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Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range

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Abstract. Post-fire soil erosion is of considerable concern because of the potential decline in site productivity and adverse effects on downstream resources. For the Colorado Front Range there is a paucity of post-fire erosion data and a corresponding lack of predictive models. This study measured hillslope-scale sediment production rates and site characteristics for three wild and three prescribed fires over two summers and one winter using 48 sediment fences. Over 90% of the sediment was generated by summer convective storms. Sediment production rates from recent, high-severity wildfires were 0.2–1.0 kg m^{-2} year^{-1}. Mean sediment production rates from areas recently burned at moderate and low severity were only 0.02 and 0.005 kg m^{-2} year^{-1}, respectively. For a given severity, sediment production rates from prescribed fires were generally lower than from wildfires, but there was considerable variability between plots and within fire severity classes. Fire severity, percent bare soil, rainfall erosivity, soil water repellency and soil texture explained 77% of the variability in sediment production rates, while a two-parameter model using percentage bare soil and rainfall erosivity explained 62% of the variability. Model validation confirmed the usefulness of these empirical models. The improved understanding of post-fire erosion rates can help guide forest management and post-fire rehabilitation efforts.

Additional keywords: cover; fire severity; forests; models; rainfall erosivity; sediment production.

Introduction

In the last 10 years there has been a dramatic increase in the area burned by high-severity wildfires in the mid-elevation forests in the Colorado Front Range (MacDonald and Stednick 2003). The increase in the area burned is attributed to a combination of fire suppression, reduced grazing, and global climate change (Brown *et al*. 1999; Joyce and Birdsey 2000; Kaufmann *et al*. 2000*a*, 2000*b*, 2001; Huckaby *et al*. 2001; Keane *et al*. 2002). Erosion rates typically increase by several orders of magnitude from areas burned at high severity because of the loss of protective ground cover and increase in surface runoff (Inbar *et al*. 1998; Robichaud *et al*. 2000; Benavides-Solorio and MacDonald 2001, 2002).

The increase in erosion rates is of great concern to resource managers because of the potential reduction in site productivity and the adverse effects on water quality, downstream aquatic resources and human communities. For example, flooding and downstream sedimentation after the 1996 Buffalo Creek fire killed two people, repeatedly washed out a state highway, severely degraded Denver's water supply, and reduced the storage capacity of Strontia Springs Reservoir by approximately one-third (Agnew *et al*. 1997; Moody and Martin 2001). Similarly, post-fire erosion after the 560 km^2 Hayman wildfire severely degraded water quality and the important trout fishery in the South Platte River (Graham 2003; Libohova 2004).

Only a few studies have measured post-fire erosion rates in the Colorado Front Range, and these have yielded widely varying results. A high-severity wildfire in August 1966 had little or no effect on infiltration and erosion rates compared to unburned sites (Striffler and Mogren 1971). The relatively small difference between burned and unburned sites was partly due to the fact that the maximum 30-min rainfall intensity after the fire was only 11 mm h^{-1}. A study using small Gerlach traps showed that sediment flux rates from sites burned at high severity were three orders of magnitude higher than from unburned sites (Morris and Moses 1987). The higher flux rates from severely burned areas were

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attributed to the loss of ground cover and fire-induced soil water repellency (Morris and Moses 1987). However, few of the site attributes were measured, so the presumptive causal factors could not be rigorously related to the measured sediment flux rates. Uncertainties with respect to the contributing areas above the Gerlach traps means that the measured flux rates cannot be converted into sediment yields per unit area. An exceptionally high sediment yield of 6.8 kg m^{-2} $year^{-1}$ was estimated from sediment deposits after severe storms on the 1996 Buffalo Creek fire (Moody and Martin 2001), but the lack of data from multiple plots meant the variability between sites and the role of different controlling factors could not be rigorously quantified. These limitations and differences in methodology have precluded rigorous comparisons between sites and the development of predictive models.

Studies outside the Colorado Front Range have shown that a wide range of factors can control post-fire runoff and erosion rates, including fire severity, percentage bare soil, rainfall intensity, soil water repellency, soil texture, slope, and aggregate stability (Hendricks and Johnson 1944; Dyrness and Youngberg 1957; Megahan and Molitor 1975; Wright *et al.* 1976; Inbar *et al.* 1998; Prosser and Williams 1998; Robichaud and Brown 1999; Marcos *et al.* 2000; Robichaud 2000; Pierson *et al.* 2001). More recent field studies in the Colorado Front Range found that both wild and prescribed fires induce soil water repellency in forested areas, but this post-fire soil water repellency was relatively shallow and of short duration (Huffman *et al.* 2001; MacDonald and Huffman 2004). Rainfall simulations on 1-m^2 plots in the northern Colorado Front Range confirmed that fire severity was an important control on post-fire erosion rates. Plots burned at high severity had a mean sediment yield of 1.2 kg m^{-2}, while plots burned at moderate and low severity had mean values of 0.18 kg m^{-2} and 0.05 kg m^{-2}, respectively (Benavides-Solorio and MacDonald 2001, 2002). Percentage bare soil was closely correlated with sediment yields ($R^2 = 0.78$, $P < 0.0001$), but it is not clear whether these results can be extrapolated to natural storm events at the hillslope or catchment scale.

A key knowledge gap is the duration of elevated erosion rates after both wild and prescribed fires. Studies in other areas have identified the first two rainy seasons as the most critical period for post-fire flooding and sedimentation (Inbar *et al.* 1998; Robichaud *et al.* 2000), but it is not known whether these results can be applied to the Colorado Front Range. Morris and Moses (1987) found that the first season after burning was the most critical, while Moody and Martin (2001) suggested that post-fire erosion rates will approach background levels by the fourth year after burning. This time to recovery is much longer than the measured longevity of fire-induced soil water repellency (Huffman *et al.* 2001; MacDonald and Huffman 2004), implying that other factors are controlling the duration of elevated post-fire erosion rates.

To reduce the risk of high-severity wildfires, land managers are increasing their use of prescribed fire and forest thinning (MacDonald and Stednick 2003; USDA Forest Service 2005). The lack of data on erosion rates after prescribed fires in the Colorado Front Range means that land managers cannot rigorously compare the potential benefits and risks of prescribed fires relative to wild fires.

The primary goal of this study was to quantify post-fire erosion rates from both wild and prescribed fires in ponderosa and lodgepole pine forests in the Colorado Front Range. The main objectives were to: (1) measure post-fire sediment yields at the hillslope scale from both wild and prescribed fires of varying ages; (2) compare sediment production rates from snowmelt events *v.* summer rainstorms; (3) quantify the effect of different site attributes on sediment production; and (4) develop and test empirical models to predict post-fire sediment production rates in the Colorado Front Range.

Study areas

Study plots were established on three wild and three prescribed fires in the northern Colorado Front Range (Fig. 1; Table 1). The fires were selected to represent a range of ages in order to evaluate changes in erosion rates and site conditions with time since burning. The oldest fire was the 1994 Hourglass wildfire (Omi 1994), and the most recent fire was the June 2000 Bobcat wildfire. The other four fires

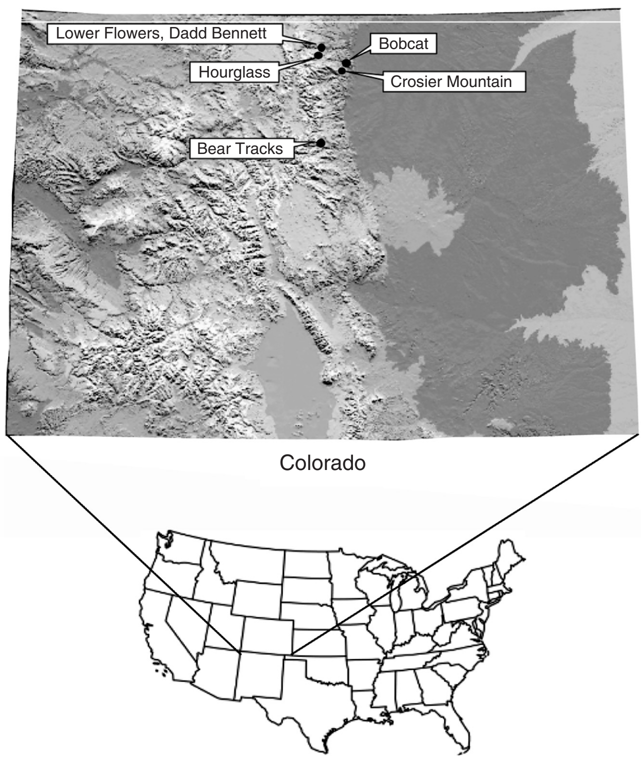

Fig. 1. Locations of the six fires in the northern Colorado Front Range used in this study.

burned in 1998 or late 1999. Five fires were in the more fire-prone mid-elevation zones dominated by ponderosa pine (*Pinus ponderosa*) and lodgepole pine (*Pinus contorta*). The 1998 Bear Tracks wildfire was above 2700 m and this area was dominated by subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) (Table 1).

The soils at all sites are coarse-textured, and they range from sandy loams to loamy sands. Soil types range from Typic Argicryolls to Ustic Haplocryalfs (E. Kelly, Colorado State University, personal communication, 2001). The underlying lithology includes coarse-textured granitic rocks, metamorphic rocks, sandstones, limestones and quartzite (Gary 1975).

The study plots within each fire were stratified by burn severity because the litter and soil conditions after burning are a primary control on post-fire runoff and erosion rates (DeBano *et al.* 1996). Burn severity was qualitatively classified in the field as high, moderate or low (Wells *et al.* 1979; USDA Forest Service 1995). High-severity sites are defined by the complete consumption of the surface organic layer and visible alteration of the structure or color of the surface layer of the underlying mineral soil. In moderate-severity sites the litter and duff layers are consumed but the underlying mineral soil is not visibly altered. In low-severity sites the litter and duff are only partially consumed so there is much less exposure of the mineral soil (Wells *et al.* 1979; USDA Forest Service 1995). In the older fires, severity was determined primarily by the amount and condition of the litter and underlying mineral soil, and secondarily by the condition of the tree crowns.

Mean annual precipitation (MAP) in the Colorado Front Range generally increases with elevation, and the estimated MAP for the different study sites ranges from ~380 to 500 mm year^{-1} (Miller *et al.* 1973; Gary 1975, 1985). From about mid-October to April or May, most of the precipitation falls as snow. Most of the rainfall in July and August is from short-duration, high-intensity convective storms (Gary 1975). Precipitation in the spring and fall is generally from longer-duration, lower-intensity frontal storms, and frequently shifts between rain and snow.

Methods

Sediment production

Sediment production rates were measured from 48 plots using sediment fences (Robichaud and Brown 2002) (Table 1; Fig. 2). The fences were constructed between fall 1999 and spring–summer 2000 on both planar hillslopes and in small swales. For the purpose of this study a swale is defined as a convergent area or hollow that generally was unchanneled before burning. For each plot the contributing area was defined by local topography. The average distance from the ridgetop to the sediment fences was 68 m, and the range was from 27 to ~130 m. As indicated by Table 1, the sediment fences were preferentially placed in areas burned at high severity because these areas typically have the highest post-fire sediment production rates and are therefore of greatest concern. Sixteen of the 48 fences were set up in the

Fig. 2. Typical sediment fence on a planar hillslope in an area burned at high severity in the Bobcat wildfire. Picture was taken ~15 months after burning in summer 2001.

Table 1. Study areas and number of plots by fire and fire severity

Fire	Type	Date burned	Area (ha)	Primary vegetation type	Elevation range (m)	No. plots: High severity	Moderate severity	Low severity or unburned	Total
Bobcat	Wildfire	June 2000	4289	Ponderosa pine	1670–2580	13	2	1	16
Dadd Bennett	Prescribed fire	January 2000	200	Ponderosa pine	2100–2730	0	3	2	5
Lower Flowers	Prescribed fire	November 1999	300	Ponderosa pine	2530–2940	4	4	2	10
Crosier Mountain	Prescribed fire	September 1998	1011	Ponderosa pine, lodgepole pine	2160–2580	4	1	0	5
Bear Tracks	Wildfire	June 1998	196	Ponderosa pine, subalpine fir, Engelmann spruce, lodgepole pine	2740–3050	3	0	2	5
Hourglass	Wildfire	July 1994	516	Lodgepole pine	2590–2930	5	1	1	7
Total						29	11	8	48

Bobcat fire, as this was the largest, most recent and most accessible fire.

The sediment fences were broadly U-shaped and installed transverse to the slope in order to pond surface runoff and capture the entrained sediment (Fig. 2). The fences were constructed from a geotextile fabric (Lumite®) attached to 1.2-m long pieces of steel rebar. The specific procedure is described at http://www.fs.fed.us/institute/middle_east/platte_pics/silt_fence.htm. A layer of fabric in front of the fence facilitated the identification and removal of the trapped sediment. Underflow was prevented by securing the upslope edge of the fabric to the mineral soil surface with large wire staples. On average, the sediment fences were 8 m long and could trap ~2–3 Mg of wet sediment. At some plots a second fence was installed to increase the sediment storage capacity, as excessive sediment loads overtopped seven fences in summer 2000 and six fences in summer 2001. The term 'sediment fence' is used to emphasize that the fences act as sediment traps rather than filters for capturing silt. Previous studies (Robichaud and Brown 2002), the coarse-textured soils, and our comparisons of the quantities of sediment captured in the first and second fences all indicate a high trap efficiency.

The fences were regularly checked for sediment after large storms and snowmelt events. The sediment was collected in 20-L buckets and weighed to the nearest 1/4 kg. Samples were taken to determine percentage moisture. The measured moisture content was used to convert the field-measured wet weights to a dry mass. As nearly all of the sediment was generated from summer rainstorms, the fences were generally not cleaned out between late fall and early spring. Because the study period spanned two summers and only one winter, the data generally are reported as summer and winter sediment yields, with summer being roughly from 1 June through 31 October.

The mass of sediment produced from each sediment fence was normalized by contributing area because contributing area explained 50–66% of the variability in sediment production when the data were stratified by fire, fire severity and year (Benavides-Solorio 2003). Mean sediment production rates were calculated by summing the sediment collected from the pertinent group of sediment fences and dividing by the total contributing area. The largest and most complete dataset is from the Bobcat fire in summer 2001 because the sediment from these fences was collected on a more frequent basis and can be related to specific storm events.

Site characteristics

The characteristics measured at each fence included contributing area, slope, aspect, hillslope position (swale or planar), soil texture, soil water repellency and percentage ground cover. Contributing area was determined by walking the topographically defined perimeter with a GeoExplorer II GPS unit (Trimble, Sunnyvale, CA, USA). Hillslope and axis gradients were measured with a clinometer, and the aspect of the hillslope or swale axis was determined with a compass.

Soil texture was determined from three samples taken at 0–5 cm depths within each contributing area. The three samples were composited, dried and sieved to determine the proportion of coarse material ($\geq$2 mm). The particle-size distribution of the fine fraction (<2 mm) was assessed by the hydrometer method (Gee and Bauder 1986) after removing the organic matter by hydrogen peroxide (Gee and Bauder 1986) or burning (Cambardella *et al.* 2001). The data from sieving and the hydrometer analysis were combined to determine the D_{95}, D_{84}, D_{75}, D_{50} and D_{16} (Scott 2000).

Soil water repellency was assessed at six locations within each contributing area at 1-cm intervals to a depth of 5 cm using the water drop penetration time (WDPT) (DeBano 1981). Observations were limited to 120 s. In contrast to the procedure followed by Huffman *et al.* (2001), measurements began at the surface of the ash or litter layer. WDPT was measured under the driest conditions possible in summer 2000 and summer 2001, and the data were treated as a continuous variable.

Each year the surface cover was characterized in mid to late summer at a minimum of 100 points. The points were systematically spaced along 5–10 equally spaced transects, and the surface cover at each point was classified as bare soil, litter, live vegetation, moss, rocks larger than 2 mm, or woody debris. Percentage ground cover was defined as 100 minus percentage bare soil.

Precipitation

Rainfall was measured with tipping-bucket rain gages installed near each set of sediment fences except at Bear Tracks. The number of recording rain gages ranged from one each for the Crosier, Hourglass and Lower Flowers fires to five for the Bobcat fire. Rainfall data from the gage at Crosier Mountain were used for the Bear Tracks fire as this was the closest and presumably most representative rain gage. Precipitation data were collected only from June to October ('summer'), as unshielded and unheated tipping-bucket rain gages cannot accurately measure snowfall (Doesken and Judson 1997; Yang *et al.* 1999). The Bobcat fire had a shorter rainfall record in summer 2000 than summer 2001 because the rain gages were not installed until after the fire had been extinguished by a mixture of rain and snow in late June. The shorter rainfall record in summer 2000 has little effect on the results because the Bobcat fire occurred after an exceptionally dry spring and early summer, and there was little evidence of erosion from the cold, low-intensity storm that helped extinguish the fire.

The kinetic energy and rainfall erosivity were calculated for each storm with at least 5 mm of precipitation, following Renard *et al.* (1997). Storms were separated by periods of at least 1 h with no rainfall. The threshold of 5 mm was selected because field observations indicated that storms with less than 5 mm of precipitation produced little or no sediment.

Statistical analysis

The sediment production data were log-transformed before statistical analyses to approximate a normal distribution (Ott and Longnecker 2001). One-way analysis of variance (ANOVA) was used to determine if there were significant differences in sediment production rates by fire severity, hillslope position (i.e. planar or swale), between fires for each year, and soil particle-size distributions. If there was a significant difference, multiple comparisons through least square means (LSmeans) were used to determine the significant differences by fire severity and between fires (SAS Institute 1999). LSmeans were used because this adjusts the mean values for significant covariates and enhances the ability to detect differences between groups.

The relationship between each independent variable and summer sediment production was initially assessed by simple linear regression. The General Linear Model (GLM) procedure was used to develop multivariate models for predicting post-fire summer sediment production, as this procedure considers both categorical and continuous variables (SAS Institute 1999). The data from all six fires were used to develop the models because the data from each fire were insufficient to develop and cross-validate multivariate models, and our goal was to develop more robust, regionally applicable models. A series of progressively simpler models was developed because land managers often lack the detailed site data collected in this study, and to quantify the declines in model accuracy as the number of predictive variables was decreased. Models were selected by maximizing R^2 values, and each independent variable had to be significant at $P \leq 0.05$. Model fit in absolute terms was evaluated by calculating the Root Mean Square Error (RMSE) using:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}, \quad (1)$$

where n is the number of observations, P_i is the predicted sediment yield for site i, and O_i is the observed value (Willmott *et al.* 1985). The multivariate models were validated with an independent dataset from 12 plots burned at high severity in the Bobcat fire (Wagenbrenner 2003). The validation process included a graphical comparison of measured *v.* predicted values, calculation of the least square error (LSE) using:

$$LSE = \sum_{i=1}^{n}(P_i - O_i)^2, \quad (2)$$

(DeCoursey *et al*. 1982; Sorooshian and Gupta 1995), and calculation of the standard error of the prediction (SEP) using:

$$SEP = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n - p}}, \quad (3)$$

where p is the number of parameters in the model being tested (Salas and Smith 1999). A regression line was fit to the plot of predicted *v.* observed data, and the slope of this line indicates the overall trend in the predicted values relative to the 1 : 1 line (Willmott *et al.* 1985).

Results

Rainfall

In summer 2000 the total rainfall at the different gages ranged from 115 to 219 mm (Table 2). Most sites had a similar amount of rainfall in summer 2001, but at Lower Flowers the rainfall was 20% lower than in summer 2000, while at Crosier Mountain the rainfall was 58% higher (Table 2). The number of storms per summer ranged from 56 to 121, but nearly 90% of these storms had less than 5 mm of rain (Table 2).

The number of storms per summer with at least 5 mm of rain ranged from 6 to 15 (Table 2). The maximum 30-min intensity for these storms was usually less than 30 mm h^{-1}, but a 30-min intensity of 60–70 mm h^{-1} was recorded for one storm in summer 2000 at Dadd Bennett and one storm in summer 2001 at Lower Flowers (Table 2).

Table 2. Total rainfall, number of storms, and characteristics of storms with at least 5 mm of rain for each fire in summer 2000 and summer 2001

Fire	Rain gage	Total rainfall (mm)		Total no. storms		Storms > 5 mm: No. storms		Max. I_{30} (mm h^{-1})		Erosivity (MJ mm ha^{-1} h^{-1})		Total erosivity (MJ mm ha^{-1} h^{-1})
		2000	2001	2000	2001	2000	2001	2000	2001	2000	2001	
Bobcat	Snowtop	150	201	73	97	9	9	17.6	26.0	220	303	523
	Galuchie	129	179	67	103	8	10	17.6	26.8	193	271	464
	Green Ridge	115	117	56	46	6	6	12.0	18.0	63	137	200
Dadd Bennett	Mom Gulch	173	172	84	117	9	9	70.6	33.0	812	369	1181
Lower Flowers	Lower F.	219	177	97	113	15	6	22.4	61.0	226	891	1117
Crosier Mountain	Crosier	159	252	83	95	10	13	12.8	27.2	90	608	698
Hourglass	Pingree Park	171	168	102	121	9	9	19.2	23.6	144	253	397

Summer rainfall erosivities varied much more than the amount of rainfall, as the total erosivities ranged from 63 to 891 MJ mm ha^{-1} h^{-1}. Most of the erosivity resulted from three to four high-intensity storms, and these generally occurred in August. Comparisons between years show that summer erosivities at the Bobcat and Hourglass fires were 50–100% higher in 2001 than in 2000 (Table 2). At Lower Flowers and Crosier Mountain the calculated erosivities for summer 2001 were, respectively, seven and four times higher than for summer 2000. Because the Dadd Bennett fire was subjected to an unusually high intensity storm in August 2000, this was the only site that had less erosivity in summer 2001 than summer 2000 (Table 2).

Soils

The percentage of coarse material (>2 mm) ranged from 5 to 56%, and most of this material was less than 4 mm in diameter. At all plots the fine fraction consisted of 60–80% sand and no more than 5% clay. Within the Bobcat fire, the Green Ridge plots had significantly coarser soils (79% sand, 19% silt and 2% clay) than the plots at Bobcat Gulch and Jug Gulch (62% sand, 34% silt and 4% clay); hence the data from these two areas were treated separately for certain analyses. There were no other consistent differences in soil texture between plots within a fire or between fires (Benavides-Solorio 2003).

There was little evidence of soil water repellency at the surface of the ash or residual litter (Table 3). In summer 2000 relatively strong soil water repellency was detected at 1–2 cm depths in the plots burned at high or moderate severity in the Bobcat, Lower Flowers, Dadd Bennett and Bear Tracks fires. There was some evidence of soil water repellency in the older Crosier Mountain fire, but very little evidence of soil water repellency in the much older Hourglass fire. For all plots the soil water repellency was weaker at 3, 4 and 5 cm than at 1–2 cm (Table 3). Comparisons between years generally showed weaker soil water repellency in 2001 than 2000 except at 1–3 cm depths in the high- and moderate-severity plots in the Bobcat fire (Table 3).

In general, the plots burned at low severity exhibited soil water repellency only at depths of 1–2 cm (Table 3). The decline in WDPT over time and differences between depths were not as clear or consistent for the plots burned at low severity, and this can be attributed to the much lower values of WDPT. The lack of soil water repellency in older fires and the declines in soil water repellency over time are consistent with the results of more detailed studies on these same fires using the critical surface tension test (Huffman *et al.* 2001; MacDonald and Huffman 2004). The observed longevity of soil water repellency on the high- and moderate-severity plots in the Bobcat fire is greater than reported by MacDonald and Huffman (2004), and this discrepancy may be due in part to differences in methodology and the associated definitions of soil water repellency (Doerr 1998).

Percentage cover

The amount of ground cover generally decreased with increasing fire severity and increased with time since burning (Table 4; Fig. 3). The recent Bobcat, Lower Flowers and Dadd Bennett fires all had less than 5% live vegetative cover in summer 2000, regardless of fire severity. In contrast, all of the plots in the three older fires had at least 20% live vegetative cover except for the high-severity plots in the 1998 Crosier Mountain fire. Other than the Lower Flowers prescribed fire, the plots burned at high severity generally had less than 10% litter, needlefall and woody debris. On plots that had recently burned at moderate or low severity, 19–63% of the ground surface in summer 2000 was covered with needlefall, residual litter and, to a lesser extent, woody debris (Table 4). On average, rocks larger than 2 mm accounted for 10–25% of the ground cover in each fire, except the Bobcat fire where the mean percentage rock cover was less than 6% (Table 4) (Benavides-Solorio 2003).

In summer 2000 the mean percentage bare soil in the plots burned at high severity in the Bobcat fire was over 90%. Plots that had recently burned at moderate severity generally had 50–60% bare soil. Areas burned at low severity generally had less than 30% bare soil (Table 4). By the end of year 2, which is typically the third summer after burning for wildfires in Colorado, the percentage bare soil in the areas burned at high severity had declined to less than 50%. Most of the decrease in percentage bare soil was due to a corresponding increase in the amount of live vegetation (Table 4). For each burn severity class there is a strong, non-linear decline in the amount of bare soil with time since burning (Fig. 3).

Contributing area, slope and aspect

The mean contributing area for the 48 sediment fences was 1250 m^2, and the range was from 190 to 6600 m^2. The mean contributing area for the 29 plots burned at high severity was 1300 m^2, compared to 1600 m^2 for the 11 plots burned at moderate severity and 660 m^2 for the eight plots burned at low severity. These differences were not significant, and the lower mean contributing area for the low-severity plots was due to the difficulty of finding topographically defined, contiguous areas that had burned at low severity. There was no significant difference in the mean contributing area for the fences on planar hillslopes *v.* the fences in swales.

Most of the plots had slopes of 25–45%. The overall mean was 31%, and the range was from 13 to 55%. There were no significant differences in mean slope by fire severity or between fires.

The aspect of the sediment fences was largely controlled by the aspects of each fire and the location of the access roads. The sediment fences were located on all aspects, but 81% of the plots had a northerly, easterly or south-easterly aspect (Benavides-Solorio 2003).

Table 3. Mean soil water repellency in seconds by fire, fire severity, depth and year

Values in parentheses are the standard deviation; – indicates that no sediment fence was installed for this severity. WDPT, water drop penetration time

Fire	Severity	No. plots	WDPT at surface (s)		WDPT at 1 cm (s)		WDPT at 2 cm (s)		WDPT at 3 cm (s)		WDPT at 4 cm (s)		WDPT at 5 cm (s)	
			2000	2001	2000	2001	2000	2001	2000	2001	2000	2001	2000	2001
Bobcat	High	13	2 (4)	0	63 (31)	78 (41)	54 (28)	78 (40)	30 (16)	35 (40)	16 (9)	14 (17)	11 (8)	4 (11)
	Moderate	2	45 (51)	0	81 (37)	120 (0)	68 (40)	110 (14)	53 (39)	80 (57)	41 (27)	30 (14)	24 (23)	7 (4)
	Low	1	4	0	23	120	21	100	4	10	2	10	3	0
Lower Flowers	High	4	2 (2)	0	78 (39)	53 (26)	63 (33)	43 (5)	28 (6)	0	10 (3)	0	13 (25)	0
	Moderate	4	0.5 (1)	0	63 (34)	38 (33)	55 (31)	40 (37)	23 (18)	10 (20)	5 (5)	0	1 (3)	0
	Low	2	0	0	15 (21)	15 (21)	60 (85)	20 (28)	25 (35)	0	5 (7)	0	0	0
Dadd Bennett	High	0	–	–	–	–	–	–	–	–	–	–	–	–
	Moderate	3	0	0	23 (6)	10 (17)	57 (25)	10 (17)	27 (15)	0	8 (3)	0	0	0
	Low	2	0	0	85 (21)	90 (14)	85 (7)	40 (14)	31 (16)	0	8 (4)	0	0	0
Crosier Mountain	High	4	5 (5)	0	26 (36)	8 (15)	51 (26)	30 (22)	30 (31)	3 (5)	17 (19)	0	11 (12)	0
	Moderate	1	0	0	32	0	56	0	73	0	41	0	24	0
	Low	0	–	–	–	–	–	–	–	–	–	–	–	–
Bear Tracks	High	3	12 (8)	2 (3)	100 (20)	63 (21)	113 (12)	37 (12)	50 (10)	8 (3)	14 (5)	3 (3)	3 (3)	0
	Moderate	0	–	–	–	–	–	–	–	–	–	–	–	–
	Low	2	0	0	50 (14)	13 (4)	30 (14)	5 (0)	8 (4)	0	2 (2)	0	0	0
Hourglass	High	5	0	0	0	2 (3)	16 (16)	2 (3)	2 (2)	0	0	0	0	0
	Moderate	1	0	0	0	0	0	0	0	0	0	0	0	0
	Low	1	10	0	50	0	20	0	5	0	0	0	0	0

Table 4. Percentage cover by fire, fire severity and year
– Indicates that no sediment fence was installed for this severity

Fire	Severity	Date burned	No. plots	Bare soil (%) 2000	Bare soil (%) 2001	Litter and woody debris (%) 2000	Litter and woody debris (%) 2001	Rocks (%) 2000	Rocks (%) 2001	Live vegetation (%) 2000	Live vegetation (%) 2001
Bobcat	High	June 2000	13	92	62	2	6	6	6	0	26
	Moderate		2	52	21	44	43	4	6	0	30
	Low		1	50	17	50	69	0	0	0	14
Dadd Bennett	High	January 2000	0	–	–	–	–	–	–	–	–
	Moderate		3	56	25	27	16	15	19	2	40
	Low		2	28	18	47	51	25	22	0	9
Lower Flowers	High	November 1999	4	62	41	27	33	10	9	1	17
	Moderate		4	51	29	29	30	16	18	4	23
	Low		2	21	16	63	66	13	6	3	12
Crosier Mountain	High	September 1998	4	47	20	8	6	23	18	22	56
	Moderate		1	36	7	24	28	14	8	26	57
	Low		0	–	–	–	–	–	–	–	–
Bear Tracks	High	June 1998	3	68	41	8	20	10	11	14	28
	Moderate		0	–	–	–	–	–	–	–	–
	Low		2	25	19	19	20	13	7	43	54
Hourglass	High	July 1994	5	27	19	12	14	22	20	39	47
	Moderate		1	38	29	3	6	4	2	55	63
	Low		1	3	1	35	41	23	18	39	40

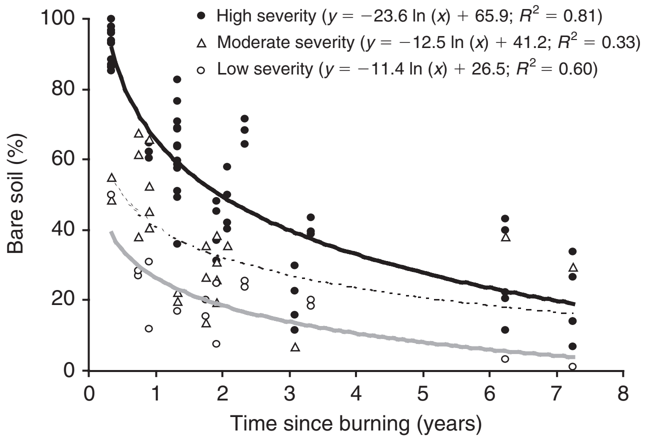

Fig. 3. Relationship between percentage bare soil and time since burning by fire severity. The solid line represents plots burned at high severity, the dotted line represents plots burned at moderate severity and the solid gray line represents plots burned at low severity.

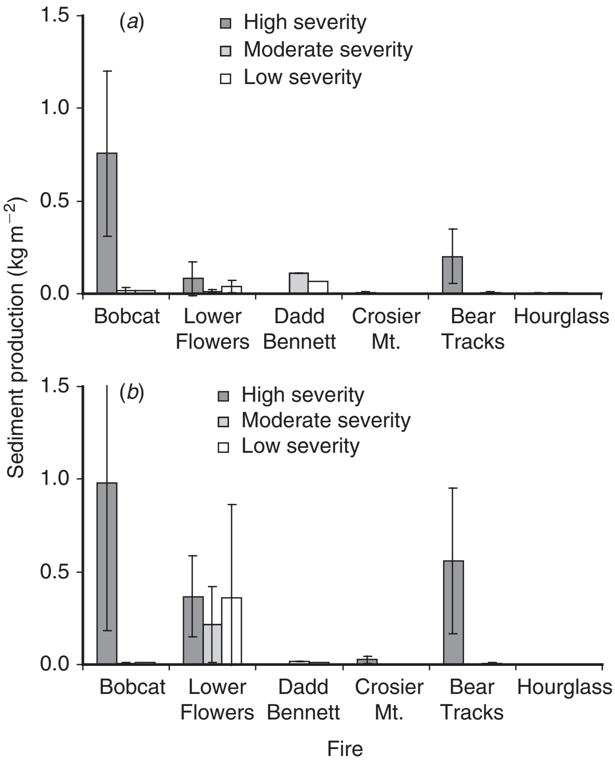

Fig. 4. Sediment production per unit area by fire and fire severity for: (*a*) June–October 2000 and (*b*) June–October 2001. Bars represent 1 standard deviation.

Sediment production

Nearly all of the sediment collected from the sediment fences was generated from high-intensity, summer convective rainstorms rather than frontal rainstorms or snowmelt. The total mass of sediment collected from all the fences was 14.8 Mg in summer 2000 and 18.6 Mg in summer 2001 (Fig. 4). From November 2000 through May 2001 total sediment production was only 1.2 Mg, or just 7% of the mean rate in summer. Field observations suggest that the sediment generated from November to May was due to rain storms or intermingled rain and snow storms rather than snowmelt. On average, the period from November to May accounts for only 10% of the annual erosivity in the northern Colorado Front Range (Renard *et al.* 1997), and this proportion is consistent with the sediment production data reported here.

In general, the highest sediment production rates were from plots that had recently burned at high severity (Fig. 4). The highest mean sediment production rate in summer 2000 was 0.76 kg m^{-2} for the plots that had burned at high severity in the June 2000 Bobcat wildfire (Fig. 4*a*). In comparison, the mean sediment production rate for the four plots burned at high severity in the recent prescribed fires was only 0.081 kg m^{-2}, or ~10% of the mean value from comparable plots in the Bobcat wildfire. The mean sediment production rate was less than 0.006 kg m^{-2} for the plots that had burned at high severity in the 1998 Crosier Mountain and 1994 Hourglass fires (Fig. 4*a*). The sediment production rates from the high-severity plots in the Bobcat fire were significantly higher than from the high-severity plots in each of these other fires.

The plots burned at moderate severity produced less sediment per unit area than the plots burned at high severity (Fig. 4). In summer 2000 the mean sediment production rate for the two plots that burned at moderate severity in the Bobcat wildfire was only 0.025 kg m^{-2}, or ~3% of the mean value from the high-severity plots. At Lower Flowers, the mean sediment production in summer 2000 for the four plots burned at moderate severity was only 0.014 kg m^{-2}, or one-sixth of the mean value for the four plots that burned at high severity. In contrast, the three moderate-severity plots at the nearby Dadd Bennett prescribed fire produced 0.085 kg m^{-2}, or six times as much sediment as the comparable plots in the nearby Lower Flowers prescribed fire (Fig. 4*a*). This difference can be attributed to the unusually intense rainstorm at Dadd Bennett in August 2000 (Table 2). As might be expected, the plots burned at moderate severity in the older fires produced very little sediment (Fig. 4).

In summer 2000 the mean sediment production rate for plots burned at low severity ranged from less than 0.004 kg m^{-2} at the Hourglass fire to 0.067 kg m^{-2} at the Dadd Bennett fire (Fig. 4*a*). These values are surprisingly similar to the sediment production rates from the plots burned at moderate severity that were not subjected to an extreme storm event, but the validity of these comparisons is hindered by the small sample sizes.

Sediment production rates in summer 2001 were generally higher than in summer 2000 (Fig. 4). For the high severity plots in the Bobcat fire, the mean sediment production rate in summer 2001 was 0.98 kg m^{-2}, or nearly 30% greater than in summer 2000. Similarly, the mean sediment production rate from high-severity plots was nearly three times higher in summer 2001 than in summer 2000 for the Bear Tracks fire, four times higher for the Lower Flowers prescribed fire, and five times higher for the Crosier Mountain fire (Fig. 4). Because both soil water repellency and percentage bare soil generally decreased from summer 2000 to summer 2001 (Tables 3, 4), the higher sediment production rates in summer 2001 can be attributed to the 50–400% increase in rainfall erosivity (Table 2).

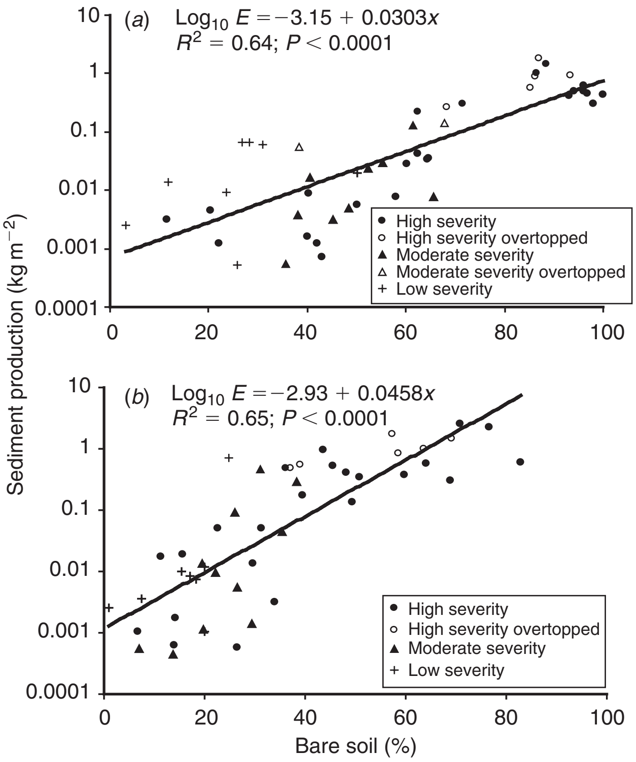

Fig. 5. Relationship between sediment production and percentage bare soil for: (*a*) summer 2000 and (*b*) summer 2001. For each equation E is the total sediment yield from June to October in kg m^{-2}, and x is percentage bare soil.

In contrast to the high-severity plots, sediment production rates generally were lower in summer 2001 than summer 2000 for the plots that had burned at moderate and low severity (Fig. 4). Other than Lower Flowers, the mean sediment production rates for plots burned at moderate and low severity were less than 0.005 kg m^{-2}. At Lower Flowers the plots burned at moderate severity generated 21 times more sediment than in summer 2000, and sediment production rates in the plots burned at low severity were 11 times higher (Fig. 4). Again these higher sediment production rates are best attributed to the four-fold increase in summer erosivity (Table 2).

Effect of percentage bare soil

Univariate regressions show that percentage bare soil can explain nearly two-thirds of the variability in sediment production rates for both summer 2000 and summer 2001 ($P < 0.0001$) (Fig. 5). Data from each summer are plotted separately because the slope of the equation derived from the 2001 data is significantly greater than the slope of the equation for summer 2000 ($P = 0.01$). A comparison of the two equations shows that the difference in predicted sediment yields increases from a factor of five at 30% bare soil to a

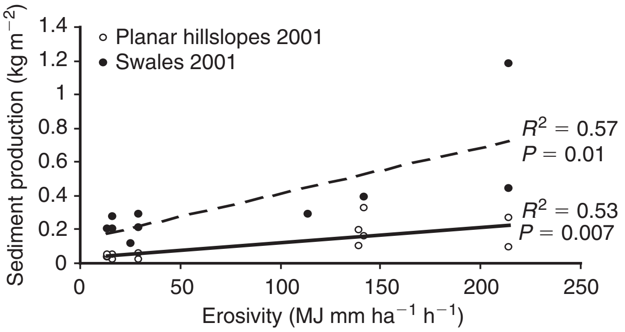

Fig. 6. Relationship between sediment production and rainfall erosivity by hillslope position for individual storms at Bobcat Gulch and Jug Gulch in the Bobcat fire in summer 2001. The dashed line represents the data from swales and the solid black line represents the data from planar hillslopes.

factor of nearly 30 at 80% bare soil. The differences in predicted sediment yields per unit area are much larger than the observed differences in rainfall erosivities, suggesting that other factors or processes are having a non-linear effect on post-fire sediment yields.

Effect of hillslope position

Sediment production rates per unit area generally were higher for the swales than the planar hillslopes, but this difference was significant only for plots with relatively high sediment yields. In summer 2000 the mean sediment production rate for severely burned swales in the Bobcat fire was 1.1 kg m^{-2}, compared to 0.53 kg m^{-2} for the severely burned plots on planar hillslopes. This difference was significant at $P = 0.01$, but the true difference was even larger because four of the swale fences were overtopped by a large storm in August 2000. The more detailed data from the Bobcat fire in summer 2001 shows that the plots in swales produced three to four times more sediment per unit area and rainfall erosivity than the plots on planar hillslopes, and this difference was significant at $P = 0.04$ (Fig. 6).

At the Bear Tracks wildfire, the mean sediment production rate for two swale plots was four times higher than a planar hillslope plot in summer 2000, and eight times higher in summer 2001. While these differences could not be statistically tested due to the lack of replication, the data help confirm that swales generally produce more sediment per unit area than the planar hillslopes. The small number of plots in the other fires precluded similar comparisons.

Effect of soil water repellency

Sediment production rates were positively correlated with WDPT at 1 and 2 cm depths for both summer 2000 and summer 2001. In each case the R^2 was less than 0.3 but the relationships were strongly significant ($P = 0.001$). The significance of these relationships was largely due to the plots that burned at high severity, as these plots generally had high sediment production rates and high WDPT (Table 4). Restricting the regression to the high-severity plots strengthened the relationships between sediment production and soil water repellency at both 1 and 2 cm ($R^2 \approx 0.4$; $P < 0.001$). Further analysis showed that the relationships between sediment production and soil water repellency were controlled largely by the data from the high-severity plots in the older Hourglass fire, as these plots had very low sediment production rates and very little evidence of soil water repellency. If the Hourglass data are excluded, there was no significant relationship between sediment production and soil water repellency for either the high-severity plots or the entire dataset.

Effect of rainfall erosivity

The high variability in sediment production rates and site conditions means that rainfall erosivity was not significantly related to sediment production for either summer 2000 or 2001 when all the plots were pooled. However, rainfall erosivity explains 57% of the storm-by-storm variability in the 2001 sediment production rates for the plots burned at high severity in the Bobcat fire (Fig. 6), and 46% of the variability in sediment production for the planar hillslopes in the Bobcat fire in summer 2000. Each of these relationships appears to be linear up to the maximum observed erosivity of ~215 MJ mm ha^{-1} h^{-1}.

The effect of rainfall erosivity on sediment production rates from larger storm events can be shown by comparing the data from the moderate-severity plots in the adjacent prescribed fires at Lower Flowers and Dadd Bennett. In summer 2000 the Dadd Bennett site was subjected to a storm with a maximum I_{30} of nearly 71 mm h^{-1}, and the total summer erosivity was over 800 MJ mm ha^{-1} h^{-1} (Table 2). The resulting mean sediment production rate from the plots burned at moderate severity was 0.085 kg m^{-2} (Fig. 4*a*). At Lower Flowers the total rainfall erosivity was only 226 MJ mm ha^{-1} h^{-1}, or 28% of the value at Dadd Bennett, and the mean sediment production rate from the plots burned at moderate severity was only one-sixth of the rate measured from the comparable plots at Dadd Bennett. In summer 2001 the situation was reversed, as Lower Flowers was subjected to a storm with a maximum I_{30} of nearly 61 mm h^{-1} and the total summer erosivity was nearly 900 MJ mm ha^{-1} h^{-1} (Table 2). The mean sediment production rate for the moderate-severity plots at Lower Flowers increased by more than 20 times to 0.30 kg m^{-2}. At Dadd Bennett the total erosivity was 369 MJ mm ha^{-1} h^{-1}, or 41% of the value from Lower Flowers, and the mean sediment production rate for the moderate-severity plots at Dadd Bennett was just one-seventh of the mean value at Lower Flowers (Fig. 4). Because each site was subjected to a large storm event, the differences in sediment production cannot be attributed to an inherent difference in site characteristics.

Table 5. Model parameters and statistics for the four models developed to predict post-fire sediment production per unit area
RMSE, root mean square error

Complete model (Model 1)		Constrained model for validation (Model 2)		Simplified three-parameter model (Model 3)		Simplified two-parameter model (Model 4)	
Variable	*P*-value	Variable	*P*-value	Variable	*P*-value	Variable	*P*-value
Fire severity	<0.0001	Fire severity	<0.0001	Fire severity	0.0012	Percentage bare soil	<0.0001
Percentage bare soil	<0.0001	Percentage bare soil	<0.0001	Percentage bare soil	<0.0001	Rainfall erosivity	<0.0001
Rainfall erosivity	<0.0001	Rainfall erosivity	<0.0001	Rainfall erosivity	<0.0001		
Water repellency at 1 cm	0.0016	Time since burning	0.0018				
D_{84}	0.0131						
Overall model	<0.0001	Overall model	<0.0001	Overall model	<0.0001	Overall model	<0.0001
R^2	0.77	R^2	0.73	R^2	0.70	R^2	0.65
RMSE	0.54	RMSE	0.58	RMSE	0.61	RMSE	0.65

The implication of these data is that sediment production rates increase non-linearly with increasing rainfall erosivity for the largest events.

Effect of soil particle size

Univariate analyses showed that the percentage of sand, silt or clay in the contributing area was not significantly related to sediment production. However, each of the three parameters representing the coarse end of the soil particle-size distribution (D_{95}, D_{84} and D_{75}) was inversely related to the log of sediment production ($R^2 = 0.16$–0.18; $P < 0.0001$). The decline in sediment production rates with increasing particle size may be attributed to the fact that larger particles are more difficult to detach and transport, and that larger particles may help protect the smaller particles against rainsplash, sheetwash and rill erosion (Renard *et al*. 1997). The observed decrease in sediment production with increasing particle size further suggests that soil water repellency is not an important control on sediment production, as fire-induced soil water repellency generally strengthens with increasing particle size (Huffman *et al*. 2001).

Modeling post-fire sediment production

A wide variety of models can be developed for predicting post-fire sediment production depending on the data available and the modeling goals. Initial efforts to develop predictive models for absolute (kg) and normalized (kg m^{-2}) sediment production rates yielded poor results. Log-transformation of the sediment production values was needed to normalize the distribution of the data and the residuals, and to improve the accuracy of the predictive models.

The best multivariate model for predicting normalized sediment production rates used the discrete variable of fire severity and four continuous variables (percentage bare soil, rainfall erosivity, soil water repellency at 1 cm, and the D_{84} of the soil) (Table 5). Each of these variables was significant at $P \leq 0.01$. This so-called 'complete' model had an R^2 of 0.77, an RMSE of 0.54 (Table 5), and a slight tendency to overpredict at low sediment production rates and underpredict at high sediment production rates (Fig. 7*a*). Eliminating the data from fences that overtopped had little effect on model structure or model coefficients. Similarly, excluding the data from the Bear Tracks wildfire, which lacked on-site rainfall data, had little effect. Hence the entire dataset was used for model development and validation.

Validation of the complete model was not possible because soil water repellency and particle-size data were not available for the 12 validation plots. Hence these two variables were excluded and a new 'constrained model' (Model 2) was developed. The four significant parameters in this model were percentage bare soil, rainfall erosivity, fire severity and time since burning (Table 5). This model had a slightly lower R^2 (0.73) and a slightly higher RMSE (0.58) than the complete model, and the same tendency to overpredict low sediment production rates and underpredict high sediment production rates (Table 5; Fig. 7*b*). Comparisons against the validation data indicate that Model 2 consistently underpredicts sediment production, and this underprediction increases slightly with increasing sediment production rates (Fig. 8*a*). The LSE for the validation data was 9.49 and the SEP was 0.34 log units, or about a factor of two in absolute terms (Table 6).

The best three-parameter model (Model 3) included fire severity, percentage bare soil and rainfall erosivity. This model had a slightly lower R^2 and a slightly higher RMSE than Model 2 (Table 5; Fig. 7*c*). The three-parameter model also tended to underpredict the validation data, but the slope of the regression was parallel to the 1 : 1 line (Fig. 8*b*). Both the LSE and the SEP were slightly better than for Model 2 (Table 6).

The best two-parameter model (Model 4) dropped the categorical variable of fire severity and used only the continuous variables of percentage bare soil and rainfall erosivity (Table 5). The R^2 decreased to 0.65 and the RMSE increased to 0.65 (Table 5; Fig. 7*d*). Validation showed a similar but slightly greater tendency to underpredict sediment production rates than Model 3 (Fig. 8*c*), and a slightly greater LSE and SEP (Table 6).

These results show the expected decline in R^2 with decreasing model complexity, but the decline in performance from Model 1 to Model 4 was surprisingly small (Tables 5, 6).

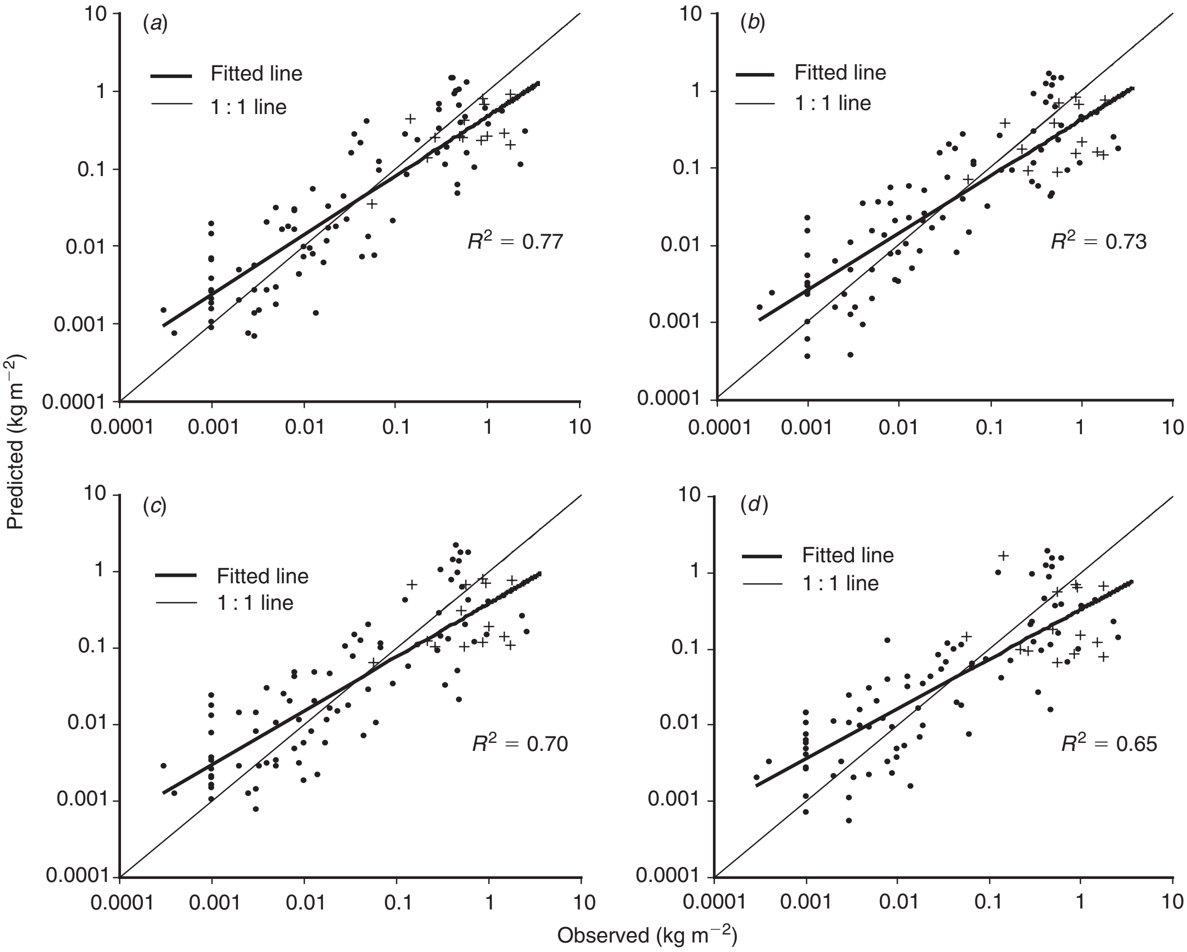

Fig. 7. Predicted *v.* observed sediment production values for the: (*a*) complete model, (*b*) constrained model, (*c*) three-parameter model, and (*d*) two-parameter model. The crosses represent data from overtopped fences.

Model calibration and validation both suggest that a relatively simple model using percentage bare soil and rainfall erosivity can do nearly as well in predicting post-fire sediment production rates as more complex models.

Discussion

Controls on sediment production

Both Fig. 4 and the multivariate modeling indicate that fire severity is one of the most important factors controlling post-fire soil erosion rates. This finding is consistent with studies from other areas (e.g. Campbell *et al.* 1977; Robichaud and Waldrop 1994; Pierson *et al.* 2002). The effect of fire severity on sediment production can be attributed primarily to its effects on the amount of bare soil, soil water repellency (Huffman *et al.* 2001), particle cohesion and surface roughness. The problem is that fire severity is a qualitative, categorical index. The advantages of fire severity are that it can be readily inferred from aerial photographs or remote sensing (RSAC 2004; van Wagtendonk *et al.* 2004), and maps of burn severity are commonly available after large wildfires.

Our results indicate that percentage bare soil is a much stronger predictor of sediment production rates than the categorical variable of fire severity. When all the data were pooled, percentage bare soil explained 64% of the variability in unit area sediment production rates in summer 2000 and 65% in summer 2001 (Fig. 5). Percentage bare soil also was retained in the two-parameter model while fire severity was dropped (Table 5). Previous work in the Colorado Front Range found the highest sediment flux rates when percentage bare soil was 85% or higher (Morris and Moses 1987). In this study the highest sediment production rates were from recently burned, high-severity sites with at least 60% bare soil (Fig. 5). Sediment production rates from the 1996 Hourglass fire were negligible, regardless of fire severity and rainfall erosivity (Fig. 4; Table 2), and this can be attributed to the fact that percentage bare soil was always less than 40% and percentage live vegetation was at least 39% (Table 3).

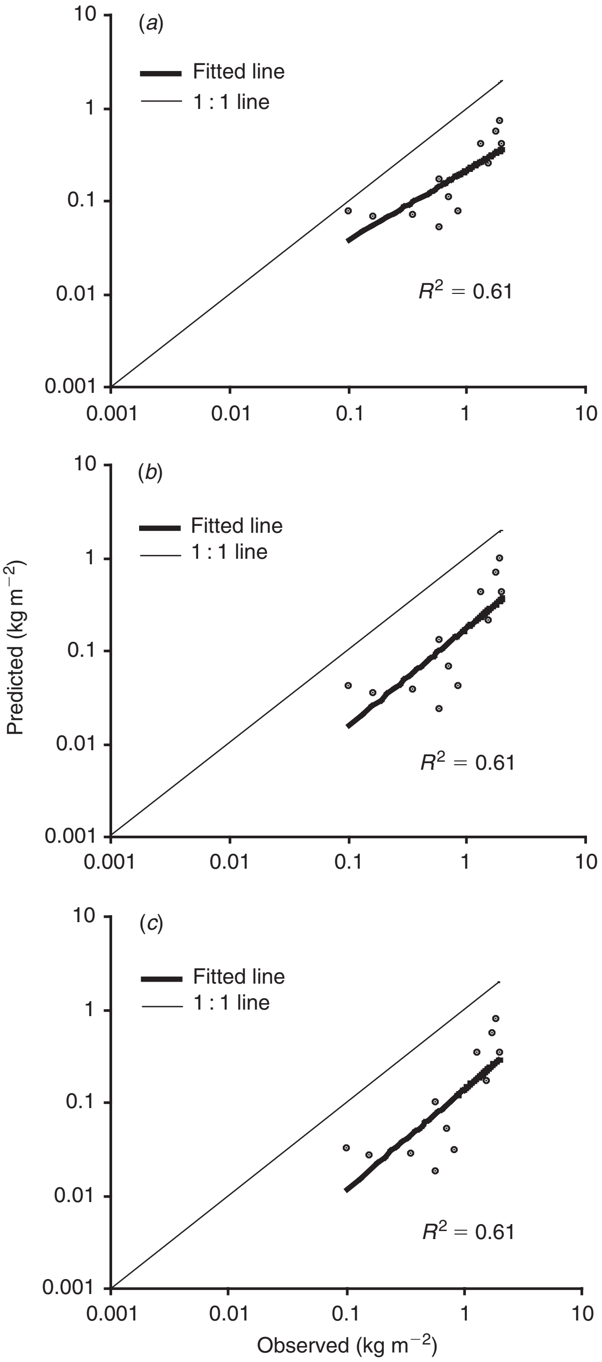

Fig. 8. Validation of three different sediment production models using an independent set of data for the: (*a*) constrained model, (*b*) three-parameter model, and (*c*) two-parameter model.

Percentage bare soil is a better predictor of post-fire erosion rates than fire severity because it is a continuous rather than a discrete variable, it is less subjective, and it directly reflects the increase in ground cover as sites recover. Percentage ground cover is strongly related to erosion rates because ground cover reduces the detachment and dispersal of soil particles by raindrop impact (Osborn 1953) and reduces surface runoff velocities (McNabb and Swanson 1990). From a management perspective, percentage bare soil (or percentage ground cover) is useful because it can be easily measured in the field and can be estimated by remote sensing (Miller *et al*. 2003). Alternatively, Fig. 3 shows that percentage bare soil can be predicted from fire severity and time since burning. Data on fire severity and time since burning are readily available to land managers on a spatially explicit basis. Land managers can use either the measured or predicted amounts of bare soil to help identify the areas that should be given higher priority for emergency rehabilitation treatments. Similarly, by tracking percentage bare soil over time, resource managers can identify which areas continue to have a high erosion risk.

If the amount of ground cover is specified or limited to a fairly narrow range, rainfall erosivity becomes the dominant control on post-fire erosion rates (e.g. Fig. 6). Some insights into the complex interactions between percentage bare soil, rainfall erosivity and sediment production can be obtained by selected comparisons between plots and over time. For the severely burned plots on the Bobcat fire, the mean percentage bare soil decreased from 92% in summer 2000 to 62% in summer 2001 (Table 3). Figure 5 and the multivariate equations in Table 6 indicate that this decline should have substantially reduced sediment production rates, but the mean sediment production rate in summer 2001 was 30% higher than in summer 2000 (Fig. 4). Since rainfall erosivity in summer 2001 was ~40% higher at most sites and 100% higher at Green Ridge (Table 2), these data indicate that there was insufficient vegetative recovery in the first year after burning to substantially reduce sediment production rates from the severely burned plots in the Bobcat fire (Fig. 5*b*).

By the second summer after burning the moderately burned plots in the Bobcat fire averaged 52% bare soil. The mean sediment production rate from these plots was only 0.025 kg m^{-2}, or 3.3% of the value from severely burned plots. This 30-fold difference in sediment production suggests that 48% ground cover was sufficient to significantly reduce post-fire erosion rates. Other studies have indicated that at least 70% ground cover is needed to reduce erosion effectively (Singer and Blackard 1978; Evans 1980).

While both the univariate analyses and the multivariate models indicate that percentage bare soil is the most important control on sediment production rates, exceptionally large storm events can initiate post-fire erosion even when there is relatively little bare soil. In summer 2001 the plots burned at moderate and low severity at Lower Flowers had a mean sediment production rate of 0.36 kg m^{-2} despite having 70–85% ground cover. Field observations indicate that the very large storm event on 7 July 2001 initiated rill erosion on the planar hillslopes above the sediment fences. In this event the type of ground cover also may have played a role, as ponderosa pine needles were the predominant ground cover.

Table 6. Regression equations for the four models and their performance relative to the validation data
E is total sediment yield from June to October in kg m^{-2}, BAR is percentage bare soil, R is the rainfall erosivity from June to October in MJ mm ha^{-1} h^{-1}, WR_1 is the soil water repellency in seconds at a depth of 1 cm, TSB is the time since burning in years; D_{84} is the diameter of soil particles at 84% of the cumulative distribution using a phi scale; LSE is least square error; SEP is standard error of the prediction

Model	Model number	n	Fire severity	Regression equation	Model R^2	Validation		
						R^2	LSE	SEP
Complete model	1	96	High	$\text{Log}_{10}E = -3.303 + 0.0283BAR + 0.00195R + 0.00504WR_1 + 0.136D_{84}$	0.77	Not validated		
			Moderate	$\text{Log}_{10}E = -3.977 + 0.0283BAR + 0.00195R + 0.00504WR_1 + 0.136D_{84}$				
			Low	$\text{Log}_{10}E = -3.515 + 0.0283BAR + 0.00195R + 0.00504WR_1 + 0.136D_{84}$				
Constrained model for validation	2	96	High	$\text{Log}_{10}E = -2.528 + 0.0247BAR + 0.00163R - 0.0119TSB$	0.73	0.61	9.49	0.34
			Moderate	$\text{Log}_{10}E = -3.320 + 0.0247BAR + 0.00163R - 0.0119TSB$				
			Low	$\text{Log}_{10}E = -2.839 + 0.0247BAR + 0.00163R - 0.0119TSB$				
Simplified three-parameter model	3	96	High	$\text{Log}_{10}E = -3.525 + 0.0349BAR + 0.00193R$	0.70	0.61	8.86	0.30
			Moderate	$\text{Log}_{10}E = -4.103 + 0.0349BAR + 0.00193R$				
			Low	$\text{Log}_{10}E = -3.507 + 0.0349BAR + 0.00193R$				
Simplified two-parameter model	4	96	All pooled	$\text{Log}_{10}E = -3.631 + 0.0358BAR + 0.00175R$	0.65	0.61	10.18	0.32

Laboratory studies have shown that a 40–70% cover of ponderosa pine needles is only moderately effective in preventing rill erosion on study plots subjected to 34 mm h^{-1} of simulated rainfall and additional overland flow (Pannkuk and Robichaud 2003). Ponderosa pine needles were less effective in preventing inter-rill erosion because the long, curved needles have poor contact with the soil and are less effective in slowing overland flow (Pannkuk and Robichaud 2003). At Lower Flowers the maximum I_{30} was 61 mm h^{-1}, and the resulting surface runoff apparently overwhelmed the ability of the ground cover to prevent rill erosion. On the Bobcat wildfire the decline in percentage bare soil was due largely to the growth of annual herbs with single stems, and the high sediment production rates in the second summer indicate that these plants also provided relatively little protection against rainsplash, sheetwash and rill erosion.

The effect of exceptionally large storms on sediment production rates can be further demonstrated by comparisons over time at Lower Flowers. In summer 2000 the plots burned at moderate severity averaged 51% bare soil and had a mean sediment production rate of 0.014 kg m^{-2} when subjected to a rainfall erosivity of 226 MJ mm ha^{-1} h^{-1}. In summer 2001 the rainfall erosivity was four times higher than in 2000, but the mean sediment production rate was ~17 times higher even though the mean percentage ground cover had increased from 49 to 71%. This non-linearity is in contrast to the data in Fig. 6, which indicate a linear relationship between low to moderate rainfall erosivity values and sediment production rates. The coefficients in the multivariate predictive models indicate that sediment production rates increase relatively slowly as rainfall erosivities approach 300 MJ mm ha^{-1} h^{-1}, and increase non-linearly beyond this point. For example, the estimated erosivity of the 10-year storm is 680 MJ mm ha^{-1} h^{-1}, or approximately twice the mean annual erosivity (Renard *et al.* 1997). According to the empirical equations in Table 6, this storm should generate four times as much sediment as a year with the mean annual erosivity of 300 MJ mm ha^{-1} h^{-1}. The 100-year storm event after the 1996 Buffalo Creek fire resulted in an estimated sediment yield of 6.8 kg m^{-2} year^{-1} from the Spring Creek catchment (Moody and Martin 2001), and this is nearly ten times the mean value from the high-severity plots on the Bobcat fire.

Models such as the Revised Universal Soil Loss Equation assume a linear relationship between rainfall erosivity and erosion (Renard *et al.* 1997), but recent work suggests that erosion predictions can be improved by incorporating a non-linear relationship between rainfall erosivity and erosion rates (Tran *et al.* 2001). Additional data from a variety of burned sites are needed to better quantify the complex interrelationships between sediment production, ground cover and rainfall erosivity, particularly for the more extreme storm events.

Sediment yield from wildfires v. *prescribed fires*

The mean sediment production rates from high-severity plots in the recent wildfires (Bobcat and Bear Tracks) were higher than the corresponding values from prescribed fires. The higher sediment production rates in the wildfires are probably due to a higher percentage of bare soil, as the entire canopy was consumed and there was little subsequent needlefall. The areas burned at high severity in wildfires also tended to be larger and more continuous. The prescribed fires typically had a small-scale, patchy distribution of fire severity, so the plots burned at high severity tended to receive some needlefall from nearby trees, and this probably helped reduce sediment production rates from all but the most severe storm events. A more patchy distribution of fire severity also will allow some of the runoff and sediment from high-severity patches to be captured in downslope areas that burned at lower severity. The patchy generation and capture of runoff and sediment in prescribed fires may be similar to the observed patterns in semi-arid environments (Dunkerley and Brown 1995; Reid *et al*. 1999).

Influence of topographic position and soil type

Data from the Bobcat and Bear Tracks fires indicate that swales produced at least two to three times more sediment per unit area than planar hillslopes. However, the categorical variable of slope position was not included in the predictive models, and this may be due to the high variability between plots, the lack of a topographic effect for the moderate- and low-severity sites, and the relative importance of other factors, particularly percentage cover and rainfall erosivity.

The higher sediment production rates from convergent areas can be attributed to the greater depth and velocity of overland flow. Surface runoff on planar hillslopes is likely to be sheetflow or concentrated in small rills during the higher-intensity rainstorms. The overland flow in swales is more likely to become concentrated in a single channel where it will have a greater capacity for detaching and transporting sediment (Knighton 1998). Moody and Martin (2001) estimated that 86% of the sediment yield after the Buffalo Creek fire was derived from rill and channel erosion rather than hillslope erosion.

Field observations in the Bobcat fire indicate that the granitic soils were more susceptible to rill erosion, whereas sheetwash dominated in the areas with metamorphic soils. Although a single soil property cannot accurately predict the susceptibility of a soil to rilling, soil aggregation and shear strength are two of the most important factors (Bryan 2000). Granitic soils generally have less aggregation and shear strength than the metamorphic soils (Soil Survey Staff 1999), and this may explain the higher rate of rilling in granitic areas. This indicates that more intensive erosion control efforts may be required in areas with granitic soils because of their greater susceptibility to rill erosion and higher erosion rates per unit area. Sites with unusually coarse soils also may produce sediment over longer time periods because the low water-holding capacity inhibits vegetative regrowth. Further research is needed to evaluate the relative importance of sheetwash *v.* rilling in post-fire erosion, the differences in erosion rates with topographic position and soil type, and the underlying processes causing these differences.

Model parameters and limitations

The predictive models developed here can help land managers calculate post-fire erosion risks and direct post-fire rehabilitation efforts to higher-risk areas. None of the models included percentage slope, and only the most complete model included a factor representing soil texture. Other studies have shown that slope is a key control on erosion rates (e.g. Kilinc and Richardson 1973; McCool *et al*. 1987; Fox and Bryan 1999), but most of the plots in this study had slopes of 25–45%. The limited range of slopes probably explains why the effect of slope was masked by the other controlling variables. Similarly, soil texture is generally regarded as an important control on erosion rates (Renard *et al*. 1997), but all of our study plots had coarse-textured soils (Benavides-Solorio 2003). Slope and texture could become important parameters if data were collected from a wider range of slopes and soils, but the plots in this study are representative of most forested areas at elevations of 1600–3000 m in the Colorado Front Range.

The simpler models are likely to be more useful to land managers because the predictive variables are readily available. Resource managers are unlikely to have spatially explicit data on soil water repellency and the complete particle-size distribution of the soil, and the use of simpler models causes a surprisingly small reduction in accuracy.

The basic relationships identified in this study should be applicable to other burned areas, but the empirical models can only be applied to sites with similar conditions. This means that the models will be most useful for forested areas in the Colorado Front Range with coarse-textured soils and slope ranges of ~15–50%. The empirical models also are subject to the limitations of the field data. In particular, the sediment production rates are probably underestimated because sediment seven fences were overtopped in summer 2000 and six sediment fences were overtopped in summer 2001 (Figs 5, 7). The reported sediment production rates also may be biased, as in summer 2000 the total erosivity was below the long-term mean of ~340 MJ mm ha^{-1} h^{-1} (Renard *et al*. 1997) at all sites except Dadd Bennett (Table 2). In 2001 the rainfall erosivities were below the long-term mean at each gage on the Bobcat fire and the Hourglass fire, but above average at the other sites. The problem is that the higher erosivities in summer 2001 probably do not compensate for the lower erosivities in summer 2000, as most plots had substantially more ground cover in 2001 and therefore produced less sediment despite the higher erosivities.

The strong dependence of sediment production rates on rainfall erosivity, when combined with the unpredictability of future storm events, mean that predicted post-fire erosion rates should be probabilistic rather than deterministic. Because the empirical models in Table 6 allow land managers to predict post-fire sediment production as a function of rainfall erosivity, an immediate need is to provide land managers with spatially explicit probabilities of different rainfall erosivity values. A second need is to determine the characteristic size of the convective storms that generate most of the erosivity, as the size of these storms will determine the maximum spatial scale for applying the models developed in this study. At larger spatial scales the maximum unit area runoff and sediment production rates should decline quite rapidly because the highest intensity storms cover a relatively small area.

Despite these limitations, the models developed here can provide a first-order estimate of post-fire sediment production rates in the Colorado Front Range and similar environments. More importantly, the multivariate analyses provide new and useful insights into the relative importance of the different controlling variables and their interactions.

Conclusions

Sediment production rates were measured over two summers and one winter from 48 hillslope-scale plots on three wild and three prescribed fires. Approximately 90% of the sediment was generated from high-intensity summer rainstorms, and only ~10% was due to frontal rainstorms and snowmelt between November and May.

The highest mean sediment production rates were 0.8–1.0 kg m^{-2} from plots burned at high severity in recent wildfires. While there was considerable variability between plots and between fires, the sediment production rates from plots burned at moderate and low severity were generally much lower than the values from plots burned at high severity. High-severity plots in recent wildfires produced at least 2.5 times more sediment than the corresponding plots in recent prescribed fires. The lower sediment production rates in prescribed fires are attributed in part to the higher amounts of ground cover stemming from post-fire needlefall.

By 6 years after burning, sediment production rates were very low and comparable to the sediment production rates measured from low-severity plots in the more recent fires. Efforts to characterize the decline in sediment production rates with time since burning were hindered by the confounding effects of rainfall erosivity and the lack of data from plots 3–6 years after burning.

The dominant control on sediment production rates is the amount of bare soil, and this can be predicted from fire severity and time since burning. Rainfall erosivity is the second most important control on sediment production rates, and the data suggest that sediment production rates increase linearly with rainfall erosivity for the small and moderate-sized storms, and non-linearly for the more extreme storm events. Sediment production rates per unit area were higher from convergent swales than planar hillslopes, and this is attributed to the concentration of runoff and resulting increase in rill erosion.

Approximately 77% of the variability in sediment production rates per unit area could be explained by a five-parameter empirical model that included percentage bare soil, rainfall erosivity, fire severity, soil water repellency at 1 cm, and the D_{84} of the soils. Progressively simpler models explained less of the variability, although a two-parameter model using percentage bare soil and rainfall erosivity still explained 65% of the variability in sediment production. Validation against an independent dataset confirmed the usefulness of the different models for predicting post-fire sediment production.

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