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# Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range

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## Abstract:

Wildfires in the Colorado Front Range can trigger dramatic increases in runoff and erosion. A better understanding of the causes of these increases is needed to predict the effects of future wildfires, estimate runoff and erosion risks from prescribed fires, and design effective post-fire rehabilitation treatments. The objective of this project was to determine whether runoff and sediment yields were significantly related to the site variables of burn severity, percent cover, soil water repellency, soil moisture, time since burning, and slope. To eliminate the variability due to natural rainfall events, we applied an artificial storm of approximately 80 mm $h^{-1}$ on 26 1 $m^2$ plots in the summer and fall of 2000. The plots were distributed among a June 2000 wildfire, a November 1999 prescribed fire, and a July 1994 wildfire.

For 23 of the 26 plots the ratio of runoff to rainfall exceeded 50%. Nearly all sites exhibited strong natural or fire-induced water repellency, so the runoff ratios were only 15–30% larger for the high-severity plots in the two more recent fires than for the unburned or low-severity plots. The two high-severity plots in the 1994 wildfire had very low runoff ratios, and this probably was due to the high soil moisture conditions at the time of the simulated rainfall and the resulting reduction in the natural water repellency. Sediment yields from the high-severity sites in the two more recent fires were 10–26 times greater than the unburned and low-severity plots. The plots burned at high severity in 1994 yielded only slightly more sediment than the unburned plots. Percent ground cover explained 81% of the variability in sediment yields, and the sediment yields from the plots in the 1994 wildfire are consistent with the observed recovery in percent ground cover. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS fire; rainfall simulator; runoff; erosion; pine forests; Colorado Front Range

## INTRODUCTION

Under undisturbed conditions forested lands are notable for their high infiltration rates, lack of overland flow, and low erosion rates (DeBano, 1981, 2000a; Hewlett, 1982). Since forests typically grow in wetter areas, forest lands are the primary source of high-quality water in many regions, including Colorado (Dissmeyer, 2000).

Fire is a common disturbance in forest lands. High-severity wildfires are of particular concern because they can trigger dramatic changes in runoff and erosion processes that adversely affect water resources. Numerous studies have shown that runoff and erosion rates after wildfires can increase by as much as one to three orders of magnitude (e.g. Helvey, 1980; Morris and Moses, 1987; DeBano *et al.*, 1996; DeBano 2000b; Robichaud *et al.*, 2000).

The effects of fire on runoff and erosion are a major concern in the Front Range of Colorado because the increasing forest density poses a greater risk of wildfire, the proximity of fire-prone ponderosa (*Pinus ponderosa*) and lodgepole (*Pinus contorta*) pine forests to urban areas, and the potential for severe post-fire flooding and erosion (Agnew *et al.*, 1997). The 1996 Buffalo Creek fire was particularly noteworthy, in that high-intensity thunderstorms caused peak flows from small basins to increase from less than 2 $m^3$ $s^{-1}$ to around 60 $m^3$ $s^{-1}$ (R. Jarrett, USGS, personal communication, 2000). Rainsplash, sheetwash, rilling, and

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channel incision generated tremendous amounts of sediment, and the downstream transport of this sediment temporarily dammed the South Platte River and reduced the capacity of the Strontia Springs Reservoir by approximately one-third. The fire-induced changes in runoff and erosion killed two people and repeatedly destroyed a major highway. The high concentrations of ash and sediment in the runoff have caused severe problems for the water-treatment plants that serve the city of Denver (Agnew *et al.*, 1997).

The greater forest density in the Colorado Front Range relative to pre-settlement periods (Veblen and Lorenz, 1991; Mast, 1993) means that similar wildfires will almost certainly occur in the future. Efforts to mitigate the post-fire increases in runoff and erosion are well meaning, but there is a lack of process-based understanding to design effective emergency rehabilitation treatments (Robichaud *et al.*, 2000). Prescribed fires are being used to reduce the risk of wildfires, but there are few quantitative data on the effects of wild and prescribed fires on runoff and surface erosion rates in the Colorado Front Range.

The large increases in runoff after wildfires are commonly ascribed to the development of a water-repellent layer at or near the soil surface that restricts infiltration and induces overland flow (DeBano *et al.*, 1970; Shahlaee *et al.*, 1991; Scott and Van Wyk, 1990; Prosser and Williams, 1998; Inbar *et al.*, 1998). The strength of the water-repellent layer is generally believed to increase with increasing fire intensity due to the greater soil heating and consumption of the litter and soil organic matter (Tiedeman *et al.*, 1979; DeBano, 2000b). Though many forest soils are naturally water repellent (DeBano, 1981; Barret and Slaymaker, 1989; Burch *et al.*, 1989), the hydrophobic compounds are not sufficiently concentrated to restrict infiltration over entire hillslopes.

The change from subsurface to overland flow after wildfires can also be facilitated by the loss of the protective litter layer and the potential for rainsplash to cause soil sealing (DeBano, 2000b). In high-severity wildfires the organic matter in the soil surface can be consumed, and the resultant loss of aggregate stability can reduce the number of large pores and further reduce the infiltration rate.

The loss of the protective litter layer and the changes in the soil surface can lead to very large increases in soil erosion. After a high-severity fire the mineral soil surface is exposed to rainsplash erosion (Inbar *et al.*, 1998), and the reduction in infiltration rates can lead to large amounts of sheetwash and rill erosion.

In the case of the Colorado Front Range, Delp (1968) observed relatively low erosion rates after a wildfire, and he emphasized the need for more data on soil erosion rates from high-intensity rainstorms. Morris and Moses (1987) found sediment flux rates on hillslopes to increase by as much as three orders of magnitude after wildfires in ponderosa pine. They attributed this increase to the reduced forest canopy and ground cover, as well as to the formation of a water-repellent layer near the soil surface. After the Buffalo Creek fire Agnew *et al.* (1997) noted that the lack of data and understanding made it difficult to assess the potential for catastrophic flooding and erosion. MacDonald *et al.* (2000) developed a spatially-explicit model to predict post-fire erosion in central and western Colorado, but the reliability of this model is limited by the lack of data for calibration and validation. More generally, DeBano *et al.* (1996) noted the limited amount of data on the effects of fire in ponderosa pine forests on runoff and water quality.

The effect of wild and prescribed fires on downstream water resources will also depend on the rate at which sites return to pre-disturbance conditions (MacDonald, 2000). Most studies have shown that the greatest increases in runoff and erosion occur within the first 1 or 2 years after burning (Helvey, 1980; Robichaud and Waldrup, 1994; Inbar *et al.*, 1998), although this general pattern will be affected by the timing of high-intensity rainfall events (Helvey, 1980). Nearly all studies have shown that soil erosion rates return to background (i.e. pre-disturbance) levels within 3 to 9 years after burning (Robichaud *et al.*, 2000). In the Colorado Front Range, several studies have shown that soil erosion rates are similar to undisturbed values 3 to 4 years after burning (Morris and Moses, 1987; Martin and Moody, 2001), but there are few data on the post-fire erosion rates immediately after burning.

Another limitation to measuring the changes in runoff and erosion after a wildfire is the temporal and spatial variability in natural precipitation events. In the Colorado Front Range, high-intensity summer convective storms generate the largest flows and the highest erosion rates (Morris and Moses, 1987), and these storms also have the greatest spatial variability.

 

The use of rainfall simulators can largely obviate the problems of measuring rainfall and comparing sites that are subject to different storm events (Meyer, 1988). By applying consistent amounts of rainfall one can directly compare runoff and erosion from plots with different site characteristics, and statistically evaluate the effect of these site characteristics on runoff and sediment yields. Although the extrapolation of rainfall simulations to larger areas and natural rainstorms is difficult, rainfall simulations are the most predictable and cost-effective means to compare runoff and sediment yields between sites (Meyer, 1988).

Given this background, the objectives of this project were to: (1) compare runoff rates and sediment yields from burned plots in the Colorado Front Range; (2) relate the dependent variables of runoff and sediment yield to the independent site variables of burn severity, percent cover, soil water repellency, soil moisture, time since burning, and slope. A rainfall simulator was used to standardize the storm events on each plot. The overall goal was to measure and understand the effects of fires—both prescribed and wild—on runoff and erosion in the ponderosa and lodgepole pine forests in the Colorado Front Range. This information is urgently needed to predict fire-induced changes in runoff and erosion, assign priorities for fuel treatments, and design effective post-fire rehabilitation programs.

## METHODS

*Study sites*

The study plots were located in three different fires in the northern Colorado Front Range (Figure 1). All three fires were in the fire-prone, mid-elevation zones dominated by ponderosa (*P. ponderosa*) and lodgepole pine (*P. contorta*) (Table I). The soils are generally classified as sandy loams, and the soil type ranges from Typic Argicryolls to Ustic Haplocryalfs (E. Kelly, Colorado State University, personal communication, 2001).

The Bobcat fire was a wildfire that burned 4300 ha in June 2000. Most of the burned area was dominated by ponderosa pine, but there were also small stands of lodgepole pine and Douglas fir.

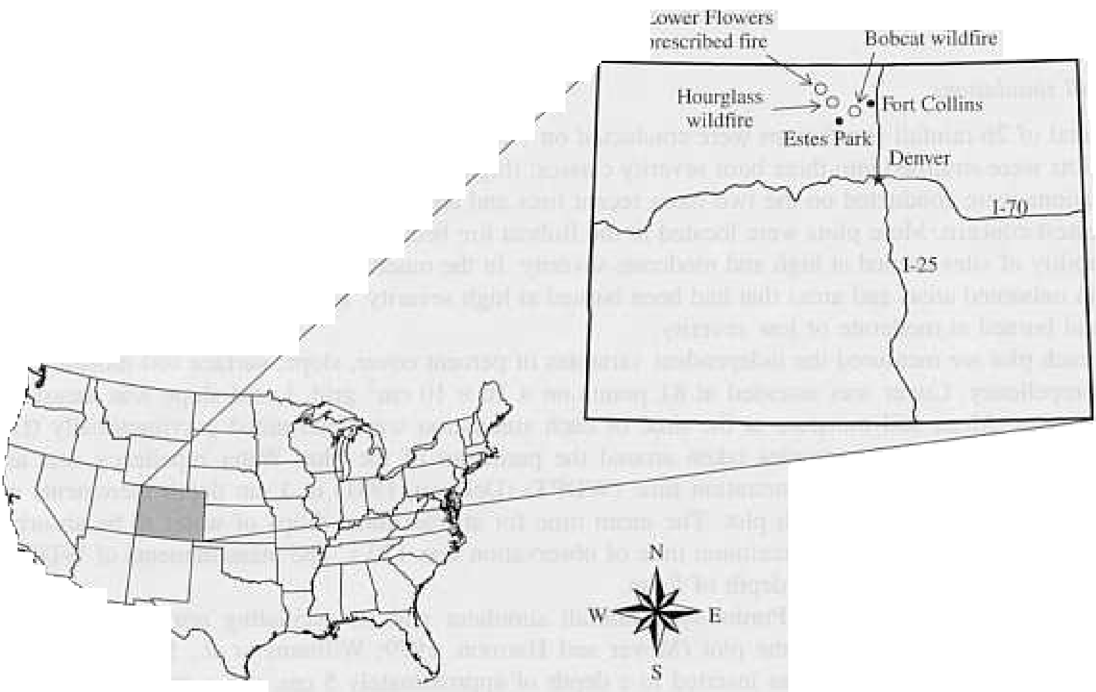


Figure 1. Location of the three fires used in this study

 

Table Characteristics of each fire and number of simulations by fire and burn severity

| ïre | Type | Date burned | Area (ha) | Primary vegetation type | Elevation range (m) | Number of simulations | | | Totals |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | High severity | Moderate severity | Low severity or unburned | |
| Bobcat | Wildfire | June 2000 | 4289 | Ponderosa pine | 2000–3230 | 7 | 5 | 4 | 16 |
| Lower Flowers | Prescribed burn | November 1999 | 200 | Ponderosa pine | 2530–2940 | 2 | 2 | 2 | 6 |
| Hourglass | Wildfire | July 1994 | 516 | Lodgepole pine | 2590–2930 | 2 | 0 | 2 | 4 |
| **Totals** | | | | | | 11 | 7 | 8 | 26 |

The Lower Flowers fire was a 200 ha prescribed burn that occurred in November 1999 (Table I). The burned area was dominated by ponderosa pine with small portions of lodgepole pine. Most of the area was burned at moderate to low severity, although there were some patches of high severity.

The Hourglass fire was the third study site, and this was a wildfire that occurred in July 1994 at a slightly higher elevation where lodgepole pine was dominant (Table I). This fire burned 516 ha, and most of the burned area was classified as high severity (Omi, 1994).

The study plots within each fire were stratified by burn severity because this is a primary control on post-fire runoff and erosion (DeBano *et al.*, 1996). Burn severity was classified according to the criteria developed by Wells *et al.* (1979) and applied by the USDA Forest Service (1995). In high-severity sites the entire organic layer is consumed and there is visible alteration of the structure and colour of the surface layer of the mineral soil. In moderate-severity sites the entire litter and duff layer is either consumed or charred, but the underlying mineral soil is not visibly altered. In low-severity sites the surface litter and duff can be scorched or partly burned, but there is no visible effect on the underlying mineral soil.

*Rainfall simulations*

A total of 26 rainfall simulations were conducted on 1 $m^2$ plots in densely forested areas (Tables I and II). The plots were stratified into three burn severity classes: (high, moderate, and low severity or unburned. More simulations were conducted on the two more recent fires and areas burned at high severity because these are of greatest concern. More plots were located in the Bobcat fire because it had better road access and a greater availability of sites burned at high and moderate severity. In the much older Hourglass fire plots were located only in unburned areas and areas that had been burned at high severity, as we could not reliably identify sites that had burned at moderate or low severity.

At each plot we measured the independent variables of percent cover, slope, surface soil moisture, and soil water repellency. Cover was assessed at 81 points on a $10 \times 10$ $cm^2$ grid. Local slope was measured with a clinometer. Mean soil moisture at the time of each simulation was determined gravimetrically (Gardner, 1986) from three 0–5 cm samples taken around the perimeter of the plot. Water repellency was assessed by measuring the water drop penetration time (WDPT) (DeBano, 1981) in 1 cm depth increments in three pits around the perimeter of each plot. The mean time for at least three drops of water to be absorbed was determined for each depth; the maximum time of observation was 120 s. The measurements of WDPT began at the surface and extended to a depth of 5 cm.

Rainfall was applied with a Purdue-type rainfall simulator and an oscillating nozzle that was usually 2·8–3·0 m above the centre of the plot (Meyer and Harmon, 1979; Williams *et al.*, 1995) (Figure 2). For each plot a 1 $m^2$ metal frame was inserted to a depth of approximately 5 cm, and a metal collection trench was installed at the lower end to collect the runoff. The inside edges were sealed with native soil mixed

Table II. Plot characteristics, date of rainfall simulation, and soil moisture at the time of the simulation by fire and burn severity

| Fire | Plot number | Burn severity | Date of simulation | Ground cover (%) | Slope (%) | Soil moisture (%) |
|---|---|---|---|---|---|---|
| Bobcat | | High | June 23 | 92[a] | 24 | 1·0 |
| Bobcat | 2 | High | July 20 | 11 | 25 | 1·0 |
| Bobcat | 3 | High | July 21 | 10 | 22 | 1·0 |
| Bobcat | 4 | High | July 24 | 8 | 38 | 1·0 |
| Bobcat | 5 | High | July 25 | 17 | 45 | 1·0 |
| Bobcat | 15 | High | Aug. 15 | 15 | 25 | 1·5 |
| Bobcat | 16 | High | Oct. 31 | 6 | 40 | 9·4 |
| **Mean** | | | | **23** | **31** | **2·3** |
| Bobcat | 6 | Moderate | Aug. 02 | 79 | 32 | 1·7 |
| Bobcat | 7 | Moderate | Aug. 03 | 88 | 23 | 1·5 |
| Bobcat | 8 | Moderate | Aug. 04 | 95 | 24 | 1·6 |
| Bobcat | 9 | Moderate | Aug. 07 | 90 | 21 | 1·1 |
| Bobcat | 14 | Moderate | Aug. 14 | 90 | 16 | 1·7 |
| **Mean** | | | | **88** | **23** | **1·5** |
| Bobcat | 11 | Low | Aug. 09 | 99 | 21 | 1·4 |
| Bobcat | 13 | Low | Aug. 11 | 100 | 22 | 1·6 |
| Bobcat | 10 | Unburned | Aug. 08 | 98 | 23 | 1·2 |
| Bobcat | 12 | Unburned | Aug. 10 | 100 | 23 | 1·8 |
| **Mean** | | | | **99** | **22** | **1·5** |
| Lower Flowers | 1 | High | Aug. 16 | 9 | 26 | 1·0 |
| Lower Flowers | 2 | High | Aug. 18 | 1 | 30 | 9·5 |
| **Mean** | | | | **5** | **28** | **5·3** |
| Lower Flowers | 3 | Moderate | Aug. 26 | 66 | 25 | 9·0 |
| Lower Flowers | 6 | Moderate | Oct. 19 | 91 | 19 | 5·4 |
| **Mean** | | | | **79** | **22** | **7·2** |
| Lower Flowers | 4 | Unburned | Oct. 14 | 100 | 18 | 19·1 |
| Lower Flowers | 5 | Unburned | Oct. 17 | 100 | 15 | 10·1 |
| **Mean** | | | | **100** | **17** | **14·6** |
| Hourglass | 1 | High | Sep. 02 | 79 | 30 | 20·7 |
| Hourglass | 2 | High | Sep. 02 | 100 | 36 | 27·4 |
| **Mean** | | | | **90** | **33** | **24·1** |
| Hourglass | 3 | Unburned | Sep. 19 | 100 | 21 | 3·3 |
| Hourglass | 4 | Unburned | Oct. 03 | 100 | 28 | 8·3 |
| **Mean** | | | | **100** | **25** | **5·8** |

[a]Most of the ground cover was ash

with a small amount of water and bentonite. Plots were shielded during the simulation to minimize wind effects.

Each simulation consisted of a single 60 min application of rainfall at a constant intensity. The plots were not wetted prior to the simulation because the storm events of greatest concern are the summer convective storms that typically occur when the soil surface is dry. The mean intensity of the applied rainfall was 79 mm $h^{-1}$, although the range was from 66 to 94 mm $h^{-1}$ (Table II). The mean rainfall rate of approximately 80 mm $h^{-1}$ was selected because this is comparable to the maximum 1 h intensities that have been observed in the Front Range. The rate and distribution of rainfall in each simulation was initially assessed from seven rain gauges placed in and around each plot. For most of the simulations a more accurate rainfall rate was determined by covering the plot with a plastic sheet after runoff

 

Figure 2. Photograph of the rainfall simulator and runoff plot on a high-severity site in the Bobcat fire

had ceased, and then measuring the runoff rate while the rainfall simulator was run for an additional 10 min.

Runoff rates were measured every minute during the simulation by collecting the runoff for 20–30 s and transferring it to a graduated cylinder. We also recorded the time when runoff began and when runoff ceased after the end of the simulation. For each simulation we determined the percent change in the runoff rate over the main part of the runoff hydrograph. Every second runoff sample was collected in a 500 or 1000 ml plastic bottle, weighed and filtered through a pre-weighed 5 μm paper filter. The filters and sediment were dried for 24 h at 105 °C and weighed to determine the mass of sediment in each water sample. Any sediment remaining in the runoff trough after the simulation was also collected, dried, and weighed. This mass was added to the sum of the filtered samples to obtain the total sediment yield for each plot. Each plot was excavated after the simulation to observe the depth and extent of infiltration. The dependent variables derived from these data included the time to runoff, equilibrium runoff rate, runoff/rainfall ratio, duration of runoff after the simulation stopped, percent change in runoff over the main part of the hydrograph, mean sediment concentration, and total sediment yield.

*Statistical analysis*

Analysis of variance was used to determine whether there were significant differences in the dependent variables between fires and burn severity classes within fires. If there was a significant difference at $p \leq 0.05$, multiple comparisons (LSMeans) were used to determine which means were significantly different (SAS Institute, Inc., 1999). Simple linear regression was used to assess the relationship between each independent variable and the primary dependent variables.

 

## RESULTS

### *Plot characteristics*

Most of the rainfall simulations were done in July and August 2000 under very dry conditions (Table II). Surface soil moisture values were less than 2% for all but one of the 16 simulations on the Bobcat fire. Antecedent moisture conditions were more variable in the other two fires because most of these simulations were done later in the year after natural rains or transient snowmelt. Soil moisture values were less than 10% for the four simulations in high- and moderate-severity sites in the Lower Flowers fire, and between 10 and 20% for the two simulations in unburned areas. In the case of the Hourglass fire, the surface soil moisture values were greater than 20% for the two simulations in high-severity sites, but less than 10% for the two simulations in unburned sites (Table II).

Percent ground cover was inversely related to burn severity for the study sites in the two recent fires (Bobcat and Lower Flowers) (Table II). The high-severity plots in these two fires had less than 20% ground cover, except for the first simulation in the Bobcat fire (plot 1). This simulation was done only 3 days after the fire had been controlled, and the plot was in a small depression where ash had accumulated. The other simulations in the Bobcat fire were conducted at least a month after the fire, by which time most of the ash had been removed by wind. The moderate-severity plots in these two fires generally had at least 80% cover, whereas the low-severity and unburned plots had nearly 100% cover (Table II). In the older Hourglass fire one of the high-severity plots had 79% cover, and the other three plots all had 100% ground cover.

The mean slope of all plots was 26%, and the range was from 15 to 45% (Table II). There was a significant tendency for percent bare soil to increase with percent slope ($R^2 = 0.28$; $p = 0.005$), and this is probably because fire intensity tends to increase as a fire burns upslope.

Ponderosa pine dominated the overstory for the plots in both the Bobcat and Lower Flowers fires, whereas the plots in the Hourglass fire were in lodgepole pine. This difference in vegetation is not believed to have a significant effect on runoff and erosion, as Huffman *et al.* (2001) found no significant differences in natural or fire-induced soil hydrophobicity between these two vegetation types.

The following section will first present the runoff data from the plots in the Bobcat fire, as this fire had the largest sample size and the most consistent site conditions. Runoff from the other two fires will then be compared with the results from the Bobcat fire, and the effect of the independent variables will be analysed using the pooled data from all fires.

### *Runoff*

The observed runoff hydrographs were surprisingly consistent in terms of their overall shape and equilibrium runoff rates (Figure 3). For the high-severity sites in the Bobcat fire, runoff generally began within 4 min after the beginning of the simulated rainfall (Table III), and equilibrium runoff was reached within 5 min (e.g. Figure 3a). There was little change in the runoff rate over the remaining 55 min of the simulated rainfall, and runoff at the high-severity sites ceased within 4 min after the end of the simulated rainfall (Table III). For the seven high-severity plots the mean runoff-to-rainfall ratio was 66%, with a standard deviation of 8%. The high-severity plot with high ash cover had a runoff ratio of 79%, and this value is substantially higher than any of the other plots (Table III).

The five moderate-severity plots in the Bobcat fire produced less runoff than the high-severity plots (Figure 4), and the hydrographs from the moderate-severity plots also had significantly longer rising and recession limbs (Figure 3a and b; Table III). When compared with the high-severity plots, the mean runoff ratio was 58% versus 66%, the mean time to the initiation of runoff was 4·2 minutes versus 2·4 minutes, and the duration of runoff after the end of the simulated rainfall was 8·8 minutes versus 3·5 minutes. All of these differences were significant at $p < 0.05$.

The four simulations in the Bobcat fire on low-severity and unburned sites yielded runoff hydrographs that were not significantly different from the plots burned at moderate severity (Table III; Figure 3b and c). The main difference was that the rate of runoff in some of the low-severity and unburned sites tended to increase

 

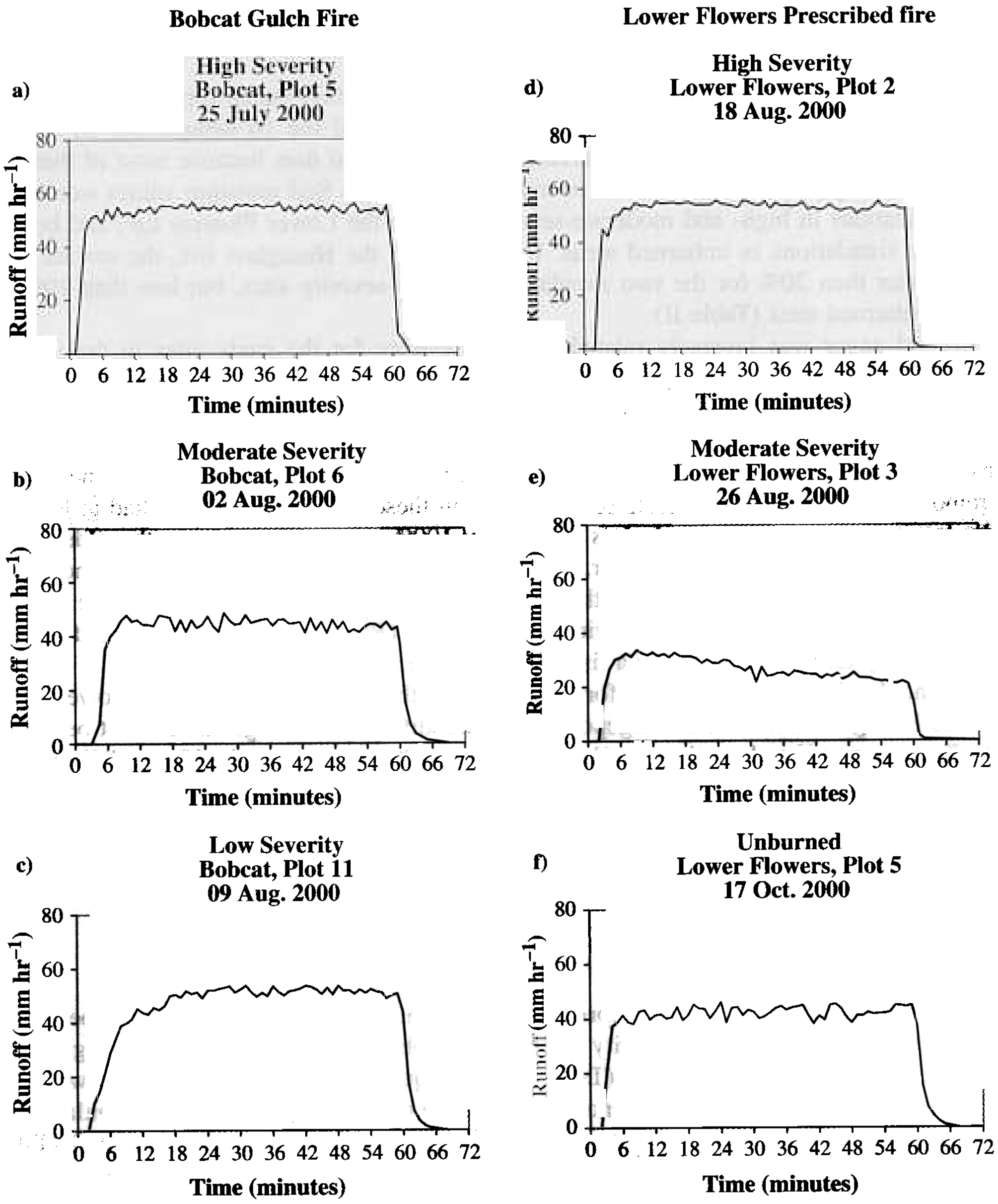


Figure 3. Typical runoff hydrographs from the Bobcat wildfire (a)–(c) and Lower Flowers prescribed fire (d)–(f) for different severities. Rainfall was applied from time 0 to 60 min at a rate of 66–94 mm h$^{-1}$

slowly over the course of the simulation (Figure 3c), but the percent change in the rate of runoff did not vary significantly with burn severity.

The runoff hydrographs from the two high-severity plots in the Lowers Flowers fire were very similar to the hydrographs from the high-severity plots in the Bobcat fire (Table III; Figure 3a and d). At both sites there was a very rapid response to rainfall and relatively constant runoff ratio over the course of the simulation. The recession limbs at Lower Flowers were slightly longer and the runoff ratios slightly less than for the high-severity sites in the Bobcat fire, but only the duration of the falling limb was significantly different ($p = 0{\cdot}002$).

Table III. Runoff data for each plot by fire and burn severity

| Fire | Plot number | Burn severity | Application rate (mm h$^{-1}$) | Equilibrium runoff (mm h$^{-1}$) | Runoff/rainfall ratio (%) | Time to initial runoff (min:sec) | Duration of runoff after rain ended (min:sec) |
|---|---|---|---|---|---|---|---|
| Bobcat | 1 | High | 93 | 80 | 79 | 2:50 | 2:50 |
| Bobcat | 2 | High | 85 | 60 | 66 | 3:25 | 3:45 |
| Bobcat | 3 | High | 84 | 60 | 70 | 2:05 | 2:30 |
| Bobcat | 4 | High | 82 | 55 | 64 | 1:55 | 3:20 |
| Bobcat | 5 | High | 86 | 54 | 61 | 1:46 | 3:15 |
| Bobcat | 15 | High | 76 | 50 | 54 | 4:05 | 4:30 |
| Bobcat | 16 | High | 94 | 66 | 68 | 4:00 | 4:00 |
| **Mean** | | | **86** | **61** | **66** | **2:26** | **3:27** |
| Bobcat | 6 | Moderate | 76 | 44 | 55 | 4:35 | 7:53 |
| Bobcat | 7 | Moderate | 80 | 55 | 63 | 4:55 | 10:00 |
| Bobcat | 8 | Moderate | 78 | 52 | 62 | 2:57 | 9:25 |
| Bobcat | 9 | Moderate | 73 | 39 | 50 | 4:03 | 8:35 |
| Bobcat | 14 | Moderate | 79 | 52 | 61 | 4:30 | 8:13 |
| **Mean** | | | **77** | **48** | **58** | **4:12** | **8:49** |
| Bobcat | 11 | Low | 80 | 51 | 58 | 3:00 | 8:10 |
| Bobcat | 13 | Low | 79 | 44 | 50 | 2:43 | 9:30 |
| Bobcat | 10 | Unburned | 74 | 48 | 58 | 6:00 | 13:10 |
| Bobcat | 12 | Unburned | 78 | 44 | 52 | 2:50 | 8:40 |
| **Mean** | | | **78** | **47** | **55** | **3:38** | **9:52** |
| Lower Flowers | 1 | High | 78 | 50 | 62 | 2:25 | 8:26 |
| Lower Flowers | 2 | High | 85 | 53 | 60 | 1:30 | 5:30 |
| **Mean** | | | **82** | **52** | **61** | **1:57** | **6:58** |
| Lower Flowers | 3 | Moderate | 80 | 27 | 32 | 3:00 | 12:48 |
| Lower Flowers | 6 | Moderate | 75 | 50 | 63 | 2:52 | 8:30 |
| **Mean** | | | **77** | **39** | **48** | **2:56** | **10:39** |
| Lower Flowers | 4 | Unburned | 77 | 42 | 59 | 3:26 | 7:30 |
| Lower Flowers | 5 | Unburned | 66 | 48 | 62 | 2:52 | 7:35 |
| **Mean** | | | **71** | **45** | **61** | **3:09** | **7:32** |
| Hourglass | | High | 75 | 34 | 43 | 1:40 | 5:00 |
| Hourglass | 2 | High | 80 | 24 | 28 | 5:15 | 4:20 |
| **Mean** | | | **77** | **29** | **36** | **3:27** | **4:40** |
| Hourglass | 3 | Unburned | 63 | 42 | 64 | 3:20 | 12:03 |
| Hourglass | 4 | Unburned | 80 | 46 | 54 | 2:48 | 8:00 |
| **Mean** | | | **72** | **44** | **59** | **3:04** | **10:01** |

The two simulations in Lower Flowers on moderate-severity sites yielded very different results. Plot 6 had a runoff ratio of 63% and a correspondingly rapid hydrograph rise and fall, whereas the other moderate-severity plot (plot 3) yielded the lowest runoff ratio (32%) and the longest recession limb (12·8 min) of all 26 simulations (Table III; Figure 3e). The low runoff from plot 3 was surprising, since it had 66% ground cover compared with 91% for plot 6, and the surface soil moisture was only slightly higher than plot 6 (9·0% versus 5·4%). Excavation of plot 3 after the simulated rainfall showed that infiltration was occurring over about 90% of the plot. Although the moderate-severity plots in Lower Flowers did have lower runoff ratios, longer times to runoff, and longer recession limbs than the high-severity plots, the small sample size and high variability meant that none of these differences was significant at $p \leq 0{\cdot}05$.

The hydrographs from the two unburned plots in Lower Flowers were comparable to the two high-severity plots (Table III; Figure 3d and f). For both sets of plots the mean runoff ratio was 61%. The time to runoff

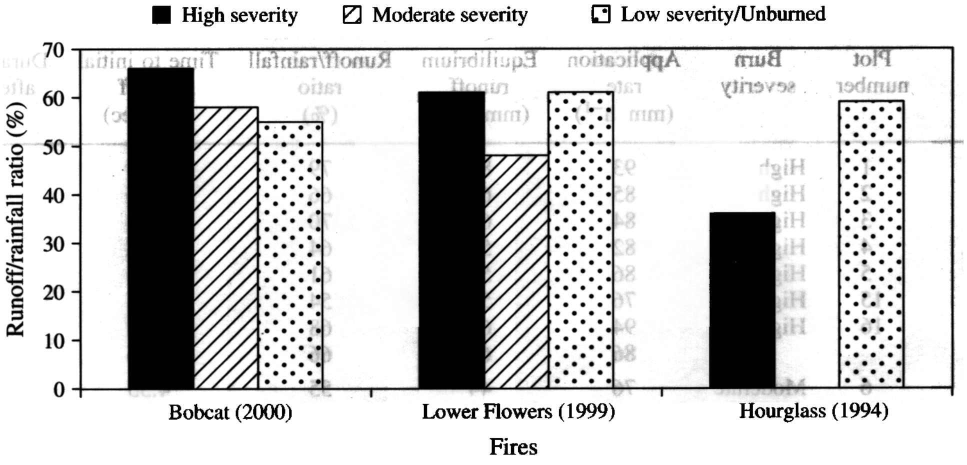


Figure 4. Mean runoff/rainfall ratios by fire and burn severity

and duration of the recession limbs for the unburned plots were slightly longer than for the high-severity plots, but none of the runoff characteristics from the unburned plots were significantly different from either the high-severity or moderate-severity plots.

The two simulations on high-severity plots in the 6-year-old Hourglass fire yielded a mean runoff ratio of only 36% and a mean falling limb duration of 4·7 min (Table III). In contrast, the two simulations in unburned areas yielded mean runoff ratios of 59% and a mean falling limb duration of 10 min. The low runoff ratios from the high-severity sites are not surprising, since the percent ground cover on these two plots was 79 and 100% (Table II). As discussed later, the low runoff ratios for the high-severity plots may be due to the high antecedent soil moisture.

There were no significant differences in the runoff ratios between the Bobcat and Lower Flowers fires when the data were stratified by burn severity (Figure 4). There were also no significant differences in the runoff characteristics between the three fires for the unburned and low-severity plots. The high-severity plots in the two more recent fires did have a significantly higher runoff ratio than the high-severity plots in the Hourglass fire (Figure 4).

*Effect of the site variables on runoff*

There were relatively few differences in soil water repellency with burn severity for either the Bobcat or the Lower Flowers fires (Figure 5a and b). The soils were generally most water repellent at 1–2 cm below the surface, and the water repellency declined relatively rapidly below about 3 cm. These results are consistent with a much more detailed study of soil hydrophobicity in the same areas (Huffman *et al.*, 2001).

In the older Hourglass fire, the sites burned at high severity showed no evidence of water repellency, whereas there was a moderate to weak water repellency at all depths in the unburned sites (Figure 5c). These results are confounded by the fact that water repellency in the high-severity sites was assessed later in the fall after a series of storm had increased the ambient soil moisture to 20% or more (Table II). Other studies (e.g. Doerr and Thomas, 2000; Huffman *et al.*, 2001) have shown that soils lose their water repellency at these higher soil moisture values.

The runoff ratio for all sites increased with increasing water repellency, as indicated by the WDPT at 2 cm ($R^2 = 0{\cdot}38$; $p = 0{\cdot}0008$) (Figure 6a). If only the high-severity sites are considered, the $R^2$ between WDPT and runoff ratios increases from 38% to 81%. There was also a highly significant decline in the runoff ratio with increasing soil moisture for the high-severity sites ($R^2 = 0{\cdot}71$; $p = 0{\cdot}001$), but this relationship was largely due to the two Hourglass plots with high soil moistures and low runoff ratios (Figure 6b).

 

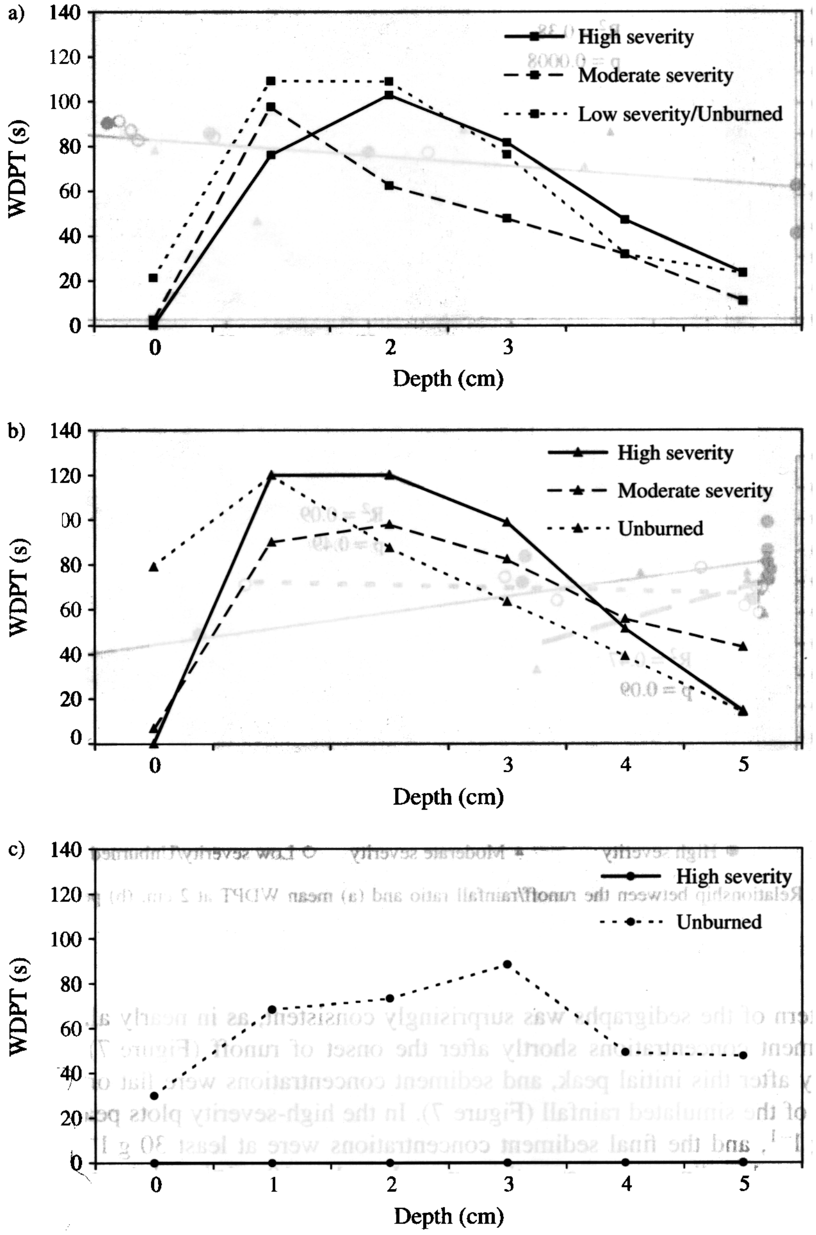


Figure 5. Water repellency from the soil surface to a depth of 5 cm as indicated by the water drop penetration test for the (a) Bobcat fire, (b) Lower Flowers prescribed fire, and (c) 1994 Hourglass wildfire. Zero depth represents the surface of the soil or litter if present. The persistence of several water drops at each depth was measured for a maximum of 120 s

The runoff ratio in the moderate-severity plots also declined with increasing soil moisture, but this was significant only at $p = 0.09$ (Figure 6b). Soil moisture had little effect on runoff ratios for the unburned plots.

There was a tendency for the WDPT to increase with decreasing soil moisture ($R^2 = 0.026$; $p = 0.009$). Runoff ratios were not significantly related to either percent slope or percent bare soil.

 

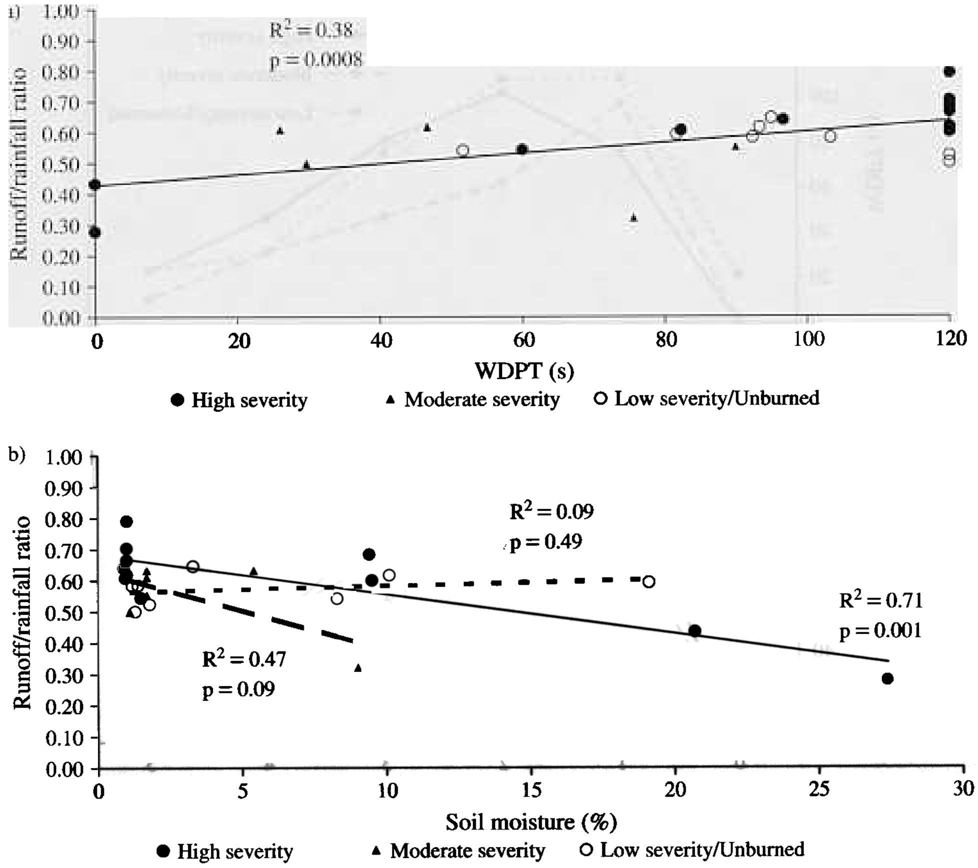


Figure 6. Relationship between the runoff/rainfall ratio and (a) mean WDPT at 2 cm, (b) percent soil moistu

*Sediment yield*

The overall pattern of the sedigraphs was surprisingly consistent, as in nearly all cases there was an initial sharp rise in sediment concentrations shortly after the onset of runoff (Figure 7). Sediment concentrations usually fell sharply after this initial peak, and sediment concentrations were flat or slowly declining over the remaining 50 min of the simulated rainfall (Figure 7). In the high-severity plots peak sediment concentrations ranged up to 90 g $l^{-1}$, and the final sediment concentrations were at least 30 g $l^{-1}$. In the low-severity and unburned plots the peak sediment concentrations were less than 10 g $l^{-1}$ and the concentrations over the rest of the simulation were less than 5 g $l^{-1}$ (Figure 7c and f).

The mean sediment yield for the high-severity plots in the Bobcat fire was 430 g, or nearly five times the mean sediment yield of 89 g for the plots burned at moderate severity (Table IV; Figure 8), and this difference was highly significant ($p < 0.0001$). The mean sediment yield for the low-severity and unburned plots was only 43 g, or half the measured value from the moderate-severity plots, but this difference was not statistically significant ($p = 0.36$). The observed differences in sediment yields were slightly greater than the differences in sediment concentrations because the high-severity plots had an equilibrium runoff rate that averaged 27% more than the moderate-severity plots (Table III). The high-severity plot in the Bobcat fire that had the highest runoff ratio and a high ash cover (Bobcat 1) yielded 27% less sediment than the mean from the other six high-severity plots, and this suggests that sediment yields are not a simple function of runoff rate. The first three simulations listed in Table IV have

 

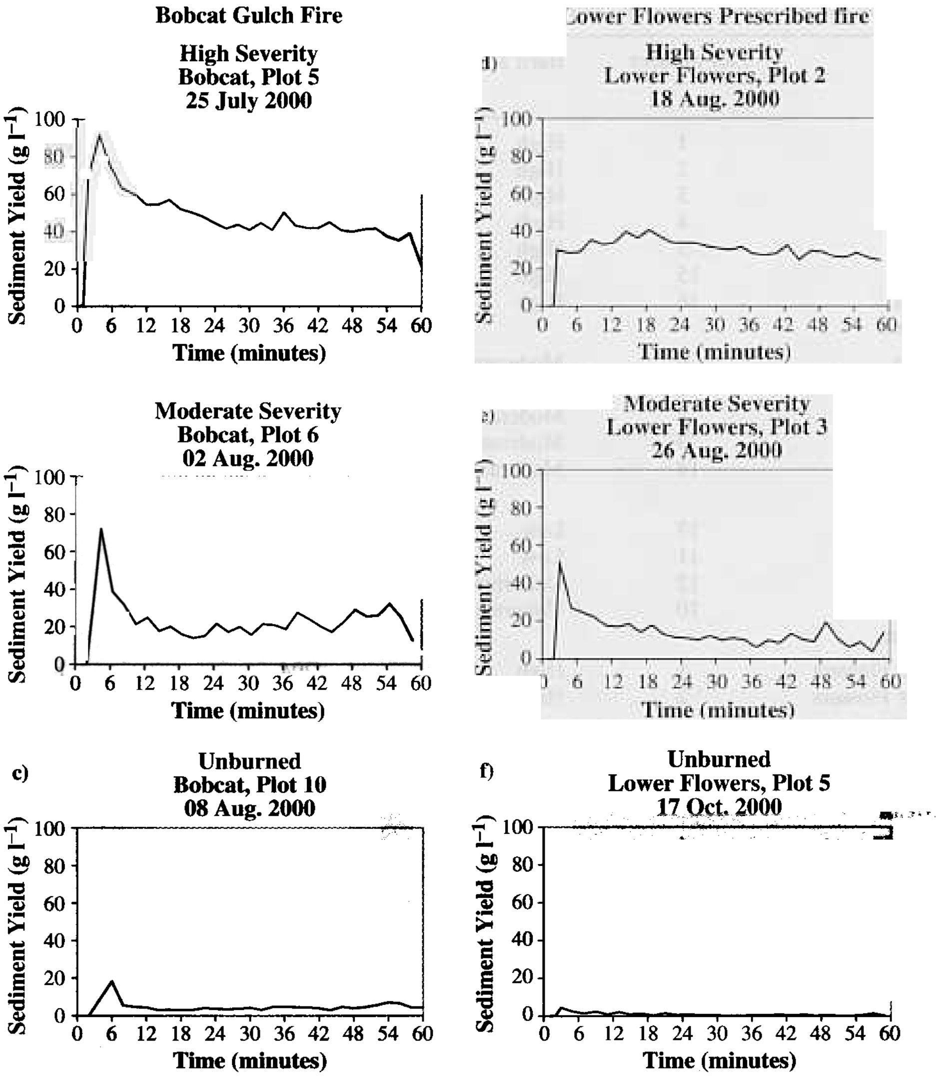


Figure 7. Typical sedigraphs from the Bobcat wildfire (a)–(c) and Lower Flowers prescribed fire (d)–(f) for different severities. Rainfall was applied from time 0 to 60 min at a rate of 66–94 mm h$^{-1}$

substantially lower sediment concentrations because more of the eroded sediment was deposited in the runoff trough.

The overall pattern of sediment yields from the plots in the Lower Flowers fire were very similar to the Bobcat fire (Table IV; Figure 8). The mean sediment yield for the two high-severity plots was 342 g, and the mean sediment yield for the plots burned at moderate severity was 76 g. The two unburned plots yielded only 13 g of sediment, or 4% of the mean sediment yield from the high-severity plots. As in the case of the Bobcat fire, the difference in sediment yields between the high- and moderate-severity plots was strongly significant ($p = 0{\cdot}0075$), but the difference in sediment yields between the moderate-severity and unburned plots was not significant.

Sediment yields from all four simulations in the Hourglass fire were generally similar to the sediment yields from the low-severity and unburned plots in the Bobcat and Lower Flowers fires (Table IV; Figure 8). The

 

Table IV. Sediment yields and sediment concentrations for each plot by fire and burn severity

| Fire | Plot number | Burn severity | Total sediment (g) | Sediment concentration (g $L^{-1}$) |
|---|---|---|---|---|
| Bobcat | | High | 327 | 11·0 |
| Bobcat | 2 | High | 549 | 19·3 |
| Bobcat | 3 | High | 574 | 17·6 |
| Bobcat | 4 | High | 439 | 32·3 |
| Bobcat | 5 | High | 423 | 30·1 |
| Bobcat | 15 | High | 317 | 25·5 |
| Bobcat | 16 | High | 368 | 28·6 |
| **Mean** | | | **428** | **23·5** |
| Bobcat | 6 | Moderate | 147 | 5·4 |
| Bobcat | 7 | Moderate | 125 | 5·6 |
| Bobcat | 8 | Moderate | 51 | 3·6 |
| Bobcat | 9 | Moderate | 50 | 2·4 |
| Bobcat | 14 | Moderate | 75 | 2·8 |
| **Mean** | | | **89** | **4·0** |
| Bobcat | 13 | Low | 39 | 1·5 |
| Bobcat | 11 | Low | 65 | 2·6 |
| Bobcat | 12 | Unburned | 21 | 1·4 |
| Bobcat | 10 | Unburned | 47 | 2·0 |
| **Mean** | | | **43** | **1·9** |
| Lower Flowers | | High | 294 | 12·3 |
| Lower Flowers | 2 | High | 389 | 21·9 |
| **Mean** | | | **342** | **17·1** |
| Lower Flowers | 3 | Moderate | 93 | 5·1 |
| Lower Flowers | 6 | Moderate | 60 | 1·9 |
| **Mean** | | | **76** | **3·5** |
| Lower Flowers | 4 | Unburned | 9 | 0·4 |
| Lower Flowers | 5 | Unburned | 18 | 0·8 |
| **Mean** | | | **13** | **0·6** |
| Hourglass | 1 | High | 47 | 2·6 |
| Hourglass | 2 | High | 7 | 0·9 |
| **Mean** | | | **27** | **1·7** |
| Hourglass | 3 | Unburned | 12 | 0·5 |
| Hourglass | 4 | Unburned | 14 | 0·5 |
| **Mean** | | | **13** | **0·5** |

average sediment yield for the two plots burned at high severity was 27 g, but the plot with 79% ground cover and a higher runoff ratio produced almost seven times as much sediment as the plot with 100% ground cover and a lower runoff ratio. The two unburned plots in the Hourglass fire produced only 12 and 14 g of sediment. Although the mean sediment yield for the two high-severity plots in the Hourglass fire was twice the mean value for the two unburned plots, this difference was not significant owing to the small sample size and variability in sediment yields from the high-severity plots.

The comparisons of sediment yields between fires showed no statistical differences in sediment yields between the Bobcat and Lower Flowers fires when stratified by burn severity (Figure 8). However, sediment yields from the high-severity sites in these two fires were significantly greater than the sediment yields from the high-severity sites in the Hourglass fire. There were no significant differences in sediment yields between the three fires for the low-severity and unburned sites.

 

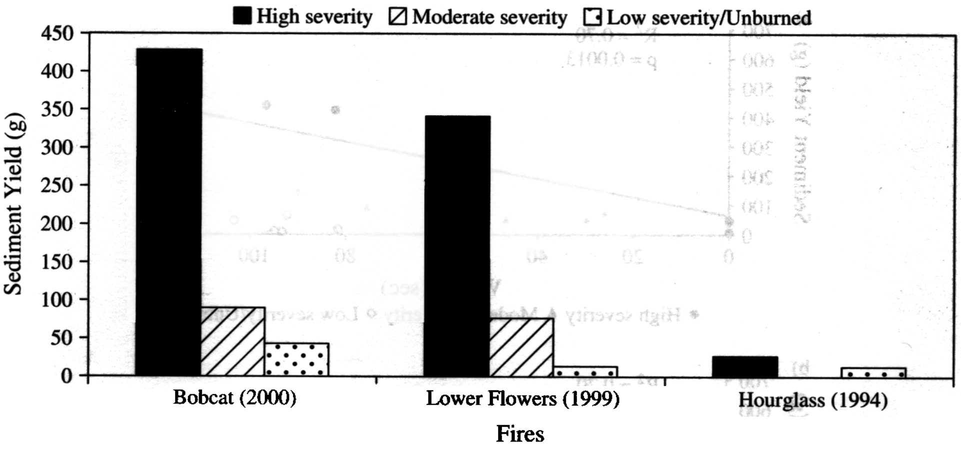


Figure 8. Mean sediment yields by fire and burn severity

*Effect of site variables on sediment yields*

Water repellency was strongly correlated with increasing sediment yields for the plots burned at high severity ($R^2 = 0.70$; $p = 0.001$) (Figure 9a). The other two burn-severity classes did not have a significant relationship between water repellency and sediment yields. Similarly, soil moisture was inversely related to sediment yields for the plots burned at high severity ($R^2 = 0.70$; $p = 0.001$), whereas there was no significant relationship between soil moisture and sediment yields for either of the other two burn-severity classes (Figure 9b). The strong correlations for the high severity plots are largely due to the fact that the two high severity plots in the Hourglass fire had very low sediment yields, high antecedent soil moisture values, and no water repellency.

Percent bare soil was strongly correlated with increasing sediment yields when all the data were pooled ($R^2 = 0.81$; $p < 0.0001$), and this relationship is largely due to the high-severity sites having little cover and high sediment yields (Figure 9c). Increasing slope was significantly associated with increasing sediment yields when all the data were pooled, but slope explained only 20% of the variation in sediment yields. As noted earlier, the steeper plots were more likely to be classified as high severity. Since slope was not significantly correlated with sediment yield when the data were stratified by burn severity, the relationship between burn severity and slope is largely responsible for the significant increase in sediment yields with increasing slope.

## DISCUSSION

*Runoff rates*

Higher fire severities are generally believed to induce stronger hydrophobic layers (DeBano, 1981), so areas burned at high severity should have lower infiltration rates than areas burned at moderate or low severities. Although few studies have evaluated soil water repellency, infiltration, and runoff rates in ponderosa or lodgepole pine forests after burning, infiltration rates were reduced by 62% in ponderosa pine sites in Arizona that had been burned at high severity (Campbell *et al.*, 1977). Zwolinski (1971) found that ponderosa pine sites burned at high and low severity had much lower infiltration rates than unburned sites in the first summer after burning.

In contrast, our results showed only small differences in the runoff/rainfall ratio after stratifying by burn severity. The mean runoff ratios for the high-severity plots in the Bobcat fire were only about 13% greater than the mean runoff ratio for the plots burned at moderate severity, and 20% greater than the mean runoff

 

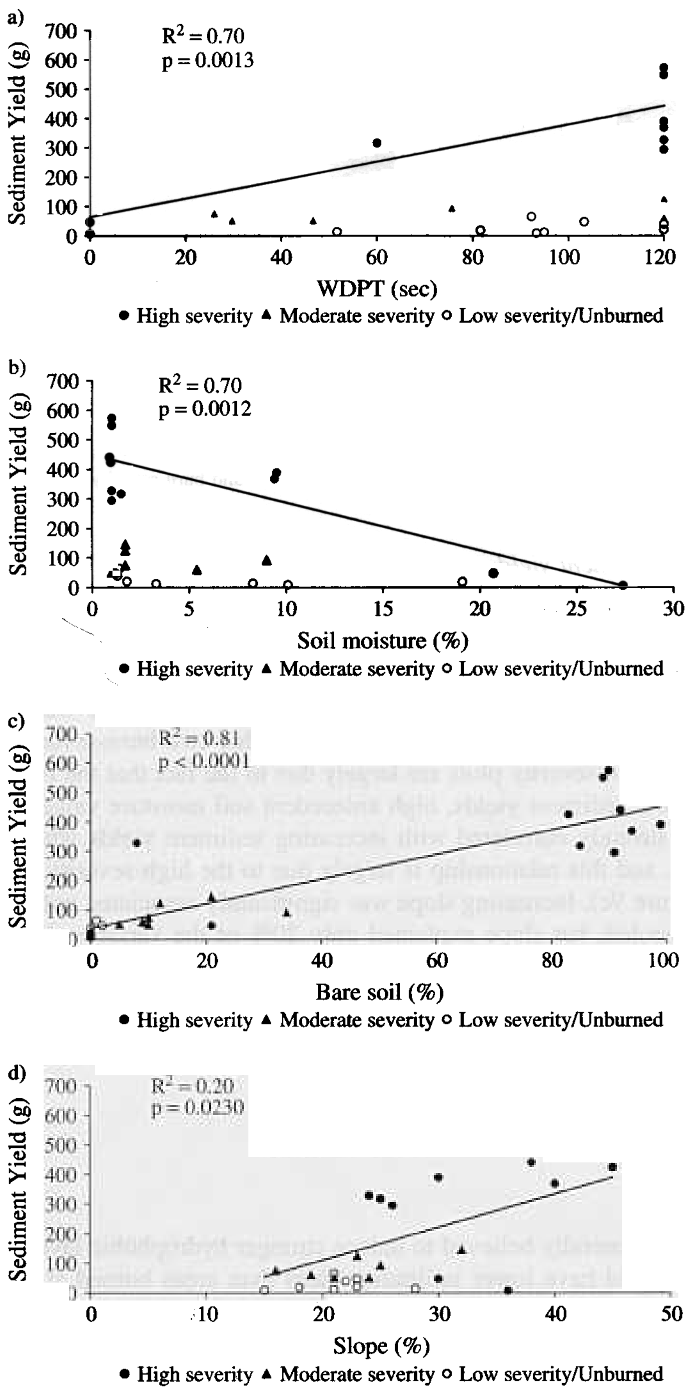


Figure 9. Relationship between sediment yields for each plot and (a) mean WDPT at 2 cm, (b) percent soil moisture, (c) percent bare soil, and (d) slope. The regression lines and statistics in (a) and (b) are only for the high severity plots

ratio for the unburned plots and plots burned at low severity (Figure 4). The differences in runoff with burn severity were less consistent for the other two fires.

One possible reason for the small differences in runoff rates with burn severity is the relatively high intensity of the simulated rainfall. The mean rainfall intensity was 79 mm $h^{-1}$, and in 23 of the 26 plots the runoff accounted for more than 50% of the applied rainfall. Even in the unburned plots the mean runoff ratio was 58%. If evaporation and interception losses are assumed to be negligible, the equilibrium infiltration rate from the unburned plots is only around 20–35 mm $h^{-1}$. If the unburned plots have a runoff ratio in excess of 50% when they are subjected to a high-intensity simulated rainfall, it is not possible to see a dramatic increase in runoff ratios from the burned plots.

The small differences in runoff observed in our study are in contrast to the results of other rainfall simulator studies in burned areas. Simanton *et al.* (1990) applied rainfall at 65 mm $h^{-1}$ and collected four times as much runoff from sagebrush sites burned at high severity than unburned sites or sites burned at low severity. Robichaud and Waldrup (1994) applied 100 mm $h^{-1}$ to forested sites in the southern USA and generated ten times as much runoff from high-severity sites as from sites burned at low severity. It seems that the small differences in runoff with burn severity in our study are due primarily to the high runoff rates from our unburned and low-severity sites relative to other researchers (e.g. Shahlaee *et al.*, 1991).

Both our field observations and the water drop penetration data suggest that water repellency–both natural and fire induced–may be one cause of the high runoff rates. Figure 5a and b indicates that the soils were water repellent at 1–3 cm below the surface in all sites in the Bobcat and Lower Flowers fires, regardless of burn severity. Robichaud and Hungerford (2000) also found that forest soils were water repellent under dry conditions in unburned areas as well as after burning. In southeastern Australia the runoff increased by 5–15% under dry conditions in eucalyptus forests due to natural soil water repellency (Burch *et al.*, 1989), and Pierson *et al.* (2001) found that unburned intercanopy areas in shrublands generated more runoff than intercanopy areas that had been burned.

In the case of the Hourglass fire, the unburned sites had weak water repellency to a depth of at least 5 cm, whereas there was no water repellency in the sites burned at high severity (Figure 5c). The lack of any water repellency in the high-severity sites in the Hourglass fire can be attributed to the fact that the antecedent soil moisture content was more than 20% (Table II). Other studies have shown that natural and fire-induced hydrophobicity is not present at such high soil moisture levels, making the soils much more wettable than under dry conditions (Shahlaee *et al.*, 1991; Doerr and Thomas, 2000; Huffman *et al.*, 2001). The high soil moisture content and corresponding lack of water repellency is probably why the two high-severity plots in the Hourglass fire had a mean runoff ratio of only 36% (Table III). Our excavation of these plots after the simulations confirmed that the wetting front had penetrated several centimetres in approximately 90% of the plot area.

The shape of the hydrographs observed in our study also suggest a relatively strong water-repellent layer under dry conditions in both the burned and unburned plots. If the soils are not water repellent the infiltration rate should decrease and the runoff rate should increase due to the progressively smaller role of capillary forces (Hillel, 1998). On the other hand, an increase in infiltration and a decrease in runoff during the simulation would suggest a progressive wetting and breakdown of a water-repellent layer. Since most of the simulations showed nearly constant runoff after the first 5–10 min, this suggests that the natural or fire-induced water repellency remained effective throughout the simulated rainfall event. Our excavation of the plots after each simulation also showed that in nearly all cases the soils were dry immediately below the surface, and in most plots the wetting front had penetrated more than a few centimetres in only a few locations. These observations also show that most sites had a relatively strong water-repellent layer at or near the surface. Since there was no consistent relationship between percent cover and the runoff ratio, soil sealing does not appear to be an important process, except in the case of the first plot on the Bobcat fire where there was a high ash cover. The implication is that water repellency and antecedent soil moisture are the primary controls on the amount of runoff from our simulated rainfall.

 

*Effect of burn severity and water repellency on sediment yields*

The differences in sediment yields with burn severity were much larger than the differences in runoff, and the measured sediment yields were generally more consistent than the runoff ratios when stratified by fire and burn severity (Table IV; Figure 8). Mean sediment yields from the high-severity plots in the Bobcat and Lower Flowers fires were respectively 4·8 and 4·5 times greater than the sediment yields from the plots burned at moderate severity. The mean sediment yields from the moderate-severity plots in these two fires were two and six times greater than the mean sediment yields from the low-severity and unburned plots (Table IV). This means that the high-severity plots in the Bobcat fire produced ten times as much sediment as the low-severity and unburned plots, and the high-severity sites in the Lower Flowers fire produced 26 times as much sediment as the unburned plots.

The mean sediment yield of 410 g $m^{-2}$ from the nine recently burned, high-severity plots in this study is higher than the values reported in other studies. In the southeastern USA, simulated rainfall rates of 130 mm $h^{-1}$ produced 65 g $m^{-2}$ from small plots (Shahlaee *et al*., 1991), and Robichaud and Waldrup (1994) measured sediment yields of 139 g $m^{-2}$ as a result of applying 100 mm $h^{-1}$ of simulated rainfall for 30 min on plots burned at high severity. Given the shorter simulation period used by Robichaud and Waldrup (1994), the latter value is actually quite comparable to our measured sediment yields. In sagebrush communities, Simanton *et al.* (1990) found that high-severity sites produced five times as much sediment as unburned sites. Prosser (1990) and Inbar *et al.* (1998) found erosion rates under natural rainstorms to increase by two to three orders of magnitude in high severity sites relative to unburned conditions.

The large increase in erosion rates with increasing burn severity is most commonly ascribed to the loss of ground cover and the increase in runoff due to soil hydrophobicity (Osborn, 1954; Morris and Moses, 1987; Inbar *et al.* 1998). In our study, percent ground cover accounted for 81% of the observed variability in sediment yields (Figure 9c). Comparable plots that produced less runoff but had less percent cover still produced more sediment (e.g. Lower Flowers plot 3 versus plot 6). Since burn severity had a large and significant effect on sediment yields but only a small effect on runoff ratios, the large differences in sediment yields with burn severity should be attributed primarily to the differences in ground cover rather than the differences in runoff, water repellency, or antecedent soil moisture.

*Erosion recovery rates*

Our results suggest that the recovery of ground cover is the most important factor in reducing post-fire erosion rates over time, at least for the plot scale addressed in this study. The two high-severity plots in the Hourglass fire had burned 6 years prior to our rainfall simulations, and the percent ground cover on these two plots was 79 and 100%. The high-severity plot in the Hourglass fire with 79% ground cover produced nearly seven times as much sediment and 50% more runoff than the plot with 100% ground cover. The mean sediment yield from these two plots was only 6·6% of the mean sediment yield from the high severity plots in the more recent Bobcat and Lower Flowers fires; the percent ground cover in the high-severity plots in these two fires was less than 20% in all but one plot (Table II). These comparisons indicate that the lower sediment yields from the high severity sites in the Hourglass fire are due to the increase in ground cover over the 6 years since burning. Preliminary results from a study of emergency rehabilitation treatments on the Bobcat fire show that mulched sites produce much less sediment than unmulched sites, and this again emphasizes the importance of surface cover on erosion rates.

The observed reduction in erosion rates over time is consistent with most other studies. Erosion rates from high severity sites in the nearby Buffalo Creek fire declined to background levels within 3 years (Martin and Moody, 2001). Studies in other areas have also shown that erosion rates decline to background levels within 3 to 9 years after burning (Martin and Moody, 2001). In the case of the Hourglass fire, the mean sediment yield from the two high-severity plots was still twice the sediment yield from the unburned plots (Table IV). Since the simulations on these two plots were conducted under wet antecedent conditions that may have depressed the runoff rate and there was a substantial difference in sediment yields between the two high-severity plots, we cannot conclusively state whether erosion rates in the Hourglass fire have completely recovered to background levels.

*Representativeness and scale effects*

The plot-scale data show a 10- to 25-fold increase in erosion from the recently burned, high-severity plots relative to the low-severity or unburned plots. In absolute terms, the erosion rate from the high-severity plots averaged 400 g $m^{-2}$ or 4 Mg $ha^{-1}$. This erosion rate is slightly larger than the reported values for most other studies in ponderosa pine in the first year after burning [see review in Robichaud *et al.* (2000)], but it is much lower than the post-fire erosion rates reported for mixed conifer forests in Arizona (Hendricks and Johnson, 1944) and ponderosa pine and Douglas-fir stands in Idaho (Megahan and Molitor, 1975).

The sediment yields from our plots may be somewhat low in absolute terms because the plots used for the rainfall simulation were only 1 m long, so rainsplash and sheetwash were the primary erosion processes (Mutchler *et al.*, 1988). In the high-severity plots the plot edges and rain gauges were coated with soil particles to a height of at least 15 cm at the end of the simulations. During the simulations most of the plot was generating runoff as sheetflow and there was little evidence of rill erosion.

Both field studies and process-based models suggest that plots must be at least several metres long before rill erosion becomes an important erosion process (Mutchler *et al.*, 1988). The research underlying the WEPP model suggests that rill erosion is the dominant process at the hillslope scale (Nearing *et al.*, 1989). The absence of rill erosion in our study plots indicates that our sediment yields per unit area would probably increase if the same rainfall event were to be applied on longer plots. The increasing importance of rill erosion at larger scales might also affect the relative importance of the different site factors; slope, for example, might become a more significant factor than is currently suggested by our plot-scale data.

The representativeness of our erosion rates are also affected by the amount and intensity of the simulated rainfall. The mean simulated rainfall rate of 79 mm $h^{-1}$ is larger than the estimated 100 year, 1 h storm of 56 mm (Miller *et al.*, 1973), but comparable to the largest storm events that have been observed in the area. In 1976, for example, 75 mm $h^{-1}$ fell for approximately 3 h in the same general area as the Bobcat fire, and in 1997 89 mm of rain fell in 1 h in Fort Collins. On 16 August 2000 a convective storm over the Bobcat fire dropped 61 mm of rainfall with a peak 1 h intensity of 29 mm. After the Buffalo Creek fire in 1996 a summer convective storm produced 63 mm of rain in 2 h, and this triggered severe flooding and erosion (Agnew *et al.*, 1997). These data indicate that our simulated storm event has a high recurrence interval but is not unrealistic for the northern Colorado Front Range.

The mean rainfall erosivity from our simulations is approximately 1790 MJ mm $ha^{-1}$ $h^{-1}$, which is approximately five times the estimated average annual rainfall erosivity of 340 MJ mm $ha^{-1}$ $h^{-1}$ (Renard *et al.*, 1997). The rainfall energy from a 10 year storm event in the area of the Bobcat Fire is nearly 700 MJ mm $ha^{-1}$ $h^{-1}$, or close to 40% of the rainfall erosivity used in our simulations. These calculated erosivities assume that our simulated rainfall has a kinetic energy that is similar to natural rainstorms with the same intensity, and this assumption is supported by the work of Meyer and Harmon (1979). Since both the rainfall rate and our calculated rainfall erosivities show that our simulations represent relatively extreme storm events, one might expect correspondingly high erosion rates per unit area. The severely burned plots did generate 10–25 times more sediment than the unburned plots, but the measured erosion rate of 400 g $m^{-2}$ is lower than might be expected from an extreme storm event, and this is probably due to the absence of rill erosion.

Any effort to extrapolate our results to a larger scale will require an explicit consideration of the shift in erosion processes from rainsplash and sheet erosion at the plot scale to rill erosion at the hillslope scale. The problems of identifying a representative storm event and changing erosion processes with increasing spatial scale mean that the measured erosion rates should be regarded as more of an index of relative differences than absolute values that can be extrapolated to entire hillslopes or drainage basins. Larger-scale simulations and repeated measurements over time are needed to help determine the extent to which these results can be used to predict the effects of future fires and to design effective post-fire rehabilitation treatments.

 

## CONCLUSIONS

Runoff rates from simulated rainfall on plots that had been recently burned at high severity were only slightly greater than from plots burned at moderate severity. Runoff rates from moderate-severity sites were not significantly different from plots burned at low severity or unburned plots. Both natural and fire-induced water repellency were present 1–3 cm below the surface in the Bobcat and Lower Flowers fires, and this, together with the high intensity of the applied rainfall, may explain the small differences in runoff with burn severity. The two high-severity plots in the Hourglass fire produced the least runoff, and this is probably due to the wet antecedent conditions and corresponding suppression of any soil water repellency. Percent ground cover and slope had little influence on runoff rates.

Burn severity had a very large effect on sediment yields in the two recent fires. The high-severity plots in the Bobcat and Lower Flowers fires produced almost five times as much sediment as the plots burned at moderate severity, and 10–26 times as much sediment as the plots burned at low severity and the unburned plots. The mean sediment yield from the two plots burned at high severity in the Hourglass fire was only twice the sediment yield from the unburned plots, and this suggests that erosion rates decline to near-background levels within 6 years after burning. Sediment yields were most strongly correlated with percent bare soil ($R^2 = 0{\cdot}81$), and only weakly correlated with the amount of runoff or percent slope. The mean sediment yield from plots recently burned at high severity was approximately 0·4 kg $m^{-2}$. This lower than expected value is probably due to the fact that the 1 m plot length was too short to generate rill erosion.

Rainsplash and sheetwash were the dominant erosion processes at the scale of our rainfall simulations. The strong relationship between percent ground cover and sediment yields suggests that the decline in erosion rates to pre-burn conditions is due primarily to the increase in ground cover. Since runoff and erosion rates depended more on burn severity than the type of fire, fire managers should minimize the area burned at high severity in prescribed fires. Post-fire rehabilitation techniques should focus on maximizing the amount of ground cover. Studies at the hillslope- and catchment-scale are needed to evaluate the changes in erosion rates and processes with increasing scale.

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A procedural error in our calculations shows that the plot-scale sediment yields should be 2–3 times higher than the values reported in Table IV in Benavides-Solorio and MacDonald (2001). The revised values for each of the 26 plots are shown in Table I. Since the errors were relatively consistent between plots, there are no changes in the significant differences between burn severities and between fires. However, the mean sediment yields for the plots burned at high severity are now 1.3 kg $m^{-2}$ for the Bobcat wildfire and 0.85 kg $m^{-2}$ for the Lower Flowers prescribed fire (Table 1). In each case these values are more than 7 times the mean value for the plots burned at moderate severity. Mean sediment yields from the high-severity plots in the Bobcat and Lower Flowers fires are respectively 16 and 32 times the mean sediment yields from the unburned plots and plots burned at low severity. The calculation error means that the plots burned at high severity now exhibit slightly more variability than originally reported. Sediment concentrations were not changed.

The revised sediment yields have not altered the significance of the relationships between sediment yields and the four site factors of soil hydrophobicity, percent bare soil, soil moisture, and slope shown in Figure 9 in Benavides-Solorio and MacDonald (2001). However, there have been some changes in the coefficients of determination. Soil hydrophobicity—as indicated by the water drop penetration time—now explains only 43% of the variability in sediment yields for the plots burned at high severity ($p = 0{\cdot}03$) (Figure 1a). Percent soil moisture also is less strongly correlated for the high-severity plots ($R^2 = 0{\cdot}43$; $p = 0{\cdot}03$) (Figure 1b). Percent slope can explain 43% of the variability in sediment yields from all plots ($p = 0{\cdot}003$), and this is due to the tendency for the more severely-burned plots with higher sediment yields to be on steeper slopes (Figure 1d). The most important variable is still percent bare soil, as this explains 79% of the variability in sediment yields from the 26 plots ($p < 0{\cdot}001$) (Figure 1c).

The corrected sediment yields for the nine recently-burned, high-severity plots average 1.2 kg $m^{-2}$. These larger values are more consistent with the hillslope and catchment-scale sediment yields that we have been measuring on the Bobcat Fire. The relatively large magnitude of these values confirm the potential seriousness of post-fire erosion rates in the Colorado Front Range.

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Table I. Corrected sediment yields for each plot by fire and burn severity. The sediment concentrations have not changed. Note that the measured concentrations were increased to account for the sediment collected in the runoff trough at the end of the simulation

| Fire | Plot number | Burn severity | Total sediment (g) | Sediment concentration (g $L^{-1}$) |
|---|---|---|---|---|
| Bobcat | 1 | High | 804 | 11·0 |
| Bobcat | 2 | High | 1100 | 19·3 |
| Bobcat | 3 | High | 1030 | 17·6 |
| Bobcat | 4 | High | 1690 | 32·3 |
| Bobcat | 5 | High | 1570 | 30·1 |
| Bobcat | 15 | High | 1040 | 25·5 |
| Bobcat | 16 | High | 1750 | 28·6 |
| **Mean** | | | **1280** | **23·5** |
| Bobcat | 6 | Moderate | 223 | 5·4 |
| Bobcat | 7 | Moderate | 279 | 5·6 |
| Bobcat | 8 | Moderate | 173 | 3·6 |
| Bobcat | 9 | Moderate | 86 | 2·4 |
| Bobcat | 14 | Moderate | 133 | 2·8 |
| **Mean** | | | **179** | **4·0** |
| Bobcat | 13 | Low | 59 | 1·5 |
| Bobcat | 11 | Low | 122 | 2·6 |
| Bobcat | 12 | Unburned | 55 | 1·4 |
| Bobcat | 10 | Unburned | 85 | 2·0 |
| **Mean** | | | **80** | **1·9** |
| Lower Flowers | 1 | High | 590 | 12·3 |
| Lower Flowers | 2 | High | 1110 | 21·9 |
| **Mean** | | | **850** | **17·1** |
| Lower Flowers | 3 | Moderate | 131 | 5·1 |
| Lower Flowers | 6 | Moderate | 90 | 1·9 |
| **Mean** | | | **111** | **3·5** |
| Lower Flowers | 4 | Unburned | 37 | 0·4 |
| Lower Flowers | 5 | Unburned | 14 | 0·8 |
| **Mean** | | | **26** | **0·6** |
| Hourglass | 1 | High | 86 | 2·6 |
| Hourglass | 2 | High | 19 | 0·9 |
| **Mean** | | | **52** | **1·7** |
| Hourglass | 3 | Unburned | 21 | 0·5 |
| Hourglass | 4 | Unburned | 23 | 0·5 |
| **Mean** | | | **22** | **0·5** |

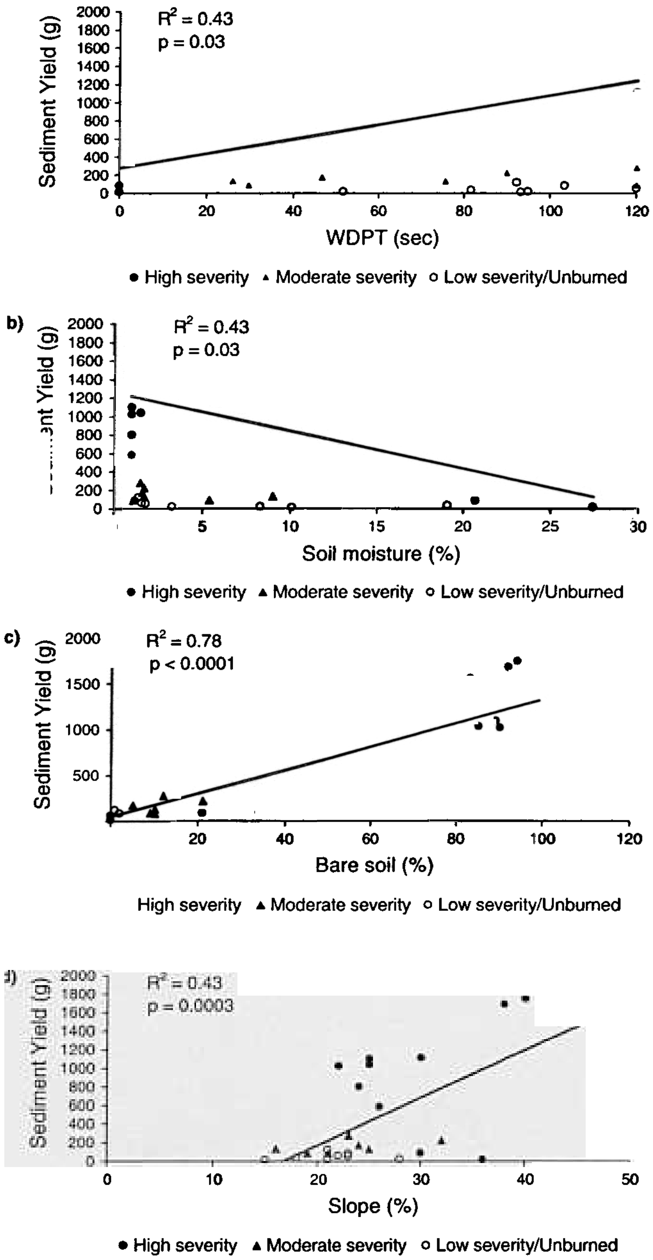


Figure 1. Corrected scatterplots and trend lines for the relationships between plot sediment yields and (a) mean water drop penetration time at 2 cm, (b) percent soil moisture, (c) percent bare soil, and (d) percent slope. The regression lines and statistics in (a) and (b) are only for the high severity plots

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