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Fire effects on rangeland hydrology and erosion in a steep sagebrush-dominated landscape†

Frederick B. Pierson,[1]* Peter R. Robichaud,[2] Corey A. Moffet,[3] Kenneth E. Spaeth,[4] Stuart P. Hardegree,[1] Patrick E. Clark[1] and C. Jason Williams[1]

[1] *US Department of Agriculture—Agricultural Research Service, Northwest Watershed Research Center, Boise, ID, USA*
[2] *US Department of Agriculture—Forest Service, Rocky Mountain Research Station, Moscow, ID, USA*
[3] *US Department of Agriculture—Agricultural Research Service, US Sheep Experiment Station, Dubois, ID, USA*
[4] *US Department of Agriculture—Natural Resources Conservation Service, Central National Technology Support Center, Forth Worth, TX, USA*

Abstract:

Post-fire runoff and erosion from wildlands has been well researched, but few studies have researched the degree of control exerted by fire on rangeland hydrology and erosion processes. Furthermore, the spatial continuity and temporal persistence of wildfire impacts on rangeland hydrology and erosion are not well understood. Small-plot rainfall and concentrated flow simulations were applied to unburned and severely burned hillslopes to determine the spatial continuity and persistence of fire-induced impacts on runoff and erosion by interrill and rill processes on steep sagebrush-dominated sites. Runoff and erosion were measured immediately following and each of 3 years post-wildfire. Spatial and temporal variability in post-fire hydrologic and erosional responses were compared with runoff and erosion measured under unburned conditions. Results from interrill simulations indicate fire-induced impacts were predominantly on coppice microsites and that fire influenced interrill sediment yield more than runoff. Interrill runoff was nearly unchanged by burning, but 3-year cumulative interrill sediment yield on burned hillslopes (50 g m^{-2}) was twice that of unburned hillslopes (25 g m^{-2}). The greatest impact of fire was on the dynamics of runoff once overland flow began. Reduced ground cover on burned hillslopes allowed overland flow to concentrate into rills. The 3-year cumulative runoff from concentrated flow simulations on burned hillslopes (298 l) was nearly 20 times that measured on unburned hillslopes (16 l). The 3-year cumulative sediment yield from concentrated flow on burned and unburned hillslopes was 20 400 g m^{-2} and 6 g m^{-2} respectively. Fire effects on runoff generation and sediment were greatly reduced, but remained, 3 years post-fire. The results indicate that the impacts of fire on runoff and erosion from severely burned steep sagebrush landscapes vary significantly by microsite and process, exhibiting seasonal fluctuation in degree, and that fire-induced increases in runoff and erosion may require more than 3 years to return to background levels. Published in 2008 by John Wiley & Sons, Ltd.

KEY WORDS erosion; fire; infiltration; interrill; rangeland; rills; runoff; sagebrush; water-repellent soils

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INTRODUCTION

Post-fire runoff and erosion rates from wildlands are commonly attributed to development or enhancement of: soil water repellency (DeBano *et al.*, 1970; Inbar *et al.*, 1998; Prosser and Williams, 1998); removal of soil-protecting litter and vegetation (Morris and Moses, 1987); reduced aggregate stability; and alteration of soil organic matter (DeBano *et al.*, 1998; Shakesby and Doerr, 2006). Soil water repellency and reductions in ground cover inhibit infiltration and promote overland flow. Removal of vegetation and litter reduces surface storage of precipitation and sediment and reduces canopy interception, increasing exposure of bare soil to rainsplash effects (Shakesby and Doerr, 2006). Burning can also reduce macrofauna populations that aid aggregate stabilization through secreted compounds and fungal hyphae production (Doerr *et al.*, 2000; Huffman *et al.*, 2001; Shakesby and Doerr, 2006). These fire-induced changes can reduce infiltration, increase and concentrate overland flow generation, and facilitate sediment entrainment.

Research has demonstrated that increases in post-fire runoff and sediment yield decline over time (Huffman *et al.*, 2001; MacDonald and Huffman, 2004). Fire-induced increases in runoff and sediment yield from wildlands are generally greatest 1 to 2 years following fire (Helvey, 1980; Inbar *et al.*, 1998; Robichaud, 2005) and are typically reduced to background conditions within 10 years (Robichaud *et al.*, 2000a). Recovery of post-burn runoff and erosion rates to pre-fire conditions usually occurs within 5 years on rangeland sites (Wright and Bailey, 1982) and is dependent on burn severity, vegetative recovery, litter deposition, debris recruitment, and soil water repellency.

Numerous studies have documented increased runoff and erosion rates resulting from fire (Meeuwig, 1971; DeBano, 1981; Simanton *et al.*, 1990; Robichaud, 2000a,b, 2005; Johansen *et al.*, 2001; Pierson *et al.*,

* Correspondence to: Frederick B. Pierson, Research Hydrologist, US Department of Agriculture—Agricultural Research Service, Northwest Watershed Research Center, 800 Park Boulevard, Plaza IV, Suite 105, Boise, ID 83712, USA. E-mail: fpierson@nwrc.ars.usda.gov
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2001, 2002a); however, uncertainty remains regarding the spatial continuity and temporal persistence of these impacts and concerning the degree of control fire-induced changes exert on rangeland hydrology and erosion (Doerr and Moody, 2004). The purpose of this study was to quantify the degree and persistence of fire impacts on infiltration, runoff, and erosion by interrill and rill processes on burned and unburned sagebrush-dominated rangelands and to derive implications for management of burned sagebrush landscapes.

METHODS

Study area

Experiments were conducted on portions of the Denio wildfire approximately 24 km southwest of Denio, Nevada, USA. The fire burned 34 400 ha during July 1999. The study area is located at 2050 m elevation on Major Land Resource Area 23 (Malheur High Plateau), 41°45′00″ latitude 118°41′09″ longitude (USDA-SCS, 1981). Annual precipitation for the area ranges from 350 to 400 mm and the average annual air temperature ranges from 5·5 to 7·0 °C. Total annual precipitation during this study was 75%, 55%, 48%, and 55% of long-term average for the year of the fire and each of the following 3 years respectively. Soils at the site average 88 cm depth to unweathered granite and are mapped Ola (coarse-loamy, mixed, superactive, frigid *Pachic Haploxerolls*) bouldery sandy loam (USDA–NCRS, 2001). The terrain is mountainous with slopes ranging from 30 to 40%. The ecological site description is loamy mountain big sagebrush (*Artemisia tridentata Nutt* ssp. v*aseyana* (Rydb.) Beetle)/Columbia needlegrass (*Achnatherum nelsonii* (Scribn) Barkworth). Dominant grasses present were Columbia needlegrass (*A. nelsonii* (Scribn) Barkworth), Idaho fescue (*Festuca idahoensis* Elmer), bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Löve), and sandberg bluegrass (*Poa secunda*) (USDA–NRCS, 1990).

Pierson *et al*. (2001) measured runoff and sediment yield from rainfall simulation plots on burned and unburned areas at the study site immediately after and 1 year following fire. The current study expands the Pierson *et al*. (2001) study to include one additional year of rainfall simulations and 4 years of concentrated flow experiments. A more detailed description of the study area is presented in Pierson *et al*. (2001).

Experimental design

Replicated study sites for burned and unburned hillslopes were chosen on the following criteria. All burned and unburned sites were located on the same soil series and plant community type, with 30–40% slopes of a northerly aspect, were within a 100 m elevation range, and were at least 250 m^2 in size. Three burned and unburned study sites were selected randomly from multiple hillslopes meeting the criteria described. Separations of study sites on burned and unburned hillslopes were an average of 1000 m and 400 m respectively. Burned hillslopes were located approximately 7–8 km from unburned hillslopes. Twenty rainfall simulation plots were installed on each burned hillslope and 10 rainfall simulation plots were placed on each unburned hillslope. Six concentrated flow plots were installed on each burned and unburned hillslope. For rainfall simulations, a greater number of sample plots were sampled on the burned hillslopes in anticipation of greater variability in response variables compared with the control (unburned) hillslopes. To assess microsite response to fire, rainfall simulations were stratified by placing half of the plots on interspace microsites (area between shrub canopies) and half the plots on coppice microsites (area underneath shrub canopy).

Soil samples (0–2 cm) adjacent to each rainfall simulation plot were collected before rainfall application and were analyzed for gravimetric soil moisture content. Bulk density and surface soil texture were analyzed using the core (Blake and Hartge, 1986) and hydrometer (Bouyoucos, 1962) methods respectively on soil samples collected immediately adjacent to plots post-simulation. Ground cover at the site in years 1 to 3 was characterized by recording cover hits at 231 points, 20 cm spacing, on all concentrated flow plots; ground cover in year 0 was obtained from cover measurements on rainfall simulation plots (Pierson *et al*., 2001). Litter grab samples were obtained on 0·5 m^2 plots from 10 representative locations outside of rainfall simulation and concentrated flow plots on burned and unburned hillslopes in year 4 (2004). Litter samples were oven dried at 60 °C and weighed to determine sample mass.

Rainfall simulations

Rainfall-simulation plot-frames (0·5 m^2) were installed immediately following the fire in 1999 and left in place for simulations in subsequent years. Initial vegetation and soil sampling and rainfall simulations began 6 weeks following the fire and occurred before any natural rainfall events. Sampling of burned and unburned plots each year was completed within 10 days of the start of rainfall simulations for each respective year. Rainfall simulations were applied under uniform hot and dry conditions.

Rainfall simulations were conducted immediately following the fire, year 0, and for two subsequent years, years 1 and 2. Portable oscillating-arm rainfall simulators (Meyer and Harmon, 1979) applied 85 mm h^{-1} rainfall for 60 min to each plot. Simulators were fitted with Veejet 80–100 nozzles positioned 3 m above plots and pressurized at 41 N m^{-2} (Meyer and Harmon, 1979). Raindrop size (2 mm) and kinetic energy (200 kJ ha^{-1} mm^{-1}) of simulated rainfall was within 1 mm and 70 kJ ha^{-1} mm^{-1} respectively of values reported for natural convective rainfall (Carter *et al*., 1974; Meyer and Harmon, 1979). The total amount of rainfall applied to each plot was obtained by integrating the pan catch of a 5-min calibration run prior to rainfall simulation. Calibration pans were designed to fit directly on plot frames

without disturbing the plot surface. The total rainfall applied was estimated on plots where shrub cover prevented placement of calibration pans; estimated rainfall was calculated as the average of all calibrations for the respective plot-frame slope. The rainfall application rate was equivalent in intensity to 5-min, 10-min, and 15-min storms with respective return intervals of 25 years, 70 years, and 125 years as observed at the Sheldon, NV, weather station, Station 26–7443 (Bonnin *et al.*, 2006). The Sheldon station is approximately 80 km west of the Denio site at 1954 m elevation. The applied intensity over the 60 min simulation period greatly exceeded the 500-year storm, but was chosen to achieve steady-state runoff during simulation.

Runoff and suspended sediment from rainfall simulations were routed through a collection tray at the bottom of each plot frame and collected on 1- or 2-min time intervals throughout rainfall simulation. The first 16 samples were collected at 1-min intervals, followed by 2-min collections throughout the remainder of the 60-min simulation. Runoff samples were analyzed for sediment concentration by weighing, drying at 105 °C, and reweighing each sample.

Concentrated flow simulations

Concentrated flow simulations were initiated in the spring of 2000 (year 0), before the first growing season, and were repeated each year through 2002 (year 2) on unburned and through 2003 (year 3) on burned sites. Sampling in spring of 2000 is considered representative of similar site conditions sampled by rainfall simulations immediately following fire in 1999 with respect to ground cover recovery. Concentrated flow plots were established independent of rainfall simulation plots, but were located in the same study domain. A flow regulator was used to apply specified inflow rates. Rates of 7, 12, 15, 21, and 24 l min^{-1} were applied to all unburned plots. Rates on burned plots initiated at 7 l min^{-1} and were increased to a maximum of 24 l min^{-1} or until high runoff rates yielded sample fill times less than 5 s, compromising sampling accuracy. Flow at each rate was released from the same 10 cm wide cross-section and applied for 12 min. Progression in flow rates was consecutive from 7 l min^{-1} to the highest rate applied. The plots were unconfined with respect to width.

Runoff and suspended sediment from concentrated flow simulations were sampled over 1-min intervals from a collection tray 4 m downslope from the release point. Runoff and sediment concentration samples were analyzed by weighing, drying at 105 °C, and reweighing each sample. Width and average depth were recorded for each flow path observed at cross-sections located 1 and 3 m downslope from the release point. Average depth was determined as the average of multiple depth measurements taken by ruler (nearest 1 mm) from each flow path at the respective cross-section. The total number of flow paths was tallied and the total rill area width and total rill flow width were measured for each cross-section. Total rill flow width was measured as the sum of free water widths of each flow path crossed at the respective cross-section. Total rill area width represents the total width between the outermost edges of the outermost flow paths at the respective cross-section. A mean impacted rill area was determined from total rill area width cross-section measurements obtained at 1 and 3 m downslope of concentrated flow release points and integrated over the 4 m simulation length scale (Figure 1). Flow velocity was determined by releasing a concentrated salt solution ($CaCl_2$) into the rill and measuring (using instantaneously reading conductivity probes) the mean travel time of the salt solution between rill cross-sections 1 and 3 m downslope of the release point. Mean travel time and subsequent flow velocity was determined as the time difference between the maximum conductivity readings on each probe.

Comparison of interrill and rill runoff and erosion

The 3-year cumulative sediment yield per unit area from rainfall simulation and concentrated flow experiments was used to compare fire effects on interrill and rill runoff and erosion. The comparison assumes the rainfall application rate would generate runoff equivalent to the maximum concentrated flow release rate once overland flow converged. Mean runoff rates from the first 15 min

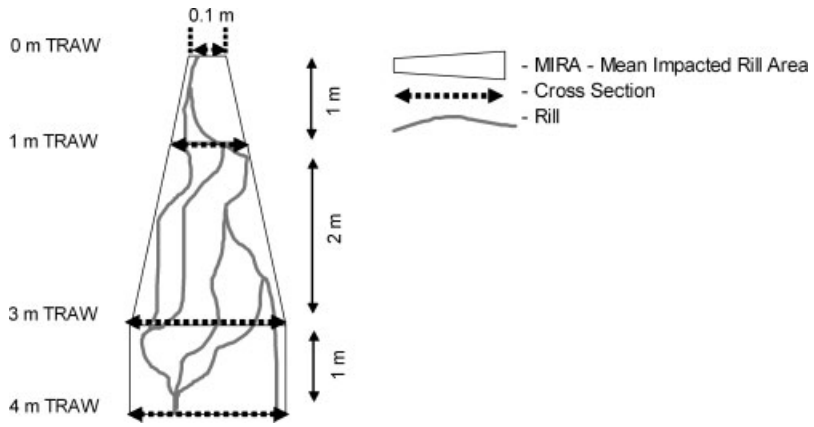

Figure 1. Illustration depicting the extent of the mean impacted rill area created by concentrated flow simulations. TRAW represents the total rill area width at the respective cross-section. The total impacted area is determined by summing areas between cross-sections at 0, 1, 3, and 4 m

of rainfall simulations on burned and unburned hillslopes were used to assess whether overland flow was substantial enough to generate and sustain concentrated flow for a period equivalent to concentrated flow simulation time, i.e. 12 min. The 15-min runoff rates from rainfall simulations (0·5 m^2 plots) were spatially extrapolated to determine the convergent contributing area required to generate concentrated flow rates from the rainfall intensity applied. The 3-year cumulative sediment yield per unit area from interrill processes on burned and unburned hillslopes was determined by summing the respective mean cumulative sediment yields from the first 15 min of simulated rainfall years 0 to 2. The 3-year cumulative sediment yield per unit area from rill processes on burned and unburned hillslopes was determined by summing the respective cumulative sediment yields per unit area from inflow rates 7, 12, and 15 l min^{-1} for years 0 to 2. Concentrated flow cumulative sediment yield per unit area for each rate each year was calculated by dividing the measured cumulative sediment yield by the mean impact rill area for the respective rate.

Data analysis

The average infiltration rate for each sample interval was calculated as the difference between applied rainfall and measured runoff divided by the time of the sample interval. The final infiltration rate was the average infiltration rate of the 58–60 min time interval. The minimum infiltration rate was chosen as the lowest average infiltration rate of all sample intervals. The average runoff rates, sediment concentration, cumulative runoff, and sediment yield were determined for all rainfall and concentrated flow simulations. The average runoff rates were calculated for each sample interval as the runoff volume for the interval divided by the time of the interval. Average sediment concentrations were calculated for each sample interval as the mass of sediment for the interval divided by the runoff volume for the interval. Cumulative runoff was calculated as the integration of runoff rates over the total time of runoff. A runoff/rainfall ratio was calculated for rainfall simulation plots by dividing cumulative runoff by the total amount of rainfall applied. Cumulative sediment yield was calculated as the integrated sum of sediment collected during runoff and was extrapolated to a unit area based on plot size. Sediment to runoff ratio was calculated by dividing cumulative sediment yield by cumulative runoff. The percentage of plots with runoff was calculated for concentrated flow simulations as the number of plots producing runoff divided by the number of simulations. A water repellency index was calculated as the difference in final and minimum infiltration rates divided by the final infiltration rate and expressed as percentage water repellency WRI% (Pierson *et al.*, 2001).

All measured and derived variables for rainfall and concentrated flow simulations were tested for normality. Cumulative sediment yield and sediment to runoff ratio for rainfall simulations were log transformed to achieve normal distributions. Log-transformed data are reported backtransformed. Differences between treatments on rainfall simulation plots were tested by analysis of variance (ANOVA) using a split-plot design, and treatment means were separated using the Waller–Duncan test (Steel and Torrie, 1980) with a 95% confidence interval.

ANOVA was performed on year 0 to year 2 unburned concentrated flow data to test whether the year effect was significant in the unburned sites. No significant year effects were found for unburned site concentrated flow simulations; therefore, all measured and calculated variables for unburned sites were averaged across years for the unburned condition. Analyses of concentrated flow data were further conducted in a one-way ANOVA of five treatments: burned year 0, burned year 1, burned year 2, burned year 3, and unburned (mean unburned results for year 0 through year 2). Normality of concentrated flow errors was tested using the Shapiro–Wilk test within each level of an effect. No log transformations were necessary to achieve normality. Homogeneity of error variance was tested with Levene's test. Welch's F-test was used to test for significant effects where Levene's test was significant. In cases of significant F-tests with homogeneous error variances, a least-significant-difference (LSD) was computed using the pooled error and was used to separate means. LSDs were computed using separate error terms for each contrast if error variances were not homogeneous.

RESULTS

Vegetation and soils

The fire uniformly removed all the vegetation canopy and litter from burned hillslopes, leaving 99% bare ground (Table I). Percentage bare ground (Figure 2) remained significantly greater on burned hillslopes through year 3. Bare ground averaged 8% on unburned hillslopes throughout the study. Grass cover was significantly less on burned hillslopes through year 3 and was 65% of that observed on unburned hillslopes in year 3 (Table I). Coverage of woody dead material on burned hillslopes was significantly less than on unburned hillslopes through the study and remained 27% of that measured on unburned hillslopes 3 years post-fire (Table I). Litter cover 1 year post-fire was 45% of mean unburned litter cover (Table I) and, along with total ground and herbaceous cover (Figure 2), remained significantly lower on burned hillslopes through year 2. Differences in litter, total ground, and total herbaceous coverage on burned and unburned hillslopes were not significantly different in year 3. Forb coverage on burned hillslopes was significantly greater than on unburned hillslopes at 2 and 3 years post-fire (Table I). The mean litter mass observed 4 years post-fire (2004) on burned and unburned hillslopes was 1 kg m^{-2} and 13 kg m^{-2} respectively.

Pierson *et al.* (2001) reported variations in surface soil texture, bulk density, and surface soil water contents between burned and unburned hillslopes in the study

Table I. Percentage representation by cover type observed for burned and unburned hillslopes immediately following fire and 1, 2, and 3 years post-fire

Cover type	Cover (%)				
	Burned				Unburned (mean)
	Year 0	Year 1	Year 2	Year 3	
Rock	0·5	2·4*	0·5	0·2	0·2
Litter	0·9*	18·0*	29·4*	36·5	39·4
Bare ground	98·6*	66·4*	37·6*	22·4*	8·3
Standing dead	0·0	0·5	0·3	0·0	4·0
Shrub	0·0	1·3	5·1	4·1	5·6
Forb	0·0	4·6	18·8*	15·9*	5·3
Grass	0·0*	5·2*	6·7*	19·6*	30·2
Moss	0·0	0·0	0·1	0·0	2·0
Woody dead	0·0*	1·6*	1·4*	1·3*	4·8

* Value is significantly different ($P < 0{\cdot}05$) from respective mean unburned value.

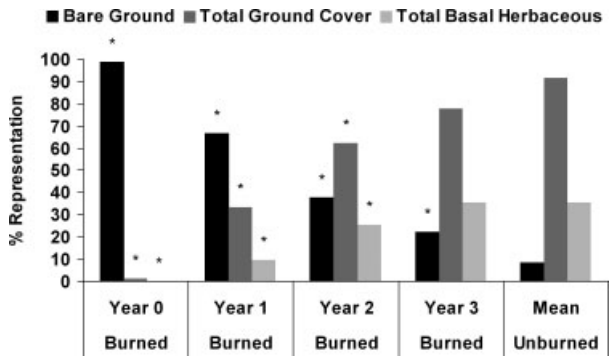

Figure 2. Percentage bare ground, total ground cover, and total basal herbaceous cover on burned and unburned hillslopes immediately following fire and 1, 2, and 3 years after fire. An asterisk above the burned value indicates significant differences ($P < 0{\cdot}05$) in burned and unburned values for the respective cover type and year

area immediately after and 1 year following fire. Burned hillslopes (83·5% sand, 10·0% silt, 6·5% clay) had higher sand and lower silt contents than unburned slopes (68·6% sand, 24·3% silt, 7·1% clay) from the same soil series. The textural difference was attributed to inherent site variability; however, texture of sand, silt, and clay are within the model limits of the Ola soil map unit component. Bulk densities were higher on burned hillslopes than on unburned sites. Pierson *et al.* (2001) inferred that these differences were associated with fire-induced reductions in organic material near the surface soil layers. Soil water content on unburned hillslopes was 5·0%, 3·6%, and 2·7% in years 0, 1, and 2 respectively. Soil water contents at 0 to 2 cm depth on burned hillslopes were 0·6%, 1·0%, and 1·7% in years 0, 1, and 2. No significant differences between treatments were observed in soil water contents during the study.

Interrill processes

The results of rainfall simulation are presented as a 1 year expansion of the year 0 and year 1 results from Pierson *et al.* (2001). Mean infiltration rates were higher

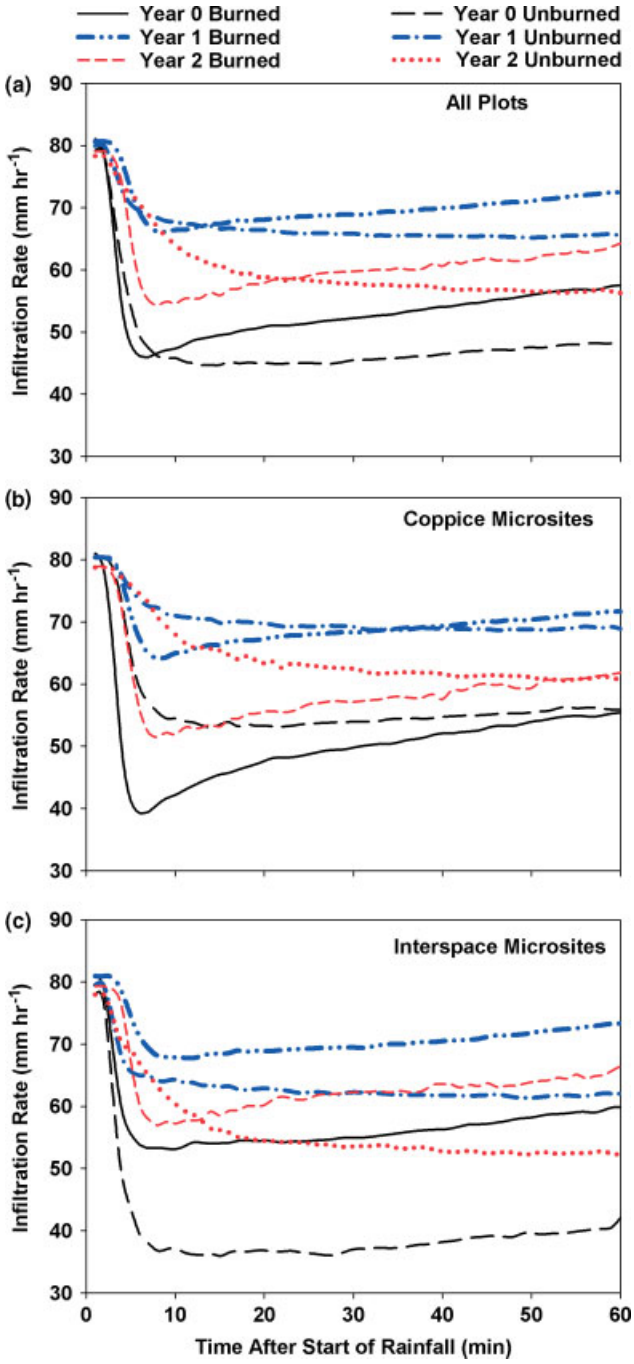

Figure 3. Average infiltration rate over time for (a) all rainfall simulation plots, (b) coppice plots, and (c) interspace plots on burned and unburned hillslopes immediately after fire (year 0), and 1 year and 2 years post-fire

1 year post-fire than immediately after and 2 years following fire (Figure 3a). As a result of this temporal variability, fire effects on hydrologic variables were analysed within each year, rather than between years (Table II). Throughout the study, runoff from all plots began within the first 2 to 5 min, and minimum infiltration rates (peak runoff) for all plots were reached within the first 5 to 14 min of rainfall simulation (Table II, Figure 3a). Unburned plots averaged 2·1 min more time to reach peak runoff each year, but the difference was only statistically different in year 0. The time to runoff was greater for burned hillslopes in year 1. No significant

Table II. Average runoff, infiltration, sediment, and water repellency response variables for rainfall simulations on burned and unburned hillslopes immediately following (year 0), 1, and 2 years after fire. Burned and unburned means within a row and respective year followed by a different lower case letter are significantly different ($P < 0{\cdot}05$)

Variable	Year 0[a]		Year 1[a]		Year 2	
	Burned	Unburned	Burned	Unburned	Burned	Unburned
Time-to-runoff (min)	1·9a	2·5a	4·2a	3·0b	3·6a	4·5a
Time-to-peak (min)	5·6b	7·1a	8·8a	9·4a	9·1a	13·3a
Cumulative runoff (mm)	27·3a	31·0a	10·5a	13·0a	17·1a	16·0a
Minimum infiltration (mm h^{-1})	45·2a	45·9a	65·2a	66·0a	52·8a	55·4a
Final infiltration (mm h^{-1})	57·6a	48·1a	72·4a	66·0a	63·8a	56·4a
Runoff/rain ratio (mm mm^{-1})	0·3a	0·4a	0·1a	0·2a	0·2a	0·2a
Cumulative sediment (kg ha^{-1})	315a	183a	100a	70a	141a	54b
Sediment/runoff ratio (kg ha^{-1} mm^{-1})	11·0a	5·9b	16·1a	10·4a	8·1a	5·5a
WRI%[b]	22·5a	7·4b	10·7a	3·5b	18·1a	1·7b
Plots with WRI >10% (%)[c]	78·3	33·3	43·3	16·7	76·7	20·0

[a] From Pierson *et al.* (2001).
[b] WRI% represents water repellency percentage and is calculated as the difference in final and minimum infiltration rates divided by the final infiltration rate.
[c] Not included in statistical analysis.

differences were observed between burned and unburned cumulative runoff, minimum infiltration, final infiltration, and runoff/rainfall ratio (Table II).

Coppice and interspace microsites responded differently to burning. Burned coppice microsites generated runoff significantly earlier than unburned coppice microsites immediately following the fire (Table III). Minimum infiltration rates were lower on burned coppice than unburned coppice microsites in years 0 and 2. WRI% was statistically greater on burned than unburned coppice microsites immediately post-fire and 2 years following fire (Table III). The time to peak runoff was significantly less on burned coppice microsites in year 2 only. No significant differences were observed between cumulative runoff, final infiltration, and the runoff/rainfall ratio.

Interspace microsites exhibited significantly lower runoff and higher infiltration rates immediately following fire (Table III). Fire had no significant effect on the time to peak runoff on interspace microsites; however, WRI% was significantly higher on burned than unburned interspaces in year 2. The time to runoff on burned interspaces was significantly different in year 1 only. Fire effects on the runoff/rainfall ratio were significant only in year 0.

The effects of fire on interrill sediment yield were confined to coppice microsites (Table III). Mean sediment/runoff ratio (a relative measure of soil erodibility) and cumulative sediment yield were greater on burned coppice than unburned coppice microsites in year 0. The sediment/runoff ratio on coppice microsites more than doubled immediately following fire and remained statistically different than unburned coppices 1 year post-fire (Table III). Cumulative sediment yield on burned coppice microsites was significantly greater than on unburned coppice and burned interspace microsites immediately post-fire and 2 years following fire. Fire effects on erosion from interspace microsites were statistically insignificant in all years (Table III).

Rill processes

The inflow rates required to generate outflow from more than 20% of the concentrated flow plots were greater for unburned hillslopes than for burned hillslopes (Table IV). Unburned hillslopes required a minimum inflow of 15 l min^{-1} to generate runoff from more than 20% of the plots (Table IV). On burned hillslopes, an inflow of 7 l min^{-1} generated runoff on 100% of plots immediately following fire and on 20% and 7% of burned plots at 1 and 2 years post-fire respectively. At 3 years post-fire, an inflow of 7 l min^{-1} did not generate runoff on burned or unburned plots. Inflows of 12 l min^{-1} and 15 l min^{-1} generated runoff on at least 65% and 90% of burned plots respectively throughout the study. The same rates generated runoff on 16% and 50% respectively of the unburned plots as averaged through the study.

Cumulative runoff on burned plots was significantly higher than on unburned plots each year and decreased for the respective inflow rates with increased time since burning (Table IV). Cumulative runoff on burned plots at an inflow rate of 15 l min^{-1} was approximately 20 times greater than the cumulative runoff observed at the same rate on unburned hillslopes within the first year. Cumulative runoff at inflow 15 l min^{-1} was reduced 50% on burned hillslopes and was approximately 11 times higher than unburned plots by year 1. In year 2, cumulative runoff at 21 l min^{-1} inflow was significantly greater on burned hillslopes than unburned hillslopes, and runoff from 15 l min^{-1} inflow was reduced to nearly a third of that observed in year 0. Runoff at inflow rate 15 l min^{-1} in years 2 and 3 was not significantly different between burned and unburned hillslopes. Runoff at 15 l min^{-1} inflow rate in year 3 on burned sites was about one-tenth of that observed in year 0. Cumulative runoff for 24 l min^{-1} inflow on burned hillslopes in year 3 was significantly different and about twice the mean runoff observed on unburned hillslopes.

Table III. Average runoff, infiltration, sediment, and water repellency response variables for rainfall simulations on burned and unburned coppice and interspace microsites immediately following fire (year 0), 1, 2, and 3 years after fire. Values across a row and within a year followed by different lower case letters are significantly different ($P > 0{\cdot}05$)

Variable	Year 0[a]				Year 1[a]				Year 2			
	Burned		Unburned		Burned		Unburned		Burned		Unburned	
	Coppice	Interspace	Coppice	Interspace	Coppice	Interspace	Coppice	Interspace	Coppice	Interspace	Coppice	Interspace
Time-to-runoff (min)	1·8b	2·0ab	3·0a	2·0ab	3·7ab	4·7a	3·7ab	2·3b	3·6a	3·7a	4·4a	4·7a
Time-to-peak runoff (min)	5·6a	5·5a	7·8a	6·3a	8·1ab	9·6ab	11·2a	7·5b	8·4a	9·7ab	13·4b	13·2b
Cumulative runoff (mm)	30·2ab	24·1b	24·1b	38·0a	11·1a	10·0a	10·1a	16·2a	19·8a	14·7a	12·6a	19·1a
Minimum infiltration rate (mm h^{-1})	37·8b	53·6a	54·0a	37·9b	63·4a	67·0a	69·3a	62·7a	49·4b	56·0a	60·4a	50·9ab
Final infiltration rate (mm h^{-1})	55·5ab	60·0a	55·9ab	40·4b	71·6a	73·2a	69·1a	62·8a	61·0ab	66·4a	60·9ab	52·3b
Runoff/rainfall ratio (mm mm^{-1})	0·4ab	0·3b	0·3b	0·5a	0·1a	0·1a	0·1a	0·2a	0·3a	0·2a	0·2a	0·2a
Cumulative sediment (kg ha^{-1})	410a	210b	123b	244b	124a	76a	48a	93a	245a	49b	17b	88b
Sediment/runoff ratio (kg ha^{-1} mm^{-1})	12·8a	9·1a	5·4b	6·4a	20·7a	11·6ab	9·6b	11·7ab	9·9a	6·4a	4·8a	6·1a
WRI%[b]	32·3a	11·6b	5·3b	9·4b	11·7a	9·7a	2·6a	4·4a	19·8a	16·5a	0·7b	2·7b
Plots with WRI >10% (%)[c]	80·0	76·7	40·0	26·7	46·7	40·0	13·3	20·0	76·7	76·7	33·3	6·7

[a] From Pierson *et al.* (2001).
[b] WRI% represents water repellency percentage and is calculated as the difference in final and minimal infiltration rates divided by the final infiltration rate.
[c] Not included in statistical analysis.

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Table IV. Rill flow characteristics by inflow rate for all burned and unburned hillslopes immediately following (year 0) through 3 years after fire (year 3). Mean impacted rill area represents the area impacted by flow from concentrated flow simulation

	Inflow		Runoff			Cum. sediment (g)	Sediment/runoff ratio (g l^{-1})	Plots with runoff (%)[a]	Num. flow paths[b]	Flow velocity[b] (m s^{-1})	Flow depth[b] (mm)	Mean impacted rill area[b] (m^2)
	Rate (l min^{-1})	Cum. (l)	Cum. (l)	Initial rate (l min^{-1})	Final rate (l min^{-1})							
Burned												
Year 0	7	84	23·1*	1·9*	1·8*	3933*	170·3*	100	1·7	0·16	8·5	0·8
	12	144	55·9*	4·5*	4·5*	6290*	112·5*	100	2·3	0·19	10·3	1·1
	15	180	99·2*	8·4*	7·9*	7552*	76·6*	100	2·3*	0·21*	10·2*	1·3
	21	—	—	—	—	—	—	—	—	—	—	—
	24	—	—	—	—	—	—	—	—	—	—	—
Year 1	7	84	2·5	0·2	0·2	44	17·6	20	—	—	—	0·8
	12	144	25·0*	1·6*	2·5*	1741*	69·6*	65	1·8	0·14	8·7	1·1
	15	180	48·6*	4·0*	4·0*	1707*	35·1*	94	1·9	0·13*	11·1*	1·1
	21	—	—	—	—	—	—	—	—	—	—	—
	24	—	—	—	—	—	—	—	—	—	—	—
Year 2	7	84	0·6	0·0	0·0	1	1·2	7	—	—	—	—
	12	144	15·3	0·9	0·9	149*	9·7*	100	1·5	0·07	3·9	1·4
	15	180	28·1	2·2	2·2	188*	6·7*	100	1·7	0·08*	4·5	1·6*
	21	252	73·2*	5·4*	6·1*	618*	8·4*	100	2·1*	0·11*	5·1*	2·2*
	24	—	—	—	—	—	—	—	—	—	—	—
Year 3	7	84	0·0	0·0	0·0	0	0·0	0	—	—	—	—
	12	144	3·9	0·3	0·3	19	4·8	100	2·4	0·06	4·8	2·2
	15	180	11·2	0·8	0·9	58	5·2	90	2·4*	0·07*	5·1	2·0*
	21	252	39·9	3·0	3·4	1032*	25·9*	100	2·6*	0·08*	6·5	2·2*
	24	288	60·4*	4·9*	5·0*	1124*	18·6*	100	2·8*	0·09*	6·6	2·3*
Unburned												
Mean	7	84	0·0	0·0	0·0	0	0·0	0	—	—	—	—
	12	144	0·6	0·1	0·0	0	0·3	16	—	—	—	—
	15	180	4·4	0·3	0·4	2	0·5	50	1·3	0·04	7·4	1·1
	21	252	18·9	1·3	1·6	22	1·1	83	1·3	0·05	8·4	1·1
	24	288	31·5	2·5	2·7	29	0·9	94	1·3	0·06	9·4	1·2

* Value is significantly different ($P < 0·05$) from mean unburned conditions for the respective variable and flow rate. Dashes indicate insufficient data replication ($n < 4$)
[a] Not included in statistical analyses.
[b] Means based solely on plots that generated runoff.

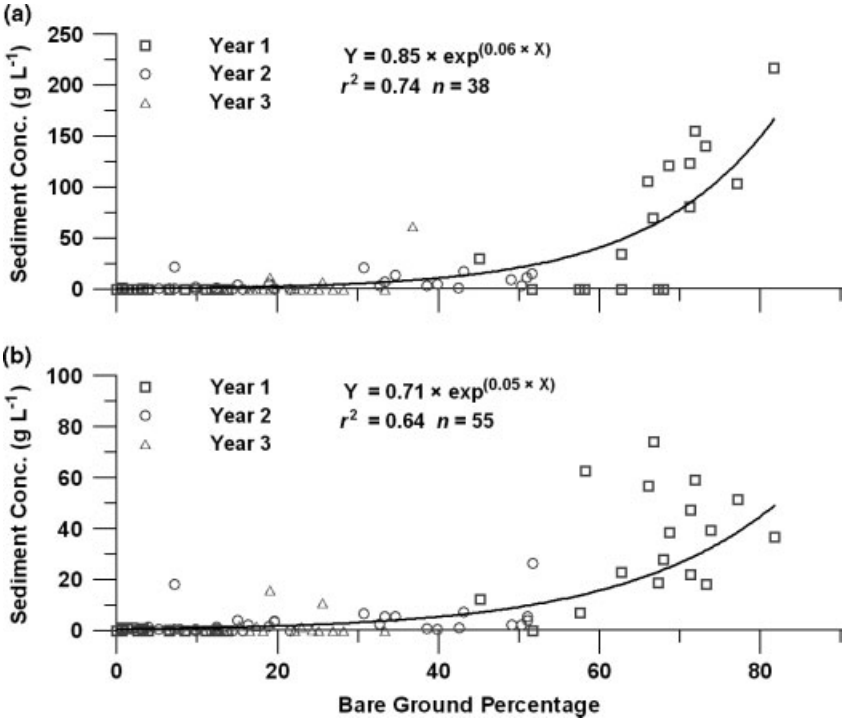

Figure 4. Sediment concentration versus bare ground measured on all concentrated plots for inflows of (a) 12 and (b) 15 l min^{-1} in years 1–3

Trends in cumulative sediment yield and sediment/runoff ratio results were similar to cumulative runoff (Table IV). Cumulative sediment and sediment/runoff were significantly different between burned and unburned hillslopes through year 2 at 15 l min^{-1} inflow. At 3 years post-fire, cumulative sediment and sediment/runoff on burned hillslopes were significantly greater for 21 and 24 l min^{-1} inflows only. Overall, the sediment concentration generated for all plots with inflows of 12 l min^{-1} and 15 l min^{-1} decreased with decreasing bare ground coverage ($r^2 = 0{\cdot}74$ and $0{\cdot}64$ respectively), with decreases occurring where bare ground dropped from 80% to 60% (Figure 4). Sediment concentration varied minimally where the percentage of bare ground ranged from 0 to 40% (Figure 4). These trends were consistent for all inflow rates.

Sediment concentrations at the initiation of concentrated flow were substantially greater on burned hillslopes than at the conclusion of simulations, and the difference in initial and final concentrations decreased with time since fire (Figure 5). Initial sediment concentrations greatly exceeded final sediment concentrations on burned hillslopes through year 2 when runoff occurred at an inflow of 15 l min^{-1} (Figure 5). Sediment concentration trends observed for an inflow of 15 l min^{-1} were consistent at all other inflow rates on burned sites. Initial, average, and final sediment concentrations were nearly equal on burned hillslopes at 3 years post-fire. Differences in initial and final runoff rates were not large enough to explain differences between initial and final sediment concentrations (Table IV).

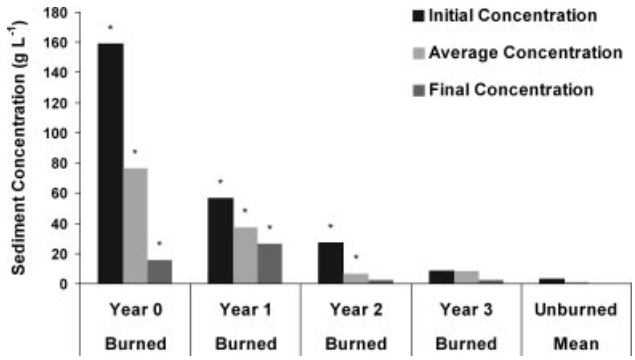

Figure 5. Initial, average, and final sediment concentrations measured on burned and unburned hillslopes during overland flow simulations at inflow rate 15 l min^{-1}. Means presented here only depict concentrations for plots that generated runoff. An asterisk above burned value indicates significant differences ($P < 0{\cdot}05$) in burned and mean unburned values for the respective year

Fire effects on rill flow velocity were observed immediately post-fire and through year 3 following fire. Concentrated flow simulations of 15 l min^{-1} inflow produced higher velocity flow on burned hillslopes than on unburned hillslopes through year 3 (Table IV). Rill flow velocity at an inflow rate of 15 l min^{-1} in year 0 was six times greater on burned hillslopes than on unburned hillslopes. Rill flow velocity in years 1 and 2 for 15 l min^{-1} inflow on burned hillslopes was reduced by 40% and 60% respectively but remained significantly greater than on unburned hillslopes. In year 3, the rill flow velocity on burned hillslopes at an inflow of 15 l min^{-1} was a third of that observed in year 0. Rill flow velocities on burned hillslopes in year 3 were significantly greater than velocities on unburned hillslopes for inflows of 15, 21 and 24 l min^{-1}. Overall, velocity on plots with inflows

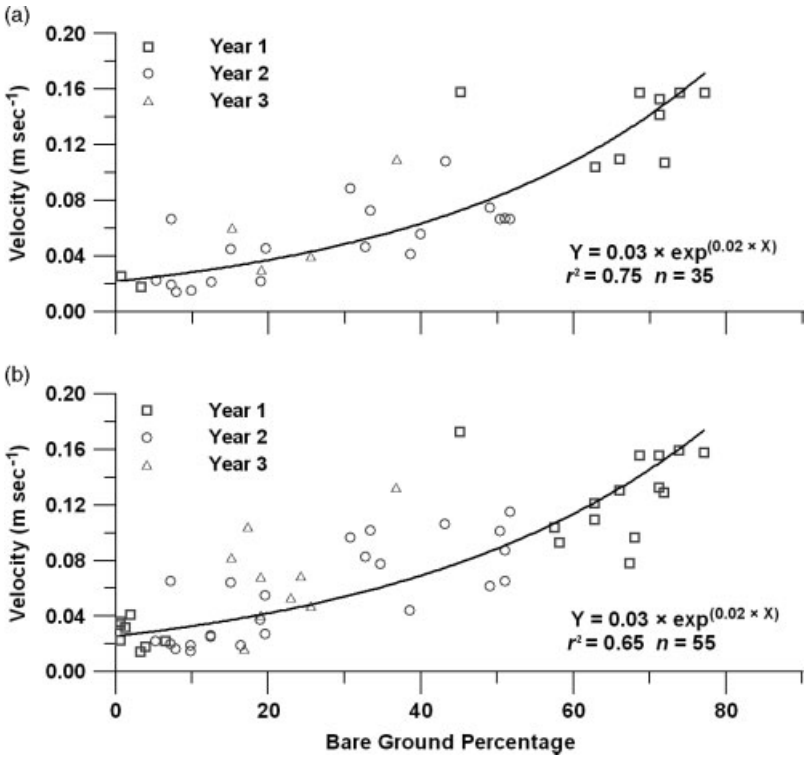

Figure 6. Rill flow velocity versus bare ground measured on all concentrated plots for inflows of (a) 12 and (b) 15 l min^{-1} in years 1–3

of 12 l min^{-1} and 15 l min^{-1} increased with increasing bare ground percentage ($r^2 = 0{\cdot}75$ and 0·65 respectively), with sharp increases occurring as bare ground increased from 40 to 80% (Figure 6).

Mean impacted rill area and the number of rill flow paths generally increased while the average rill flow depth decreased with time post-fire (Table IV). Mean impacted rill area for an inflow rate of 15 l min^{-1} increased slightly immediately post-fire, but the difference was insignificant. The mean impacted rill area at 2 and 3 years post-fire was significantly greater on burned hillslopes than on unburned hillslopes for inflows of 15, 21, and 24 l min^{-1}. The number of flow paths measured was significantly greater on burned hillslopes for inflows of 21 and 24 l min^{-1} in years 2 and 3. Concentrated flow depths on burned hillslopes were significantly greater than on unburned hillslopes at 15 l min^{-1} inflow in years 0 and 1 solely. Differences in flow depths on burned and unburned hillslopes at 2 years post-fire were significant only with an inflow of 21 l min^{-1}. Flow depths on burned and unburned hillslopes were not significantly different at 3 years following fire.

Interrill and rill runoff and erosion

Application of 85 mm h^{-1} rainfall over a period of 5 min (25-year 5-min storm) generated overland flow on 89% of burned and 84% of unburned rainfall plots at the small plot scale from years 0 to 2. The mean runoff rates from burned and unburned plots under the applied intensity from 5 to 10 min were 22·9 mm h^{-1} and 18·0 mm h^{-1} respectively. Mean runoff rates from burned and unburned rainfall plots under the applied intensity from 5 to 15 min (125-year 15-min storm) were 23·0 mm h^{-1} and 19·7 mm h^{-1} respectively. Based on these rainfall simulation runoff rates, rainfall from the 25-year 5-min storm over an area of 60 to 80 m^2 would generate overland flow that, when sustained at the same intensity for an additional 10 min (125-year 15-min storm), could support concentrated flow at 24 l min^{-1} where overland flow converged. The 3-year cumulative interrill sediment generation from simulations of the 125-year 15-min storm was 50 g m^{-2} and 25 g m^{-2} on burned hillslopes and unburned sites respectively; the 3-year cumulative rill sediment yield from concentrated flow simulations of the same storm generated 20 400 g m^{-2} on burned hillslopes and 6 g m^{-2} sediment on unburned hillslopes (Table V).

DISCUSSION

Spatial continuity of interrill and rill processes

The results from rainfall simulations imply that differing responses of microsites to disturbance can create spatial discontinuity in fire effects. Fire effects on interrill processes were most pronounced on burned coppice microsites. Greater vegetation, litter, and organic matter on coppice microsites likely increased fire temperatures and enhanced development of water-repellent soils. Formation of water-repellent soils combined with reduced litter mass contributed to significantly reduced infiltration rates on burned coppice sites during the early stages of runoff immediately following fire (Figure 3b). Roundy *et al*. (1978) found that burning of pinyon–juniper rangeland in Nevada did not change infiltration and erosion

Table V. Cumulative interrill and rill (rates 7, 12, and 15 l min^{-1}) sediment yield per unit area from simulations of the 125-year 15-min storm on burned and unburned hillslopes

	Burned				Unburned (mean)	3-year cumulative	
	Year 0	Year 1	Year 2	Year 3		Burned	Unburned
Interrill sediment yield (g m^{-2})[a]	28	9	13	—	8	50	25
Rill sediment yield (g m^{-2})[b]	16 900	3290	225	38	2	20 400	6

[a] Representative of small plot scale (0·5 m^2).
[b] Representative of rill scale (1·0–2·0 m^2).

rates on interspace microsites but did reduce infiltration and increase erosion two- to three-fold on coppice microsites. Pierson *et al.* (2002a) found that severe fire decreased infiltration and increased sediment yield on steeply sloped south-facing sagebrush hillslopes, but the post-fire erosion increase was significantly greater for interspace rather than coppice microsites. The results from the Denio Fire and those in Roundy *et al.* (1978) and Pierson *et al.* (2002a) suggest that analyses of fire treatment effects on rangeland runoff and erosion should consider spatial variability associated with microsite response.

Results from the Denio Fire indicate that the magnitude of fire effects on coppice microsites was greater for sediment yield than for runoff and infiltration (Table III, Figure 3b). Pierson *et al.* (2002b) examined hydrologic and erosional responses to rainfall simulation on varying rangeland plant communities in 11 western states and concluded that sediment yield may not be well correlated with runoff. Johansen *et al.* (2001) reported that sediment yield following severe wildfire in a semiarid ponderosa pine forest increased 25 times that of unburned conditions and runoff increased by 95%. Similar results in this study indicate severe burning of steep sagebrush sites likely has a greater impact on sediment yield than on runoff and that the impacts may be stratified by microsite.

Disparities were observed between derived fire-induced soil water repellency and infiltration rates on interspace microsites. Burning of interspace microsites reduced runoff immediately after fire and generally facilitated increased infiltration. The general shape of the infiltration curve for burned interspaces in this study (Figure 3c) is indicative of water repellency during the initial stages of simulation followed by a breakdown of water repellency through the remainder of simulation (Pierson *et al.*, 2001); the infiltration curve for unburned interspaces (Figure 3c) shows a declining infiltration rate throughout simulation. Laboratory studies of soils from chaparral and forested landscapes have demonstrated that fire may destroy background soil water repellency if burning yields soil temperatures of 250 to 350 °C (Scholl, 1975; DeBano *et al.*, 1976; Robichaud and Hungerford, 2000). It is not likely that burn temperatures in interspace microsites exceeded burn temperatures in coppice microsites where soil water repellency was elevated by burning. However, organic matter necessary for formation of soil water repellency may have been limiting in interspaces and heat transfer through the mineral soil may have been rapid, facilitating destruction of repellent layers (Doerr *et al.*, 2006). Pierson *et al.* (2002a) observed high runoff volumes from dense senescent grass mats on unburned interspace microsites with similar site conditions. In this study, the disparity of higher WRI% (Table III) and higher infiltration rates (Figure 3) on burned versus unburned interspaces may indicate the rainfall application rate and or length of the simulation were not adequate to wet-up an existing water-repellent layer within the extremely dry organic matter or surface soil on unburned interspaces or that the WRI% index does not accurately account for the influence of vegetation on infiltration as observed on similar sites (Pierson *et al.*, 2002a). In either case, the data presented in this study suggest that fire can improve infiltration on interspace microsites through destruction of naturally occurring soil water repellency or reduction in infiltration-inhibiting vegetation.

Results from 3 years of rainfall simulations and concentrated flow experiments provide a relative comparison of fire effects on sediment yield from interrill and rill processes in steeply sloped sagebrush landscapes overlying coarse soils. The potential errors associated with simplification of the processes and the variation in rainfall simulation and concentrated flow plot sizes are considered minor relative to the magnitude of the differences in interrill and rill sediment yield observed. The concentrated flow experiments exclude any sediment that would be entrained before convergence and do not consider raindrop splash effects adjacent to the rills. Sediment yield from rills is a function of the detachment and transport capacity, and entrained sediment entering rills influences detachment and transport (Nearing *et al.*, 1989). Simulating these processes with clean water may overestimate rill detachment and sediment yield. Therefore, cumulative sediment yield from inflow rates 7, 12, and 15 l min^{-1} was used in the comparison to offset overestimates from clean water simulations. Extrapolation of these results to the watershed scale is not intended. Upward scaling of interrill and rill data from small plot scales (1 to 10 m) to catchment and watershed scales is cautioned in literature due to scale dependencies in runoff and erosion processes (Wilcox *et al.*, 1997; Parsons *et al.*, 2006). Furthermore, the spatial scales at which interrill and rill processes function are different and their distribution across a hillslope

is often unknown. The need for risk assessment following wildfire remains, however, and investigations of fire effects at the small scale provide a means of investigating responses at plot scales that may influence overall watershed response.

The greatest effect of the Denio Fire was not on runoff generation at the small plot scale, but on runoff dynamics as water moved down slope. Nearing *et al.* (1997, 1999) demonstrated that flow detachment rates are strongly correlated with stream power (a function of shear stress and flow velocity) and that flow velocity in rills is not dependent on slope. Removal of 99% ground cover reduced surface storage of water and allowed overland flow to concentrate into rills where velocity increased (Table IV, Figure 6), runoff response time decreased (Table III), and runoff and sediment yield were elevated (Table IV). Stratifying interrill treatment responses by microsite found slightly lower runoff (Table III) and a threefold increase in sediment yield (Tables III and V) immediately following fire. Concentrated flow simulations at inflow rates of 7, 12, and 15 l min^{-1} on burned hillslopes generated 35 times more cumulative runoff (Table IV) and over 7000 times more sediment yield (Tables IV and V) respectively than on unburned hillslopes immediately following fire. The magnitude of hydrologic and erosional response to fire was much greater on concentrated flow plots and was larger for sediment yield than for infiltration and runoff.

Temporal persistence of fire effects on interrill and rill processes

The temporal variability in runoff and erosion observed over 3 years of rainfall simulation was greater than the effects of fire with respect to interrill processes. Minimum and average infiltration rates on interrill areas were lower immediately following and at 2 years post-fire (Figure 3). Application of 85 mm h^{-1} rainfall generated significant interrill runoff immediately after fire, but any response to burning appeared dampened 1 year following fire and returned 2 years post-fire (Table III). Dekker *et al.* (2001) demonstrated that soil water repellency in coarse soils changes with soil moisture content and that critical soil moisture thresholds may render soils as wettable or water repellent. They further indicated that fluctuations in soil wettability may be influenced by differing drying regimes during drydown periods. Wilcox (1994) found that infiltration capacity of intercanopy zones in pinyon–juniper woodlands was very dynamic and highly dependent on soil moisture content and/or frost conditions of the soil. The between-years temporal variability in infiltration on rainfall simulation plots on the Denio site may have resulted from variation in soil moisture contents at depth during different years of the study and the respective fluctuation in soil wettability. The implications infer caution in interpretation of fire treatment effects from single-year monitoring of infiltration and sediment yield, particularly with respect to transient soil water repellency (Doerr *et al.*, 2000), suggesting that multiyear studies, inclusive of annual controls, are required to assess the spatial continuity and temporal persistence of fire-induced impacts on rangeland hydrology and erosion accurately.

Rapid armouring of rills on burned sites was observed at all inflow rates through the third year post-fire (Figure 5) and suggests that sediment yield from rilling is likely more substantial in the early stages of rill development than during rill progression. The difference in initial and final sediment concentrations could not be explained by differences in initial and final runoff rates (Table IV), indicating that the erosion of sediment within rills reached a detachment-limited state for respective inflow rates. The exposure of rocks, roots, and other resistive materials likely increased following the initial winnowing of surface sediments at each inflow rate. Subsequent low final sediment concentrations for each inflow rate resulted from increased critical shear stress (exposure of more resistive materials) and decreased entrainable sediment. The rate of sediment generation during rilling, therefore, was not constant and decreased with rill progression at each inflow rate.

The decreases in rill sediment concentration and flow velocity during the Denio study as time post-fire progressed (Table IV) illustrate the influence of increased ground cover (Table I) on overland flow dynamics and suggest decreased soil detachment and or increased deposition as ground cover increased. Soil detachment is a function of soil erodibility and the difference in shear stress acting on the soil and the critical shear stress of the soil (Foster and Meyer, 1972; Nearing *et al.*, 1999). Soil is detached when the shear stress applied to the soil exceeds the critical shear stress. Critical shear stress represents the cohesiveness of the soil and its resistance to entrainment. The stress acting on the soil is a function of: the density, depth, and velocity of flowing water; friction of the soil and cover; land surface slope; and acceleration due to gravity. A ground cover of 60% is often used as an indicator of adequate hydrologic protection of a site (Gifford, 1985, Robichaud, 2000a, Johansen *et al.*, 2001, Pierson *et al.*, 2007). In this study, ground cover increased from 1·4% immediately following fire to nearly 80% at 3 years post-fire. Increased ground cover provided increased surface storage of water, allowed overland flow to spread out over larger mean impact areas, and reduced rill flow velocities (Table IV). Increased surface storage improved infiltration. Wider impact areas and lower rill flow velocities reduced the shear stress applied to the soil and resulted in lowered detachment rates. Decreased transport capacity (lower flows) and reduced detachment rates resulted in reduced sediment yield. At 3 years following fire, the rill sediment yield from rates 7, 12, and 15 l min^{-1} was less than 1% of the measured rill sediment yield in year 0 (Table V).

Numerous recent studies further illustrate the influence that bare ground has on sediment yield (Benavides-Solorio and MacDonald, 2001, 2005; Johansen *et al.*, 2001). In a silt fence study of six fire sites in the forested Colorado Front Range, Benavides-Solorio and MacDonald (2005) noted that historical accounts of post-fire

erosion (Moody and Martin, 2001) indicate that fire-induced increases in erosion return to background levels 4 years following fire. They further commented that this period was greater than the measured longevity of fire-induced soil water repellency on similar Colorado Front Range sites (Huffman *et al.*, 2001; MacDonald and Huffman, 2004) and suggested other causal factors for increased erosion post-fire. Benavides-Solorio and MacDonald (2005) measured sediment yield and runoff from natural rainfall events on three prescribed and three wildfires of varying severities and age over a period of two summers and one winter. Benavides-Solorio and MacDonald (2005) determined that approximately 90% of post-fire erosion resulted from high-intensity summer rainstorms and that the dominant control on sediment production was the amount of bare soil. Johansen *et al.* (2001) reported that sediment yield from a severe wildfire in a semiarid ponderosa pine forest was highly correlated with bare ground ($r = 0{\cdot}84$) and suggested from a synthesis of comparable studies over multiple scales in rangeland and forested landscapes that the threshold for erosion is reached when bare ground exceeds 60–70%, with sharp increases occurring where bare ground exceeds 70%. At the Denio site, sediment concentration from concentrated flow plots was slightly greater as the percentage of bare ground increased from 40 to 60% and sharply higher where bare ground exceeded 60% (Figure 4). Rill flow velocity followed similar trends as sediment concentration (Figure 6). Results from the studies noted above (Benavides-Solorio and MacDonald, 2001, 2005; Johansen *et al.*, 2001) and from the Denio site indicate that the largest impact of severe wildfires is on the removal of vegetative cover and the subsequent effect on the dynamics of overland flow and the initiation of rill runoff and erosion processes. Therefore, the length of time required for erosion from severely burned and sloping terrain in semiarid sites to return to background levels associated with low interval storms is likely well correlated with the time required to achieve 60–70% ground cover.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Wildfire can significantly influence the hydrologic response of sagebrush-dominated rangelands and that response may be spatially and temporally variable, stratified by microsite and process. The main effect of the fire on interrill runoff and erosion in this study was primarily on coppice microsites, where higher quantities of litter and organic matter were available for combustion and development of water-repellent soils. Fire increased interrill erosion from coppice microsites by threefold compared with unburned coppice microsites. The results suggest that coppice and interspace microsites may respond differently to burning and that analyses of fire treatment effects should include a stratified microsite approach.

Temporal variation in fire effects on infiltration, erosion, and runoff should be carefully considered when interpreting fire treatment effects based on single- or even multiple-year observations. In this study, the temporal variation in fire effects was greater than the spatial variability in response to fire. The cause of this was not determined, but we hypothesize that variable site characteristics (soil water repellency and or soil moisture content) independent of the treatment may have influenced infiltration rates. Results from this study indicate that temporal assessments of fire impacts should focus on long-term responses and include annual controls.

The greatest impacts of fire were on the dynamics of flow once overland flow was generated. Removal of ground cover to 1·4% reduced surface water storage and allowed flow to concentrate into rills. Higher rill flow velocities on burned hillslopes produced greater erosive energy and transport capacity. Reduced infiltration, higher transport capacities, and increased soil detachment on burned hillslopes yielded significantly more runoff and erosion than on unburned hillslopes. The results suggest that mitigation of fire impacts on runoff and erosion in coarse-textured steep sagebrush-dominated landscapes should focus on spreading out concentrated flow and dissipating erosive energy generated by concentrated flow rather than mitigation of surface infiltration and highly variable soil water repellency.

The data presented here imply that increased sediment yield on severely burned and steep sagebrush-dominated landscapes may require greater than 3 years to return to near pre-burn levels. At 2 years after the Denio fire, ground cover had increased from nearly 0% to over 60%, but sediment yield from rill processes remained elevated above unburned conditions. At 3 years post-fire, cumulative sediment yield from concentrated flow simulations on burned hillslopes remained statistically greater than that on unburned hillslopes but the differences were greatly reduced. The results indicate that re-establishment of ground cover to nearly 80% likely protected the site from storms within 100 year return probabilities. However, greater ground cover and litter mass on unburned sites facilitated surface storage, increased time for infiltration, and provided resistance to overland flow and soil detachment. These characteristics probably offered much greater protection against runoff and erosion from storms in excess of the 100-year event. Although not simulated in this study, a review of results from the design storm suggests that burned sites three growing seasons post-fire remained more vulnerable and at greater risk of substantial runoff and sediment yield from rare high-intensity storms than unburned sites.

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