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Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands

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Abstract:

Rainfall simulations allow for controlled comparisons of runoff and erosion among ecosystems and land cover conditions. Runoff and erosion can increase greatly following fire, yet there are few rainfall simulation studies for post-fire plots, particularly after severe fire in semiarid forest. We conducted rainfall simulations shortly after a severe fire (Cerro Grande) in ponderosa pine forest near Los Alamos, New Mexico, USA, which completely burned organic ground cover and exposed unprotected soil. Measurements on burned plots showed 74% of mineral soil was exposed compared with an estimated 3% exposed prior to the fire. Most of the remaining 26% surface area was covered by easily moveable ash. Rainfall was applied at 60 mm h^{-1} in three repeated tests over 2 days. Runoff from burned plots was about 45% of the total 120 mm of applied precipitation, but only 23% on the unburned plots. The most striking difference between the response of burned and unburned plots was the amount of sediment production; burned plots generated 25 times more sediment than unburned plots (76 kg ha^{-1} and 3 kg ha^{-1} respectively per millimetre of rain). Sediment yields were well correlated with percentage bare soil ($r = 0{\cdot}84$). These sediment yields were more than an order of magnitude greater than nearly all comparable rainfall simulation studies conducted on burned plots in the USA, most of which have been in grasslands or shrublands. A synthesis of comparable studies suggests that an erosion threshold is reached as the amount of soil exposed by fire increases to 60–70%. Our results provide sediment yield and runoff data from severely burned surfaces, a condition for which little rainfall simulation data exist. Further, our results contrast post-fire hydrologic responses in forests with those in grasslands and shrublands. These results can be applied to problems concerning post-fire erosion, flooding, contaminant transport, and development of associated remediation strategies. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS erosion; sediment transport; runoff; fire; wildfire; hydrologic response; surficial processes

INTRODUCTION

Hydrological processes such as runoff and erosion at the hillslope scale are sensitive to changes in land surface properties that can be greatly altered by fire. In particular, reductions in the amount of ground cover and changes in soil characteristics resulting from fire can produce amplified hydrologic responses, especially for fires that are intense (DeBano *et al.*, 1998; Sackett and Haase, 1999). Intense fires are of particular concern for the semiarid ponderosa pine forests of the western USA, where the probability of such fires is currently high. Fires occurred historically in these forests at frequent intervals, and probably at low intensities, through the latter part of the 1800s (Swetnam *et al.*, 1999). Beginning in the late 1800s, suppression of fire—which resulted initially from grazing and later from direct fire fighting efforts—led to excessive build-up of canopy fuel and organic material on the ground surface (Campbell *et al.*, 1978; Covington *et al.*, 1994; Sackett and Haase, 1999; Mast *et al.*, 1999; Moore *et al.*, 1999). Consequently, risk of catastrophic, intense fires has increased greatly along with the consequent potential for such fires to alter

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runoff and erosion processes drastically. Understanding these post-fire processes is fundamental for assessing risks and determining remediation strategies associated with flooding, erosion, sediment transport, nutrient dynamics, and contaminant transport (Foster and Hakonson, 1987; DeBano *et al*., 1998).

Hillslope runoff and erosion rates before and after fire depend on numerous factors, including surface properties, slope, rainfall intensity and amount, and the size and composition of the area of interest. Consequently, it is important to control some of these factors during field studies to allow evaluation of the effects of other parameters and to allow comparisons among different studies. An effective means of exerting this control is through the use of rainfall simulators, which allow for repeatable rainfall amounts on plots of a given size and slope. Hydrologic response varies with spatial scale (Seyfried and Wilcox, 1995; Lane *et al*., 1997; Reid *et al*., 1999), and hence rainfall simulations performed on larger plots are more likely to be representative of hillslope-scale processes than those performed on plots at the scale of vegetation patches. Large rainfall-simulators that can be applied to plots of ~3 m × ~10 m have been used extensively for evaluating hydrologic and erosional responses from hillslopes (Renard, 1986; Lane *et al*., 1986; Hakonson *et al*., 1986; Hakonson, 1999). Although rainfall simulation studies are limited in their ability to replicate rainfall patterns and energies completely, they allow for more direct comparison among different ecosystems and different site conditions (e.g. burned and unburned) than studies based on natural precipitation (Renard, 1986; Lane *et al*., 1997).

Of the reported rainfall simulation studies that focused on post-fire hydrologic response, most indicate that the magnitude of hydrologic response depends largely on the effectiveness of the fire to remove groundcover (Simanton *et al*., 1990; Emmerich and Cox, 1994; Hester *et al*., 1997; Emmerich, 1998; Wilson, 1999). Ground cover aides infiltration by impeding overland flow, thereby increasing the frequency and depth of ponding, and by protecting the soil surface from compaction and from sealing effects that can inhibit infiltration (Wilcox *et al*., 1988; Bryan, 2000). Ground cover also protects against detachment and entrainment of soil particles by shielding the soil surface from direct transfer of kinetic energy from raindrops (interill erosive forces) and from shear stress of overland flow (rill erosive forces) (Lane *et al*., 1997; Bryan, 2000).

Another factor besides ground cover that can affect post-fire runoff and sediment yield is soil alteration resulting from fire. In particular, water-repellent soils can develop during fire when organic matter at the soil surface is volatilized. The volatilized organic matter can move downward as vapour and condense as a hydrophobic coating on soil particles, thereby reducing infiltration (DeBano, 1981). Such reductions in infiltration are thought to change hydrologic response, producing greater than initial runoff from sites where hydrophobicity is a factor than from sites where it is not (Hester *et al*., 1997; Robichaud, 2000). Other effects of fire on soil properties include combustion of organic matter (Hester *et al*., 1997; Marcos *et al*., 2000) and reductions in soil aggregate sizes (Emmerich and Cox, 1994), both of which can affect soil resistance to erosive forces.

Few rainfall simulation studies are reported for conditions following intense fire. Intense fire can result in greatly amplified hydrologic responses because of the potential for large reductions in ground cover and alteration of soils. The limited number of post-fire rainfall simulation studies that have been conducted to date encompass a diverse set of ecosystems and various burn severities, but a synthesis of these studies is lacking. We sought to address these gaps, in part by measuring runoff and sediment following an intense fire in ponderosa pine forest—the Cerro Grande fire that occurred near Los Alamos, northern New Mexico, USA, in May, 2000—and by contrasting our results with other post-fire rainfall simulation studies. The Cerro Grande fire caused extensive exposure of soil that had been previously protected by duff. Our major objective was to use rainfall simulation to quantify runoff and sediment yield as related to ground cover following severe fire in this ponderosa pine forest. In addition, we compared our hillslope-scale results for ponderosa pine forests with results from other studies at similar spatial scales in different ecosystems that included grasslands, shrublands, and forests. Our results, which document amplified hydrologic responses in runoff and erosion at the hillslope scale following intense fire in ponderosa pine forest, contrast with relatively small hydrological responses observed in grasslands and shrublands.

MATERIALS AND METHODS

Study site

The study was located within the Los Alamos National Laboratory on the Pajarito Plateau, 35-miles northwest of Santa Fe, New Mexico, USA. The study was conducted predominantly in intercanopy spaces of ponderosa pine forest. The site has a semi-arid, temperate mountain climate with an average annual precipitation of ~50 cm, with a major portion of the precipitation falling in July and August (Bowen, 1990). Average annual temperature is 10·0 °C, with daily mean minimum and maximum temperatures ranging from −6 to 29·8 °C. Prior to the Cerro Grande fire, there was extensive duff beneath trees, and mixed grass and Gambel oak (*Quercus gambelii*) in open interspaces. The hydrology of a nearby site in a ponderosa pine forest has been extensively characterized with respect to actual precipitation events. At this companion study site, surface runoff may comprise 3 to 11% of the annual water budget (Wilcox *et al.*, 1997). Subsurface shallow water flow, or interflow, is another component of water loss documented for this system. This flow has been observed only in response to winter snowmelt, for which it can comprise as much as 20% of snowpack (Wilcox *et al.*, 1996, 1997; Wilcox and Breshears, 1998). The soil water dynamics for this site reflect the two large seasonal inputs of precipitation and a period of high evapotranspiration following each (Brandes and Wilcox, 2000), with soil evaporation extending to a depth of ~10 cm and downward flux of ~0·02 cm year^{-1} (Newman *et al.*, 1997). Surficial soil on the study plots is loam, consisting of 40% sand, 47% silt, and 13% clay.

The fire history of the Pajarito Plateau has been extensively documented (Foxx, 1984; Allen, 1989; Swetnam and Baisan, 1996; Touchan *et al.*, 1996; Allen and Breshears, 1998; Swetnam *et al.*, 1999), with three landscape-scale fires occurring within the last 25 years: the La Mesa fire in 1977 (Foxx, 1984), the Dome fire in 1996 (Cannon and Renaeu, 2000) and the Cerro Grande fire in 2000. Several studies document amplified hydrologic responses at the watershed scale to these fires: White and Wells (1984) and White (1996) for the La Mesa fire, and Cannon and Renaeu (2000) for the Dome fire. The most recent of these fires, the Cerro Grande fire, burned about 17 400 ha, with the most severely burned areas located in dense forests, and created water-repellent soil conditions in some locations (Interagency BAER, 2000).

Experimental design

Four plots, each 3·03 m by 10·7 m (10 by 35 ft^2), were established in areas with relatively uniform vegetation and surface slopes. Two plots were established on a severely burned area, and two control plots were established approximately 150 m away in an unburned area. The soil series, scale, slope, and amount and intensity of rainfall received were similar for the control plots and the burned plots. Vegetation canopy cover, ground cover, and surface roughness were characterized with a point frame having 245 pin drops per plot (Levy and Madden, 1933). Average plot slope was ~4·5% for unburned plots and ~7·0% for burned plots. Soil bulk density was measured in the field at six locations along plot edges. Water drop tests (DeBano, 1981) were used to assess the extent of water-repellent soils on nearby sites and on the study plots. Soil texture was measured using wet sieve analysis.

For rainfall simulation, a Swanson-type (Swanson, 1965) 16 m diameter, rotating-boom rainfall simulator was used to apply rainfall of 60 mm h^{-1}, which represented a 100 year recurrence interval at Los Alamos for a 1 h storm event. The drop-size distribution from the rainfall simulator nozzles was similar to that from natural rainfall, but the drops impacted the ground surface with about 80% of the kinetic energy of natural rain (Swanson, 1965).

Three rainfall simulations were performed on each plot pair as follows: a 1 h rainfall application at 60 mm h^{-1} (labelled ‘Dry’ run for its antecedent moisture condition) followed by a 24 h between-run interval, a second rainfall event, 0·5 h in duration (‘Wet’ run), followed by a 0·5 h between-run interval, and a final third event (‘Very wet’ run). The rain applied to each plot totalled about 120 mm. Data were normalized to correct for minor variations in actual rainfall intensities and durations associated with the simulations. Three soil samples (to a depth of 5 cm) were taken adjacent to each plot just prior to each simulation to measure antecedent soil moisture. Antecedent moisture was 4·6% by weight [±0·02% standard deviation (SD)] for Dry runs, and progressed to 13·5% (±0·02% SD) for Wet runs, and 18·9% (±0·01% SD) for Very wet runs.

The downslope end of each plot was fitted with an end-plate and gutter to collect and channel runoff and sediment through a calibrated flume, where runoff depth was measured every 2–4 min using a bubble gauge flow meter (ISCO, Lincoln, NE). Flow depth measurements were used to construct runoff hydrographs. Samples of runoff (water and sediment) were taken every 2–4 min at the flume exit during each simulation to facilitate calculation of sediment yields.

RESULTS

Changes in plot characteristics

Organic ground cover on burned plots at Los Alamos decreased greatly as a result of fire, which consumed litter, duff, and ground vegetation. The amount of bare soil increased from an estimated 3% (±3% SD) prior to burning, to an average of 74% (±8% SD) after burning. The ground cover on the remaining 26% of plot area was mostly moveable, non-persistent ash, which was counted as ground cover when found in deposits sufficiently thick (approximately 1 cm) to be easily distinguished from the blackened mineral soil. Only 6% of the post-fire surface had persistent ground cover such as rock, persistent litter, and basal vegetation, including burned root crowns (Table I).

Prior to burning, the thickness of the layer of litter and duff on burn plots, which was estimated from post-fire measurements of discolouration on stationary rocks, averaged ~2·2 cm, ranging from 0 to 4 cm. Grass and oak also provided limited pre-fire cover (living plants and litter) estimated at 10% and 5% respectively based on post-fire distribution of root crowns and charred oak stems (burned up to 2 cm diameter). As an indicator of fire severity, the closest pine trees, averaging 12 m height, were fully consumed, i.e. all needles and small branches consumed, and dead fuels up to 20 cm in diameter lying on the ground were fully consumed.

Water drop tests performed on the post-fire ground surface in the study area indicated that some of the soil had limited water repellency, which was heterogeneous with respect to both surface extent and depth. Water drop tests performed on burned plots just prior to rainfall simulation indicated no water repellency at the ashy surface. However, moderate water repellency was observed at the 1–2 cm depth interval during all four tests performed at random locations on the burned plots 1 year after the fire. By comparison, on unburned soils, only one of four tests indicated any degree of water repellency (weak repellency at the 1–2 cm depth

Table I. Surface characteristics of study plots in ponderosa pine near Los Alamos, New Mexico

Characteristics	Unburned		Burned	
	Plot 1	Plot 2	Plot 3	Plot 4
Ground cover[a]				
Bare soil (%)	38	58	69	80
Rock (>20 mm) (%)	1	0	2	1
Non-persistent litter (%)	18	18	27	13
Persistent litter (%)	17	8	0	0
Basal vegetation (%)	26	17	2	7
Surface roughness[b] (cm^2)	4·7 (1·4)	3·7 (1·1)	6·0 (1·8)	4·2 (1·3)

[a] Average from five transects per plot, with 49 measurements per transect. Standard deviations of transect averages for plots 1–4 were 8, 5, 7, and 3 respectively.

[b] Expressed as standard deviation of height measurements from ground surface along a transect to a reference elevation. Standard deviation between transects is given in parentheses.

interval). Rather than rely completely on the water drop test, which can be subjective and difficult to quantify, we sought to observe water repellency effects in the hydrologic response.

Runoff

After approximately 120 mm of applied rain, the two burned plots yielded 71 and 35 mm runoff, and the unburned plots yielded 26 and 27 mm runoff (Figure 1 shows runoff ratios). Runoff volume was positively correlated to percent bare soil ($r = 0{\cdot}76$) over 12 runoff events, and the highest runoff and the largest percentage of bare soils were both observed in plot 4 (burned). In contrast, runoff volumes were poorly correlated with surface roughness ($r = -0{\cdot}12$). The time periods between start of rainfall and runoff initiation averaged 1·9(±0·7) min for burned plots and 4·4(±0·4) min for unburned plots. Times to runoff initiation were negatively correlated to percent bare soil ($r = -0{\cdot}67$), with the shortest times from plot 4 (burned).

Hydrographs from burned and unburned plots indicated marked differences in their times to runoff initiation, and in the slopes of their rising limbs (Figure 2). The regression coefficients of the rising limbs of

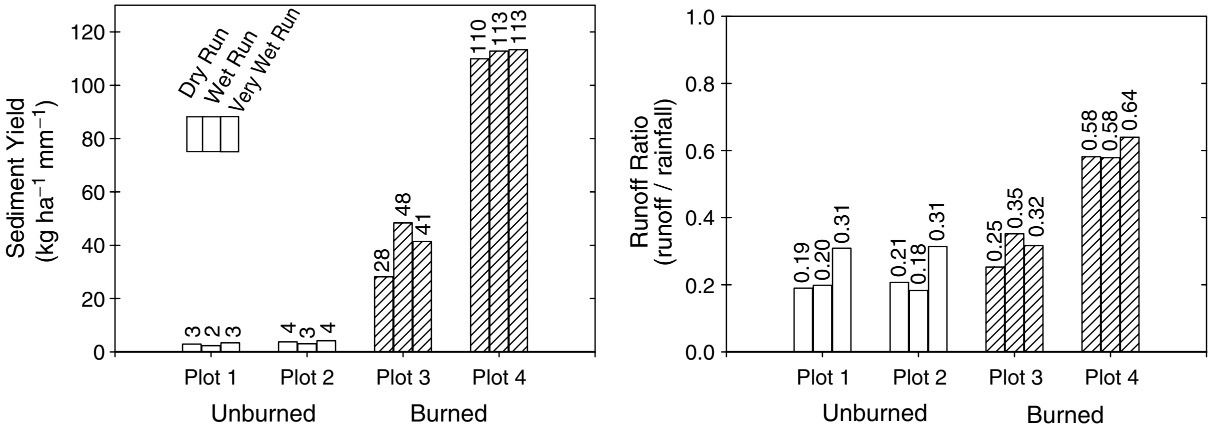

Figure 1. Sediment yields and runoff ratios for burned and unburned plots (three runs per plot: Dry, Wet, and Very wet)

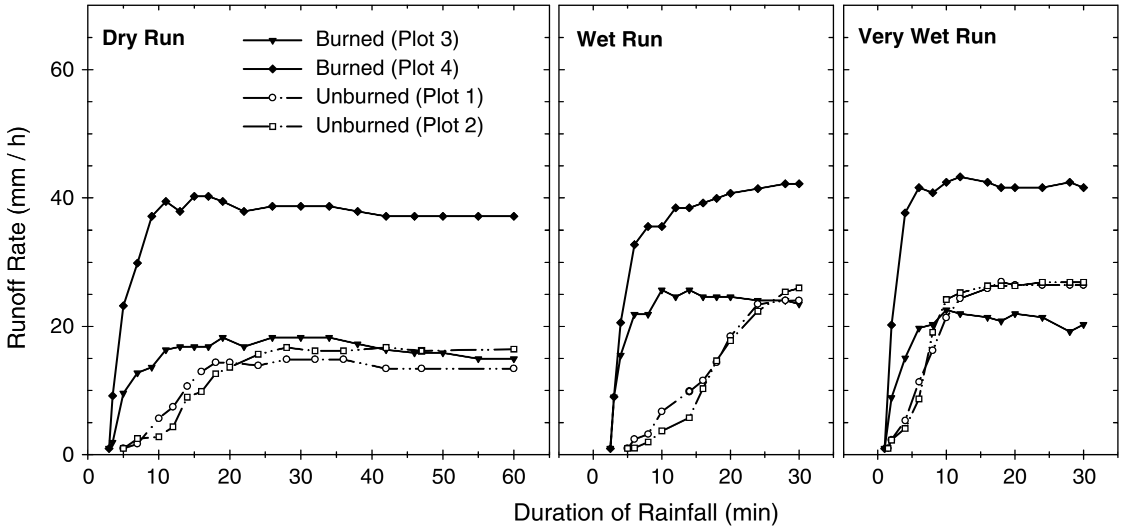

Figure 2. Runoff hydrographs on burned and unburned plots

the burned plots were consistently much steeper than those of the unburned plots [average of 5·3 mm min^{-1} (±2·2 SD) to 1·8 mm min^{-1} (±1·2 SD) respectively]. Slopes of the rising limb portions of hydrographs are affected by both infiltration and surface features, such as depression storage and ground cover that impedes flow (Frasier *et al*., 1998). If less infiltration and less surface impedence occur, the result is steeper slopes of the rising limbs.

With respect to the effects of water repellency, the shapes of the burned-plot hydrographs did not appear to confirm increases in runoff due to water repellency. In previous studies, water repellency was associated with a sharp initial spike in runoff rate with decreasing runoff rates thereafter (Shahlaee *et al*., 1991; Hester *et al*., 1997; Robichaud, 2000). These decreasing runoff rates were attributed to increases in infiltration as the soil became saturated, which has the effect of decreasing the degree of water repellency (DeBano, 1981). At Los Alamos, burned plots had relatively quick peaks in their runoff rates, but only slight reductions in runoff rates thereafter at slopes indistinguishable from those from the unburned plots ($P < 0{\cdot}05$) (Figure 2). One hydrograph associated with a burned plot even showed significant increase in runoff after initial saturation (Wet run, Figure 2). This lack of characteristic behaviour associated with hydrographs from water-repellent soils implies limited effects of water repellency on runoff from burned plots at Los Alamos.

Sediment yields

Large increases in sediment yields were measured from burned plots compared with unburned plots (Figure 1). Average sediment yields were 76 kg ha^{-1} mm^{-1} (millimetre of rainfall) from burned plots compared with 3 kg ha^{-1} mm^{-1} from unburned plots. The maximum sediment yield observed for all runs on burned plots was 113 kg ha^{-1} mm^{-1}.

Increases in sediment yields between burned and unburned plots (about a factor of 25) were disproportionately large compared with increases in runoff amounts (about a factor of two). In addition, variation in sediment yield was observed between burned plots: plot 4 had the least amount of ground cover (20% ground cover), yielding nearly three times more sediment than plot 3 (31% ground cover). Sediment yields were positively correlated with percent bare soil ($r = 0{\cdot}84$); however, this relationship is not expected to be well represented by simple correlation, as discussed below.

Post-fire rainfall simulations from different ecosystems

Rainfall simulation studies that focus on the effects of fire have been conducted in various grassland and shrubland systems, and to a lesser extent in forest systems (Table II). Of these studies, our results in ponderosa pine forest following an intense fire stand out as having the largest measured sediment yields, which are in most cases greater than other reported values by more than an order of magnitude (Table II). A previous study in eucalyptus forest (Wilson, 1999) also demonstrated high sediment yields; that study was also conducted following severe burning by a wildfire that caused extensive removal of ground cover.

In Table II, larger sediment yields were associated with higher fire intensities, whereas smaller sediment yields were associated with studies of areas subjected to low-intensity fire, often which was prescribed burning (Roundy *et al*., 1978; Knight *et al*., 1983; Simanton *et al*., 1990). Further, in one natural rainfall study after controlled, low-intensity fire was applied, a higher-intensity wildfire occurred by chance, and allowed for comparison of the relative effects of low-severity and higher-severity burning (Soto and Diaz-Fierros, 1998). Results showed sediment yields 8·5 times greater on unplanned wildfire plots compared with unburned control plots, whereas sediment yield increased only slightly on low-intensity, prescribed burn plots relative to control plots.

We plotted results from a subset of rainfall studies with similar precipitation intensities (most were approximately 60 mm h^{-1}) and plot scales (most were approximately 3 by 10 m^2), after normalizing on a per millimetre rain basis (Figure 3). These results show sediment yields from comparable studies across a wide range of ecosystem types (grasslands, shrublands, and forests) and fire intensities. Our results from study plots in the ponderosa pine forest show sediment yields an order of magnitude greater than most others from burned plots in other ecosystems (Figure 3). Further, a curvilinear relationship is seen between bare soil

Table II. Sediment yields from rainfall simulation studies on burned and unburned plots (grouped by plot size)

Location	Dominant species	Soil type	Plot size (m width × m length or m^2)	Rainfall intensity ($mm\ h^{-1}$) [duration] (min)	Burned condition[a]	Sediment yield ($kg\ ha^{-1}\ mm^{-1}$) /[bare soil] (%)		Slope (%)	Time lapse after fire	Reference
						Burned	Unburned			
NE California	sagebrush–juniper	gravelly sandy loam	3 × 10·7	65 [30–60]	intense, controlled	0·0–14·0 [40–45]	0·0–3·7 [15–17]		within days	Simanton *et al.*, (1986)
					intense, controlled	9·5–22·0 [30–40]			7 months	
					low intensity	3·0–7·3 [19–20]			1 year	
SE Arizona (Santa Rita)	introduced grass	gravelly loam	3 × 10·7	55 [45] 110 [15]	low intensity	0·4–0·6	0·3–0·4	5–6	same day	Emmerich and Cox (1992)
SE Arizona (Empire)	native grass	gravelly sandy loam	3 × 10·7	55 [45] 110 [15]	low intensity	1·6–4·2	1·3–2·4	5–7	same day	
SE New Mexico	Chihuahuan Desert grass	sand–loamy sand	3 × 10·7	60 [30–60]	low intensity	0·0–5·3 [41–48]	0·0–2·3 [17–23]	6–7	1 day	Johansen *et al.* in press
Central Colorado	shortgrass steppe	clay–clay loam	3 × 10·7	60 [30–60]	low intensity	3·5–7·2 [28–40]	1·5–2·3 [21–35]	9–10	1 day	Johansen *et al.* in press
NW N. Carolina	hardwood–pine	loam	3 × 7·5	100 [30]	low severity	0·2–0·4 [7]		30		Robichaud and Waldrup (1994)
NW N. Carolina	hardwood–pine	loam	3 × 7·5	100 [30]	high severity	0·2–27·7 [63]		30		
N. New Mexico	ponderosa pine	loam	3 × 10·7	60 [30–60]	severe, wildfire	28·2–113·3 [69–80]	2·3–4·2 [38–58]	4–8	80 days	*this study*

(*continued overleaf*)

Table II. (*Continued*)

Location	Dominant species	Soil type	Plot size (m width × m length or m^2)	Rainfall intensity (mm h^{-1}) [duration] (min)	Burned condition[a]	Sediment yield (kg ha^{-1} mm^{-1}) /[bare soil] (%)		Slope (%)	Time lapse after fire	Reference
						Burned	Unburned			
Tasmania, Australia	eucalyptus	loamy sands	15 × 20	35–162 [10–49]	intense wildfire	0·0–80·1 [>85]	0·1–14·1 (<50)	26	6 months	Wilson (1999)
Georgia	hardwood, pine	sandy clay loam	1 × 5	78–102 [30]	slash burn	0·95–2·6	–	10–30	0–12 months	Shahlaee *et al.* (1991)
Leon Prov., NW Spain	shrub	loamy sand	1	180 [5]	low severity	0·6–13·3 [30–99]	2·3	10	days–$1\frac{1}{2}$ years	Marcos *et al.* (2000)
N Idaho	mixed conifer	silt loam	1	50 [30]	prescribed burn	2·5–11·0		13–27	within days	Robichaud *et al.* (1994)
E Nevada	pinyon–juniper	loamy, mixed	0·83	84 [60]	prescribed coppice	4·0–9·7 [19–80]	1·6–3·3 [1–17]	5–8	1–2 months	Roundy *et al.* (1978)
					prescribed coppice	3·1–12·8 [6–91]			1 year	
	pinyon–juniper				prescribed interspace	7·9–26·0	10·1–21·6		1–2 months	
					prescribed interspace	11·9–32·0			1 year	
Texas	juniper	silty clay	0·5	203 [50]	prescribed low seventy	9·5 [100]	0·2 [0]	4	5 months	Hester *et al.* (1997)
	oak					22·2 [100]	0·01 [0]			
	bunchgrass					22·0 [100]	1·5 [32]			
	shortgrass					28·4 [100]	6·4 [57]			
Texas	whitebrush	sandy loam	0·4	203 [30]	prescribed	6·0 [16]	7·1 [19]		10 months	Knight *et al.* (1983)
	mesquite	clay loam		203 [30]	prescribed	12·7 [12]	19·2 [11]		10 months	

[a] Terms describing burn conditions vary between reported studies.

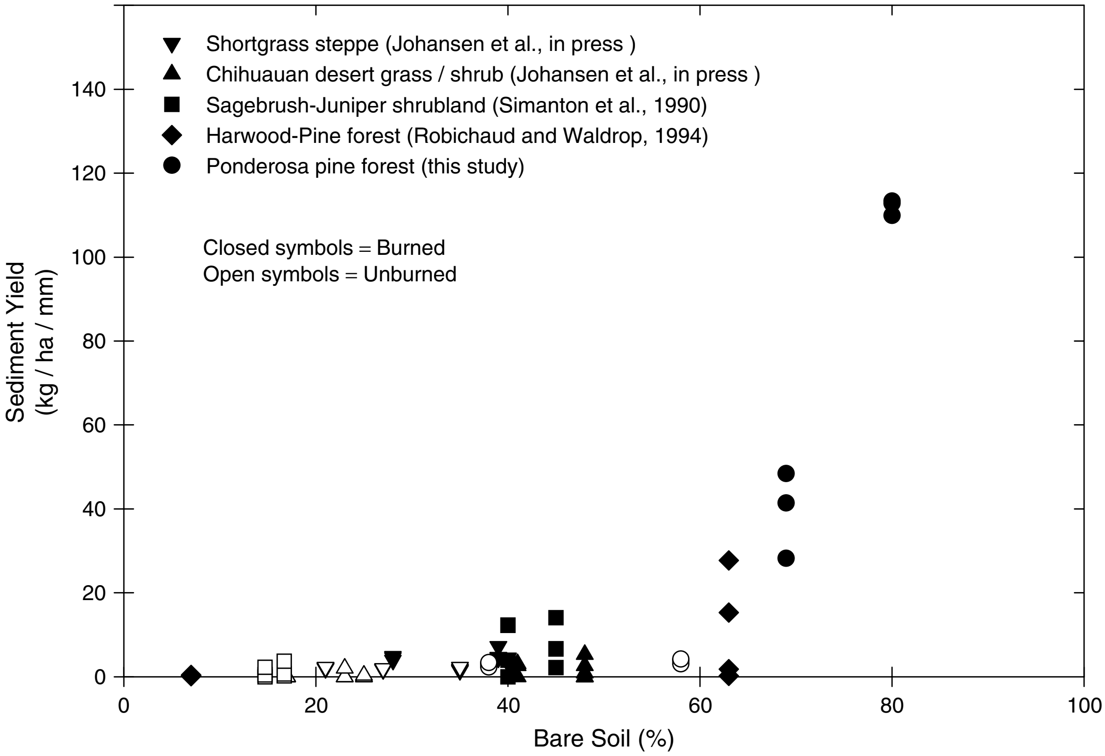

Figure 3. Sediment yields from rainfall simulations on comparably sized burned and unburned plots over a range of vegetation types

and sediment yield, with little change in sediment yield as percent bare soil varies between 0 and ~60–70%, and sharp increases in sediment yields when the amount of bare soil is greater than 60–70%.

DISCUSSION

High sediment yields following severe fire in ponderosa pine forest

Our results document large increases in sediment yields following severe fire in ponderosa pine forest. The observed sediment yields were well correlated with ground cover, which was greatly reduced by the wildfire. The surface of the burned plots had 26% ground cover, most of which consisted of moveable ash, with only 6% considered persistent cover. The burned plots, with lower amounts of ground cover than the unburned plots, had larger amounts of runoff, which in turn provided greater erosive forces and greater potential for sediment transport by overland flow. In addition, much more soil was exposed to raindrop splash and shear erosive forces (up to 42% more on burned plots than unburned plots), further contributing to the large sediment yields observed.

The removal of ground cover by fire exposed previously protected soil that was highly susceptible to erosion. The soil at the study site was apparently covered for at least 60 years by a duff layer, which would have protected the soil surface from the effects of compaction by rainfall and of armouring from erosion. Other studies have shown that soil compaction and pavement cover (i.e. armouring of the soil surface that can increase over time) provide resistance to erosive forces independent of ground cover (Simanton and Emmerich, 1994; Hakonson, 1999). For example, rainfall simulation studies in southern Arizona showed that sediment yield increased greatly when gravel and rock cover was removed (Simanton *et al.*, 1986). This increase appeared much larger than would be explained by reduction in ground cover alone, supporting the concept that sudden exposure of uncompacted, unarmoured soil increases sediment production, independent of cover amount. This is consistent with practices applied in erosion equations and models, such as the Revised Universal Soil Loss Equation, where a greater soil erodibility factor is used to model greater susceptibility to soil erosion (Renard, 1986).

Ground cover effects appeared to be more important in explaining hydrologic response than either surface roughness or slope. Burned and unburned plots in the ponderosa pine forest that we studied had similar surface roughness (Table I) even though sediment yields were much greater on burned plots. In addition, surface roughness was poorly correlated to runoff volumes. Similarly, differences in plot slope also were not thought to be a major determinant of runoff volume, as slope and runoff volume were poorly correlated. Previous observations indicate that the effect of slope is likely to be small over the range of slopes we studied (Wilcox *et al.*, 1988). Of the two burned plots, plot 3 had the greater slope, but it generated only about half the runoff volume of plot 4.

Water repellency also may have affected runoff, but we believe that this effect was not large for our study. Water repellency was evident near the site and may have been present at depth on burned plots based on surface burn characteristics. If present, water repellency would contribute to the observed high sediment yields by decreasing infiltration rates and thus contributing to runoff. In support of this, the rising limbs of the burned plot hydrographs were very steep compared with unburned plots, indicating less initial infiltration. However, hydrographs from the burned plot did not match the characteristic shape of hydrographs from water-repellent soils (Robichaud, 2000). In addition, water-repellent soil, when saturated, conducts water almost as rapidly as wettable soil (DeBano, 1981; Shakesby *et al.*, 2000). Thus, because burned plot soils became quickly saturated during the rainfall simulations, the effects of water repellency, if any, were likely small.

Rainfall simulation results from different ecosystems of varying burn severities

Our results from ponderosa pine forest, in conjunction with those from grasslands, shrublands, and other forest ecosystems, highlight two general trends related to post-fire hydrologic response. First, the data indicate that post-fire sediment yields increase non-linearly as percent bare soil increases. Specifically, sediment yields increase little, if at all, when percent bare soil varies from 0 up to ~60–70%. This observation is supported by similar rainfall simulation data gathered from undisturbed plots in southern Arizona, for which the relationship between cover and sediment yield had a slope near zero (vegetation cover varied between 17 and 66%; Simanton *et al.*, 1986). Our data from ponderosa pine forest are consistent with this observation, but also indicate that, when percent bare soil exceeds a threshold of ~60–70%, a sharp increase in sediment yield can occur. This threshold range is similar to that observed at the catchment- and watershed-scale. For example, Campbell *et al.* (1978) reported little sediment yield from unburned and moderately burned ponderosa pine forest watersheds having 8% and 61% bare soil respectively, but high sediment yield (>3800 kg ha^{-1} year^{-1}) from a severely burned watershed with 77% bare soil. Our hillslope-scale results are consistent with these catchment- and watershed-scale observations of a threshold effect, and provide further support for the occurrence of such a threshold through the controlled conditions provided by rainfall simulation. Thresholds in runoff and sediment yield are likely related to the proportion and connectivity of small patches of bare cover, which generate most of the runoff (Dietrich *et al.*, 1993; Davenport *et al.*, 1998; Reid *et al.*, 1999). More specifically, a threshold can be crossed when there is shift from low to high connectivity among patches (Davenport *et al.*, 1998). Such a shift is likely to occur as the amount of bare area approaches the threshold range of 60–70% that we observed. The threshold range is similar to that suggested by mathematical percolation theory (Stauffer, 1985). If ground cover is viewed as a grid of cells, some of which generate runoff and some of which do not, the probability of cells of a given type (e.g. bare cells that generate runoff) becoming highly connected at the hillslope scale exhibits a non-linear, threshold-like response when the proportion of bare cells is near 60% (Stauffer, 1985; Davenport *et al.*, 1998).

The threshold-type response of erosion to fire severity appears to be a function primarily of reduction in ground cover and secondarily due to changes in soil properties (DeBano *et al.*, 1998; Marcos *et al.*, 2000). We

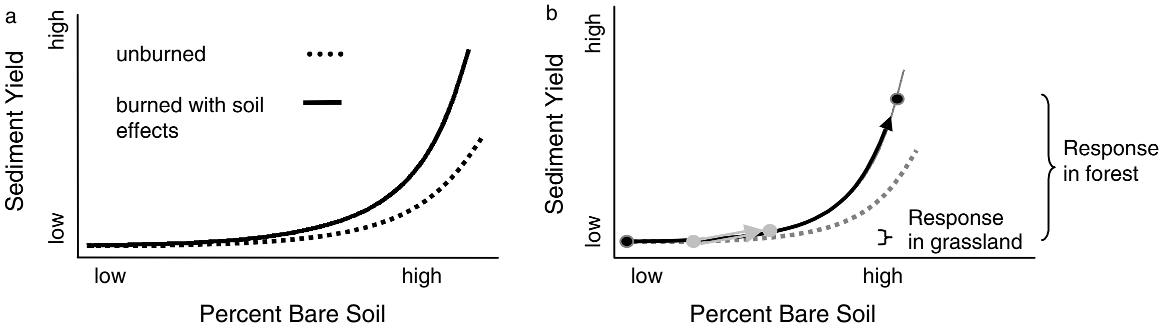

Figure 4. (a) Conceptual relationship between sediment yield and percentage bare soil for unburned and burned sites, factoring in burned soil effects. (b) Relative comparison of potential responses to fire in grassland versus forest systems

hypothesize a curvilinear relationship between sediment yield and ground cover (Figure 4a, bottom curve). We further hypothesize that this relationship can be modified by fire in at least two ways: rapid exposure of previously protected soils such that erosion rates for a given level of ground cover are increased; and, creation of water repellency or breakdown of soil aggregates that can further amplify erosion when fire is sufficiently intense to alter surface soil properties (Figure 4a, top curve). This contrast suggests that forests have a relatively greater vulnerability to increases in post-fire erosion (Figure 4b). Forests may have a much higher sediment yields than would be predicted by extrapolation of post-fire data from grasslands or shrublands. In grassland and shrubland ecosystems, residence times of fire and fire intensities are typically low, generally causing relatively small changes in ground cover and consequently causing only small increases in erosion (e.g. several studies in Table II). Because fire intensities are typically low, water repellency and other soil changes appear to be uncommon in grassland and many shrubland ecosystems. In contrast, intense fire in a ponderosa pine forest can simultaneously reduce ground cover, expose susceptible soils, and potentially create water-repellent conditions. Consequently, the hydrologic response in these systems can shift from very low sediment yield in pre-fire conditions to extremely high sediment yields after fire (Figure 4b).

Additional research is needed to assess the persistence of increases in post-fire sediment yields. Studies in Arizona show that elevated erosion rates on burned desert shrub lands can persist for at least 5 years after fire (Simanton and Emmerich, 1994). The conceptual model displayed in Figure 4a may, with more supporting data, be useful in describing reductions in sediment yields over time during recovery. Better estimates of how post-fire sediment yields change over time and the relative importance of these processes can be made when more understanding is achieved regarding rates of revegetation, soil compaction and armouring, and break-up of water-repellent soils.

In summary, our results document high sediment yields from rainfall simulation in severely burned ponderosa pine forest. These results contrast with results from grassland and shrubland ecosystems. Although these general relationships have been noted for watersheds and catchments, our study is among the first to quantify these responses systematically, particularly in a manner that controls for scale and rainfall effects, thereby allowing direct comparison of hydrologic response in grassland, shrubland, and forest ecosystems.

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