply rainfall to each runoff plot for 60 min. A rainfall rate of 85 mm h^{-1}, approximately equal to the rainfall intensity of a 10 min thunderstorm with a 10 year return period (Hanson and Pierson, 2001), was applied to each runoff plot. A spray of raindrops with similar size and velocity to that of natural rainfall (Meyer and Harmon, 1979) was quickly passed back and forth over each runoff plot. The desired rainfall intensity was achieved by delaying the movement of the spray nozzle at the end of each pass, thereby decreasing the amount of time the spray was hitting the plot.

Plot frames were installed in 1999, immediately after the fire, and left in place for subsequent samplings. Rainfall was first applied starting 6 weeks following the fire before any natural rainfall events had occurred. All burned and control plots were sampled within 10 days of the start of rainfall simulations. One year following the fire (late July, 2000), all plots were again sampled over an 8 day period when the weather was uniformly hot and dry.

All runoff was routed through a collection tray at the bottom of each plot and collected in 1000 ml bottles on 1 or 2 min time intervals (time intervals were measured from the start of rainfall) throughout the entire rainfall simulation. The first sample interval was from the start of runoff to the end of the next 1 min time interval, then 1 min sample intervals were used for the next 15 min, followed by 2 min sample intervals throughout the remainder of the 60 min simulation. Runoff samples were analysed for runoff volume and sediment concentration by weighing, drying at 105° C, and re-weighing each sample.

Experimental design

Replicated study sites on burned and unburned hillslopes were selected on the following criteria. All sites must be accessible to rainfall simulation equipment, be located on the same soil series and plant community type, have a 30–40% slope angle with a northerly aspect, be within a 100 m elevation range, and be at least 250 m^2 in size. Out of all possible hillslopes meeting the selection criteria, three severely burned hillslopes and three unburned (control) hillslopes were randomly selected. Burned hillslopes were separated by approximately 1000 m, whereas unburned hillslopes were separated by an average of 400 m. The unburned hillslopes were 7–8 km from the burned hillslopes. Unburned and burned hillslopes were sampled using 10 and 20 runoff plots (area: 0·5 m^2) per hillslope respectively. A greater number of sample plots were sampled on the burned hillslopes in anticipation of greater variability in response variables compared with the control hillslopes.

Pierson *et al*. (1994) and Blackburn (1975) noted significant differences in infiltration and erosion rates between coppice (under shrub canopy) and interspace (area between shrubs dominated by grasses and/or forbs) microsites on similar sagebrush rangelands throughout the intermountain west. Pierson *et al*. (in press) found that fire differentially impacted coppice and interspace microsites a year following a wildfire in Idaho. Therefore, hillslope sampling was stratified with half the runoff plots located on interspace microsites and half located on coppice microsites to incorporate inherent variability between microsites and to determine any differential impact of fire.

Before simulated rainfall was applied, soil samples were collected adjacent to each runoff plot and analysed for gravimetric soil moisture content. Following rainfall simulation, bulk density using the core method (Blake and Hartge, 1986) and soil texture using the hydrometer method (Bouyoucos, 1962) were determined from soil samples taken immediately adjacent to each plot. In each runoff plot, canopy and ground cover, to the nearest percent, were ocularly estimated for each plant species, standing dead, stumps, and rocks (Elzinga *et al*., 2000). Circular paper discs were prepared corresponding to 0·01, 0·5, 1·0, 5·0, 10·0, and 15·0% for the 0·5 m^2 plots. These discs were used to calibrate ocular cover estimates. The accuracy of the ocular method was evaluated on random plots by recording 500 points with a point frame. Corresponding percent differences between ocular and point cover measurements were not more than 5%.

Data analysis

In addition to measured response variables for each runoff plot, a number of derived response variables for each runoff plot were also used in the analysis. Average infiltration rate (mm h^{-1}) for each sample interval was calculated as the difference between applied rainfall and measured runoff divide by the time of the sample interval. Final infiltration rate (mm h^{-1}) was chosen as the average infiltration rate of the 58–60 min time interval. Minimum infiltration rate (mm h^{-1}) was chosen as the lowest average infiltration rate of all sample intervals. Average runoff rate (mm h^{-1}) was calculated for each sample interval as the runoff volume for the interval divided by the time of the interval. Cumulative runoff (mm) was calculated as the integration of runoff rates over the total time of runoff. A runoff/rainfall ratio (mm mm^{-1}) was calculated by dividing cumulative runoff by the total amount of rainfall applied. Cumulative sediment yield (kg ha^{-1}) was calculated as the sum of all sediment collected throughout the duration of runoff. Sediment to runoff ratio (kg ha^{-1} mm^{-1}) was calculated by dividing cumulative sediment yield by cumulative runoff.

All measured and derived variables were tested for normality, skewness and kurtosis prior to analysis. Sample adequacy of rainfall simulations was evaluated to estimate population mean final infiltration rate within 15% of the sample mean at the 90% probability level (SRM, 1986). Log_{10} transformations of cumulative sediment yield and sediment to runoff ratio were required to achieve normal distributions. Differences between treatments were tested by analysis of variance using a split-plot design, and treatment means were separated using the Waller–Duncan test (Steel and Torrie, 1980) with a 5% (or otherwise specified) confidence level. The degree of linear association of soil and vegetation variables most related to hydrologic and erosion variables was determined using a Pearson's correlation matrix (SAS Institute Inc., 1999).

RESULTS AND DISCUSSION

Soils and vegetation

All burned and unburned hillslopes were located on the same soil series, but slight differences in surface soil texture were observed. Burned hillslopes had higher sand and lower silt contents compared with unburned slopes (Table I). This difference may be due to inherent site variability, but is more likely a result of significant wind erosion of silt particles after the fire. Severe dust storms causing highway closures were common immediately after the fire. Pierson *et al*. (in press) also observed 'armouring' of the soil surface with sand and gravel after wildfire on similar coarse-textured soil types.

Bulk densities were generally low on all hillslopes, but were higher on burned hillslopes compared with unburned sites (Table I). Fire can remove organic materials from near-surface soil layers (DeBano *et al*., 1998), thus increasing bulk density. This was accentuated by the fact that the bulk densities were sampled after the completion of rainfall simulations allowing the soil to consolidate by wetting and drying. Antecedent surface soil water contents were low for all hillslopes during both years of the study. Burned hillslopes had slightly lower water contents than unburned hillslopes, but the differences were not statistically significant. It is not unreasonable to expect lower surface soil water contents on the burned hillslopes compared to vegetated hillslopes. After fire, the soil surface is blackened and is no longer insulated by vegetation canopy and litter causing increased soil temperatures and associated evaporation rates.

The fire uniformly removed all the vegetation canopy and litter from the burned hillslopes. After the fire, burned hillslopes had over 99·0% bare ground compared with less than 6% on the unburned hillslopes (Table I). The unburned hillslopes were densely covered with shrubs, grasses and litter. After a single growing season following the fire, herbaceous vegetation cover on the burned interspaces had recovered to near unburned conditions, but the percentage bare ground was still much higher compared to unburned conditions because litter cover was still quite low (Table I). Coppice microsites were slower to recover following the fire. One year post-fire, coppices still had an average of 60% bare ground and very little litter accumulation, with most of the vegetation cover coming from grasses that survived the fire (Table I).

Infiltration

The interpretation of hydrologic results from this study was complicated by significant temporal variations in hydrologic conditions between years for the unburned sites. Cumulative runoff significantly decreased and final infiltration rate significantly increased between samplings on all unburned sites (Table II). Therefore, hydrologic variables were analysed for the influence of burning on microsites within each year and not between years.

Fire had a significant influence on the time it took to initiate overland flow. Burned plots began to runoff and reached their peak runoff rates faster than did the unburned plots immediately following the fire (Table II).

Table I. Average soil and cover variables for coppice and interspace microsites on all burned and unburned hillslopes immediately following (1999) and 1 year after (2000) wildfire

Variable	1999				2000			
	Burned		Unburned		Burned		Unburned	
	Coppice	Interspace	Coppice	Interspace	Coppice	Interspace	Coppice	Interspace
Sand content 0–2 cm (%)	83·4 (3·0)[b]	83·0 (3·3)	68·5 (4·6)	68·6 (4·4)	—	—	—	—
Clay content 0–2 cm (%)	6·4 (0·9)	6·5 (0·8)	7·1 (1·5)	7·1 (1·1)	—	—	—	—
Bulk density 0–2 cm (g cm^{-3})[a]	1·10 (0·15)	1·09 (0·18)	0·82 (0·14)	0·82 (0·17)	—	—	—	—
Bulk density 2–4 cm (g cm^{-3})[a]	1·33 (0·10)	1·33 (0·10)	1·03 (0·13)	1·05 (0·15)	—	—	—	—
Antecedent surface soil moisture 0–2 cm (%)	0·6 (0·4)	0·7 (0·7)	7·3 (7·9)	4·5 (2·8)	1·0 (0·8)	1·9 (5·5)	3·6 (3·3)	5·0 (5·4)
Total herbaceous cover (%)	1·1 (1·7)	3·8 (1·6)	63·2 (26·5)	73·7 (24·4)	38·0 (22·4)	62·5 (19·4)	41·4 (22·0)	61·7 (24·5)
Grass cover (%)	1·1 (1·1)	3·7 (1·6)	60·4 (28·2)	66·9 (27·1)	2·6 (3·8)	29·7 (14·4)	34·6 (24·7)	53·4 (27·7)
Shrub cover (%)	0 (0)	0·1 (0·1)	74·3 (11·5)	0·7 (1·4)	2·5 (5·4)	3·5 (5·8)	74·4 (12·2)	1·0 (1·9)
Forb cover (%)	0 (0)	0·1 (0·4)	2·8 (3·5)	6·8 (10·7)	35·4 (22·0)	32·8 (16·2)	6·9 (7·1)	8·2 (10·2)
Litter cover (%)	1·0 (1·3)	0·8 (1·4)	98·7 (2·1)	93·9 (17·8)	0 (0)	0 (0)	94·2 (11·5)	88·9 (20·1)
Bare ground (%)	99·0 (1·3)	99·2 (1·3)	1·3 (2·1)	6·1 (17·8)	59·5 (22·9)	34·0 (20·6)	5·8 (11·5)	11·1 (20·1)

[a] Main effect of treatment is significant at $P = 0·05$.
[b] Standard deviations are included in parentheses.

Table II. Average runoff, infiltration and sediment response variables for all burned and unburned hillslopes immediately following (1999) and 1 year after (2000) wildfire. Values across a row and within a year followed by different letters are significantly different ($P < 0.05$)

Variable	1999		2000	
	Burned	Unburned	Burned	Unburned
Time-to-runoff (min)	1·9 b[a]	2·5 a[a]	4·2 a	3·0 b
Time-to-peak runoff (min)	5·6 b	7·1 a	8·8 a	9·4 a
Cumulative runoff (mm)	27·3 a	31·0 a	10·5 a	13·0 a
Minimum infiltration (mm h^{-1})	45·2 a	45·9 a	65·2 a	66·0 a
Final infiltration (mm h^{-1})	57·6 a	48·1 a	72·4 a	66·0 a
Runoff/Rain ratio (mm mm^{-1})	0·34 a	0·39 a	0·13 a	0·17 a
Cumulative sediment (kg ha^{-1})	315 a	183 a	100 a	70 a

[a] Statistically significant difference is for $P = 0.08$.

Regardless of treatment combination, all plots began initial runoff between 2 and 5 min after rainfall began, and most sites experienced their lowest infiltration rates from 5 to 10 min following the start of rainfall (Table II, Figure 1). Coppice microsites began to runoff earlier than unburned coppices immediately after the fire, but no differences were found between burned and unburned coppices 1 year after fire (Table III). Pierson *et al*., (in press) found that, under similar unburned soil and vegetation conditions in Southern Idaho, dry soil and litter along with senescent vegetation led to water-repellent conditions that produced a rapid surface runoff response. This would indicate that both burned and unburned steep granitic rangeland soils are capable of generating significant runoff at the plot scale during intense thunderstorms. The influence of fire on larger-scale overland flow and rill erosion processes needs to be assessed before the complete impact of fire can be assessed at the watershed scale.

Fire did not significantly impact average infiltration on the hillslopes (Figure 1a). Average cumulative runoff, final infiltration rate, and runoff/rainfall ratio did not significantly differ within years between burned and unburned hillslopes during the first or second years (Table II). However, microsites distributed across the hillslopes did respond differently to the impact of the fire. Fire had a significant impact on coppice microsites, where infiltration rates were reduced during the initial stages of runoff generation immediately following fire (Figure 1c). Higher vegetation and litter cover on the coppice microsites provided more combustible organic material, increased burn temperatures, and enhanced the potential to generate hydrophobic coatings on soil particles leading to water-repellent soil conditions. The impact of fire on coppice infiltration rates was not significant 1 year following the fire.

Table III. Average runoff, infiltration and sediment response variables for coppice and interspace microsites on all burned and unburned hillslopes immediately following (1999) and 1 year after (2000) wildfire. Values across a row and within a year followed by different letters are significantly different ($P < 0.05$)

Variable	1999				2000			
	Burned		Unburned		Burned		Unburned	
	Coppice	Interspace	Coppice	Interspace	Coppice	Interspace	Coppice	Interspace
Time-to-runoff (min)	1·8 b	2·0 ab	3·0 a	2·0 ab	3·7 ab	4·7 a	3·7 ab	2·3 b
Time-to-peak runoff (min)	5·6 a	5·5 a	7·8 a	6·3 a	8·1 ab	9·6 ab	11·2 a	7·5 b
Cumulative runoff (mm)	30·2 ab	24·1 b	24·1 b	38·0 a	11·1 a	10·0 a	10·1 a	16·2 a
Minimum infiltration (mm h^{-1})	37·8 b	53·6 a	54·0 a	37·9 b	63·4 a	67·0 a	69·3 a	62·7 a
Final infiltration (mm h^{-1})	55·5 ab	60·0 a	55·9 ab	40·4 b	71·6 a	73·2 a	69·1 a	62·8 a
Runoff/Rain ratio (mm mm^{-1})	0·37 ab	0·30 b	0·30 b	0·49 a	0·14 a	0·12 a	0·13 a	0·21a
Cumulative sediment (kg ha^{-1})	410 a	210 b	123 b	244 b	124 a	76 a	48 a	93 a

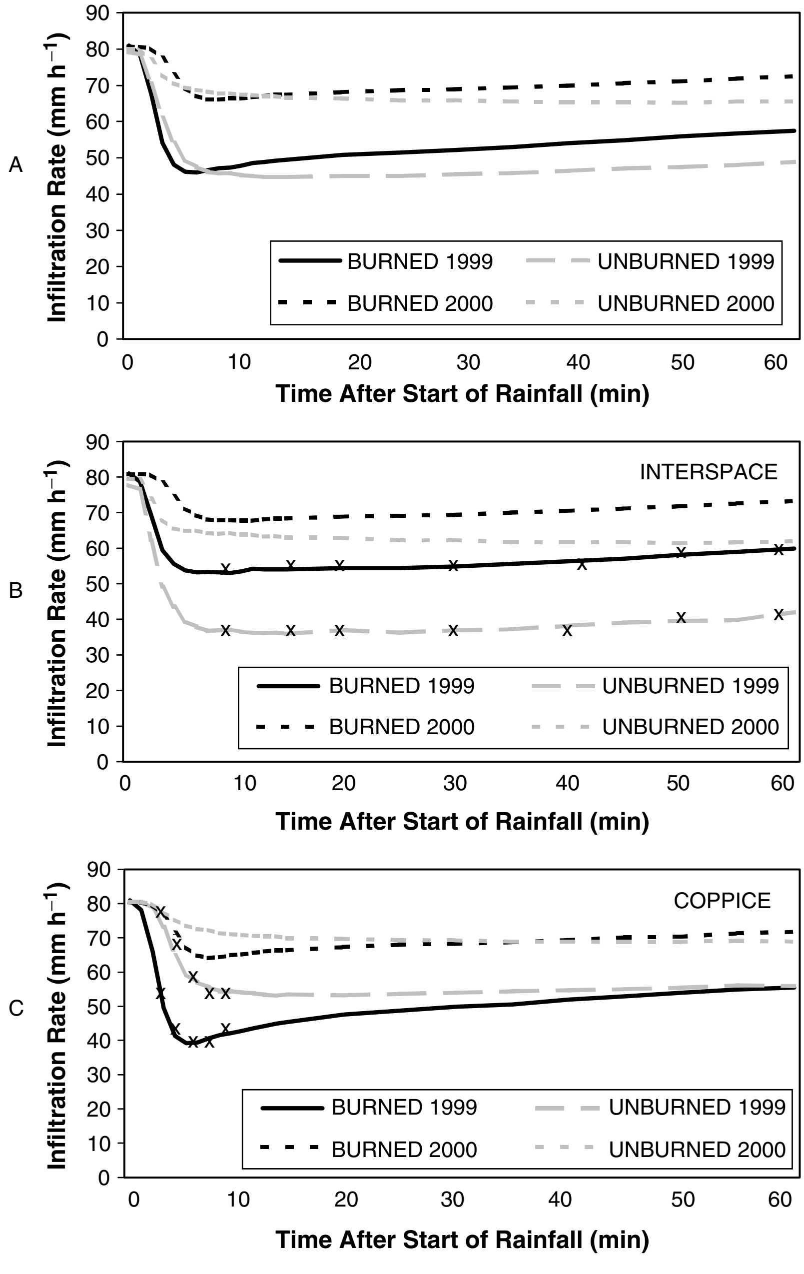

Figure 1. Average infiltration rate over time for all plots (A), interspace plots (B) and coppice plots (C) on burned and unburned hillslopes immediately after (1999) and 1 year post-wildfire (2000); x denotes that averages for the same points in time are significantly different ($P = 0{\cdot}05$)

Results indicate that fire had little influence on infiltration of interspace microsites. An unexpected result was that unburned interspace microsites in 1999 had the lowest infiltration compared with all other microsites in either year (Figure 1b). Cumulative runoff was significantly higher, minimum and final infiltration rates were significantly lower, and runoff/rainfall ratio was significantly higher on the unburned compared with the burned interspaces (Table III). Roundy *et al*. (1978) reported that infiltration rate did not change in sagebrush interspace areas as a result of fire. These results may be an artifact of the scale of measurement. Field observations during rainfall simulations concluded that the high runoff volumes (resulting in low calculated infiltration rates) were a result of water being shed off the small plots by the dense mat of senescent grass laying on the soil surface. The rainfall was not making it to the soil surface to infiltrate before running off the plot. Therefore, the burned interspace microsites may have had a lower infiltration response than the unburned interspaces that was masked by the high runoff generated from the senescent grass on the unburned plots. Variability in this phenomenon may also be the cause of the large temporal (between years) change in infiltration characteristics of the unburned interspaces.

Water repellency

Fire can vaporize organic compounds, which then coat soil particles to create a water-repellent soil layer that can impede infiltration (Debano, 1981; DeBano *et al.*, 1998; Wright and Bailey, 1982). The impact of water-repellent soil conditions on infiltration was assessed by examining the initial stages of the infiltration process. Infiltration into water-repellent soil is decreased during early stages, then increases with time as hydrophobic substances deteriorate, resulting in a gradual infiltration rate recovery over the duration of rainfall to a final equilibrium infiltration rate (Robichaud, 2000b). This phenomenon was observed for many plots on both the burned and unburned sites. To quantify the impact of soil water repellency, whether naturally occurring or induced by fire, we derived a water repellency index (WRI) defined as:

$$\mathrm{WRI} = \frac{I_{\mathrm{fin}} - I_{\mathrm{min}}}{I_{\mathrm{fin}}} \times 100$$

where I_{min} is the minimum infiltration rate throughout the rainfall simulation and I_{fin} is the final infiltration rate measured at the end of the simulation. WRI can range from 0% when I_{min} equals I_{fin} to 100% when I_{min} is zero and I_{fin} is greater than zero. To illustrate, the WRI for average post-burn infiltration responses for both burned and unburned coppice microsites immediately after the fire are compared in Figure 2. Both the burned and unburned conditions show a reduction in infiltration during the initial stages of rainfall simulation. However, the unburned condition shows only a slight reduction in infiltration (WRI = 5·0%), whereas the burned coppice has a greater, fire-induced, reduction in infiltration (WRI = 28·6%).

Immediately after the fire, burned hillslopes exhibited significantly greater water-repellent soil conditions compared with unburned hillslopes. Water-repellent soil reduced infiltration by an average 22·5% on the burned hillslopes compared with 7·4% on unburned hillslopes (Table IV). Coppice microsites experienced the greatest fire impact, with infiltration rates reduced an average of 32·3%. A uniform 29 of 30 burned coppice plots exhibited greater than 10% reduction in infiltration, whereas only three of 15 unburned coppices exhibited significant hydrophobic reductions in infiltration (Table IV). Burned interspace microsites exhibited less hydrophobic reduction in infiltration (11·6%) and had a similar average response to unburned interspaces. Eighteen of 30 burned interspaces and seven of 15 unburned interspaces had greater than 10% reduction in infiltration, suggesting that nearly 50% of interspace microsites, burned or unburned, can have significant water-repellent soil conditions (Table IV). The water repellency of the unburned interspaces could have been a result of the water repellency of the senescent vegetation and litter discussed above.

Hydrophobic substances are believed to break down over time by wetting and drying, freeze thaw, and microbial activity. Fire-induced hydrophobic reductions in infiltration were improved, but still significant 1 year after fire. Infiltration was reduced an average 10·7% on the burned hillslopes compared with 3·5% on unburned hillslopes (Table IV). Burned coppice microsites were an average 11·7% reduced, with 17 of 30 plots still exhibiting greater than 10% reduction in infiltration. Burned interspaces were an average 9·7% reduced, with 13 of 30 plots showing greater than 10% reduction (Table IV).

Interrill erosion

Fire had a significant impact on interrill soil erosion immediately following the fire. Sediment/runoff ratio, a relative measure of soil erodibility, was nearly twice as high for burned compared with unburned

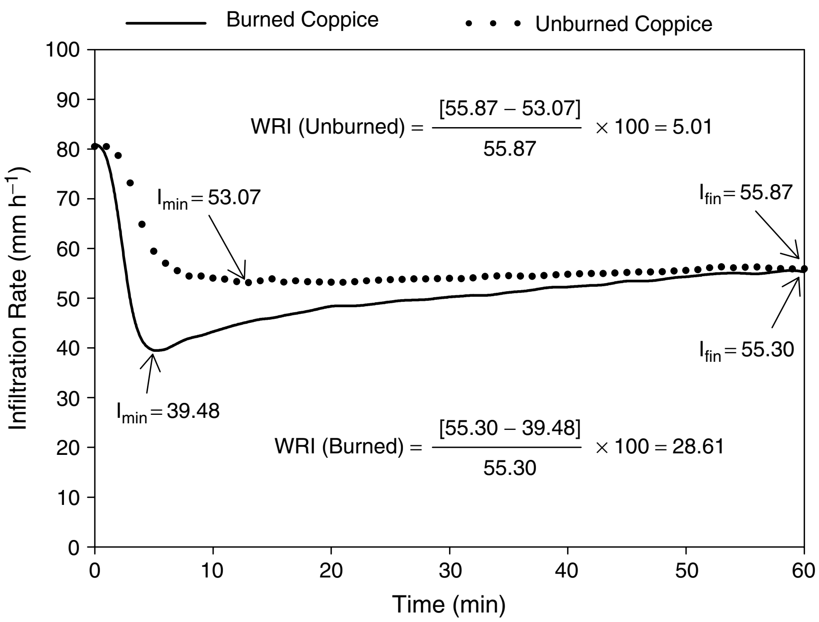

Figure 2. Average WRI for coppice microsites on burned and unburned hillslopes immediately after wildfire (1999)

Table IV. Average WRI and number of plots with WRI > 10% for all burned and unburned hillslopes and burned and unburned coppice and interspace microsites immediately following (1999) and 1 year after (2000) wildfire. Values across a row and within a year followed by different letters are significantly different ($P < 0{\cdot}05$)

Variable	1999				2000			
	Burned		Unburned		Burned		Unburned	
WRI (%)	22·5 a		7·4 b		10·7 a		3·5 b	
# Plots with WRI > 10%	47		10		30		5	
	Coppice	**Interspace**	**Coppice**	**Interspace**	**Coppice**	**Interspace**	**Coppice**	**Interspace**
WRI (%)	32·3 a	11·6 b	5·3 b	9·4 b	11·7 a	9·7 a	2·6 a	4·4 a
# Plots with WRI > 10%	29	18	3	7	17	13	2	3

hillslopes immediately after fire, but was not significantly different 1 year later (Figure 3a). Coppice microsites showed the largest fire impact, with over a twofold increase in sediment/runoff ratio still evident 1 year after fire (Figure 3c). Interrill erosion from interspace microsites was slightly, but insignificantly, elevated by fire. After 1 year of post-fire recovery, interspaces had recovered to unburned conditions (Figure 3b). Cumulative sediment yields followed similar, but less significant, yearly and microsite patterns (Tables II and III, respectively).

Temporal recovery of interrill erosion was correlated to the recovery of vegetation and ground cover. Sediment/runoff ratio was negatively correlated with total herbaceous cover (−0·58), grass cover (−0·57) and litter cover (−0·56). Ground cover on the burned interspaces recovered to 66% (Table I) after only one growing season, which was enough to provide adequate soil protection to reduce soil erosion to unburned levels. However, ground cover on the severely burned coppices recovered to only 39·5% (Table I), leaving them vulnerable to erosive forces for at least one more year.

Coppice microsites had higher fuel loads due to the presence of shrubs and dense litter layers (Table I), which could have caused an increase in fire severity compared with interspace locations. Burn temperatures

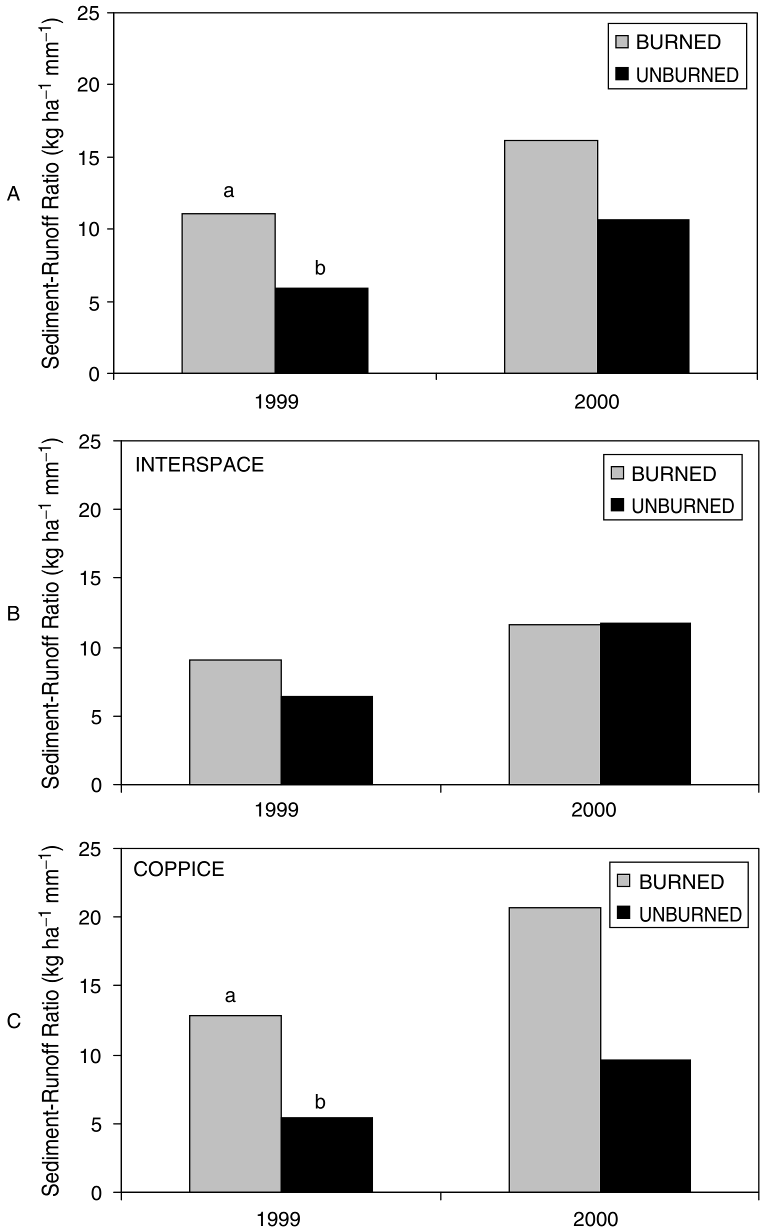

Figure 3. Average sediment/runoff ratio for all plots (A), interspace plots (B) and coppice plots (C) on burned and unburned hillslopes immediately after (1999) and 1 year post-wildfire (2000). Values within a year followed by different letters are significantly different ($P = 0{\cdot}05$)

were likely higher on the coppice microsites, leading to decreases in aggregate stability, root structure and organic matter near the soil surface, all of which have been shown to influence soil erodibility. Wright and Bailey (1982) noted that hot fires in sagebrush grassland can remove a significant portion of the organic matter from the upper 20 mm of soil. On pinyon–juniper rangeland in Nevada, Roundy *et al*. (1978) found that fire had the greatest impact on shrub (coppice) sites, with reduced infiltration and two to three times the sediment yield.

SUMMARY AND CONCLUSION

Wildfire can significantly influence the hydrologic response of sagebrush-dominated rangelands. Our results indicate water-repellent soil conditions occurred after the fire and were reduced, but still present, up to 1 year post-fire. The main impact of the fire was on coppice microsites directly under shrubs, where higher quantities of litter and organic matter are available for combustion and development of hydrophobic coatings on surface soil particles. Coppice microsites had very uniform fire-induced soil water repellency, with 29 of 30 plots exhibiting at least a 10% reduction in initial infiltration with an average 28% reduction. The magnitude of reduction in infiltration is similar to that reported by Robichaud (2000b) under forested conditions.

The fire increased interrill erosion by twofold compared with unburned conditions. Fire removed all the surface litter and organic matter from the soil surface that provide barriers to overland flow, help trap sediment and protect the soil surface from raindrop impact (Meeuwig, 1971; Roundy *et al*., 1978). Similar to infiltration, the main impact of the fire on erosion was concentrated on coppice microsites and not the interspaces between shrubs. After the fire, cumulative erosion was nearly four times higher on burned coppices compared with unburned coppices. Erosion rates were still elevated 1 year after fire because regrowth of herbaceous vegetation was slower on the severely burned coppices, still leaving these microsites unprotected from erosive forces.

The results of this study show that the lowest infiltration rates were observed on unburned interspaces that were densely covered in very dry litter and senescent grasses. This suggests that water-repellent soil and litter conditions can exist on unburned coarse-grained soils during very dry periods, as well as after wildfire. All burned and unburned plots began to runoff rapidly (2–5 min) and could produce significant overland flow when rainfall intensity exceeds initial infiltration rate and surface storage capacity. Therefore, high-intensity thunderstorms can generate rainfall excess and cause overland flow on unburned, as well as burned, sagebrush-dominated watersheds. However, on unburned slopes, vegetation and litter store water, slow runoff velocity and protect the soil surface from erosion, thereby reducing the impact of the generated runoff. Additional studies are needed to examine the impact of fire-induced litter removal, water-repellent soil conditions and increases in soil erodibility on larger-scale watershed processes.

The results of this study show that temporal variations in infiltration rate and associated soil and vegetation properties are very important factors to consider when assessing the impact of fire. Temporal variations in infiltration rates between years for all burned and unburned sites were greater than the spatial variations caused by the fire. More information is needed on the factors that create temporal variability and how resource managers should address temporal variability in management decisions.

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