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Measuring effectiveness of three postfire hillslope erosion barrier treatments, western Montana, USA†

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Abstract:

After the Valley Complex Fire burned 86 000 ha in western Montana in 2000, two studies were conducted to determine the effectiveness of contour-felled log, straw wattle, and hand-dug contour trench erosion barriers in mitigating postfire runoff and erosion. Sixteen plots were located across a steep, severely burned slope, with a single barrier installed in 12 plots (four per treatment) and four plots left untreated as controls. In a rainfall-plus-inflow simulation, 26 mm h^{-1} rainfall was applied to each plot for 1 h and 48 L min^{-1} of overland flow was added for the last 15 min. Total runoff from the contour-felled log (0·58 mm) and straw wattle (0·40 mm) plots was significantly less than from the control plots (2·0 mm), but the contour trench plots (1·3 mm) showed no difference. The total sediment yield from the straw wattle plots (0·21 Mg ha^{-1}) was significantly less than the control plots (2·2 Mg ha^{-1}); the sediment yields in the contour-felled log plots (0·58 Mg ha^{-1}) and the contour trench plots (2·5 Mg ha^{-1}) were not significantly different.

After the simulations, sediment fences were installed to trap sediment eroded by natural rainfall. During the subsequent 3 years, sediment yields from individual events increased significantly with increasing 10 min maximum intensity and rainfall amounts. High-intensity rainfall occurred early in the study and the erosion barriers were filled with sediment. There were no significant differences in event or annual sediment yields among treated and control plots. In 2001, the overall mean annual sediment yield was 21 Mg ha^{-1}; this value declined significantly to 0·6 Mg ha^{-1} in 2002 and 0·2 Mg ha^{-1} in 2003. The erosion barrier sediment storage used was less than the total available storage capacity; runoff and sediment were observed going over the top and around the ends of the barriers even when the barriers were less than half filled. Published in 2007 by John Wiley & Sons, Ltd.

KEY WORDS erosion mitigation; silt fence; contour-felled log; straw wattles; contour trenches; rainfall simulation

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INTRODUCTION

Wildfires are a significant part of the natural processes that create and maintain forested ecosystems, especially in the western USA (Agee, 1993), but also near the Mediterranean Sea (Imeson *et al.*, 1992; Inbar *et al.*, 1998; Cerda and Lasanta, 2005), in Australia (Prosser and Williams, 1998; Townsend and Douglas, 2000), and other areas. However, fire effects, as well as ecosystem recovery rates, are widely variable depending on location, climate, topography, soil type, and fire severity and extent. Increases in postfire runoff and erosion, and the subsequent increased risk of flooding and sedimentation, are major concerns to land managers. The effects of postfire flooding and sedimentation can be widespread, threatening life, property, and natural resources both within and outside of the burned area (Robichaud *et al.*, 2000). Postfire erosion by water can range from 0·01 Mg ha^{-1} $year^{-1}$ in flat terrain burned at low severity with low-intensity rainfall to 38 Mg ha^{-1} $year^{-1}$ in steep terrain burned at high severity that is impacted by high-intensity thunderstorms (Robichaud *et al.*, 2000; Spigel and Robichaud, 2007).

In an effort to mitigate the increased risk of runoff and erosion following a fire, land managers often install treatments to stabilize burned areas. Postfire assessment teams determine the (1) burn severity; (2) values at risk, such as life, property, water supplies, etc.; (3) expected hydrologic and erosion responses; and (4) the need for postfire treatments to reduce the hazards of flooding and erosion (Robichaud *et al.*, 2000). Given that increased postfire runoff and erosion are inversely related to the amount of unconsumed vegetation and organic material left protecting the mineral soil, many treatments, such as mulches and seeding, are designed to increase ground or vegetative cover (Robichaud *et al.*, 2000). Other treatments, such as erosion barriers (e.g. contour-felled logs, straw wattles, contour trenches, silt fences, etc.), are designed to slow runoff and store eroded sediment on the hillslopes, thereby decreasing the runoff's erosive energy, increasing infiltration, and reducing downstream sedimentation (Robichaud *et al.*, 2000). However, the effects of these postfire treatments on runoff have not

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been systematically tested, and their overall efficacy is inconclusive (Robichaud *et al*., 2000; General Accounting Office, 2003; Robichaud *et al*., 2003).

Seeding, mulching, and erosion barriers are the most common types of postfire treatment applied to burned hillslopes. Of the three treatment types, the fewest data are available for erosion barrier treatments (Robichaud *et al*., 2000). Two contour-felled log erosion barrier studies (McCammon and Hughes, 1980; Miles *et al*., 1989) attempted to quantify treatment effectiveness by estimating the amount of sediment stored behind the erosion barriers; however, they did not measure changes in postfire runoff, infiltration, or sediment movement. More recently, two studies used small, burned, paired watersheds to measure the effectiveness of contour-felled log erosion barriers after the 1998 North 25 Mile Fire in Washington (Robichaud, 2000a) and the 1999 Mixing Fire in southern California (Wohlgemuth *et al*., 2001). In these studies, there was either no difference in the first postfire year sediment yields between the paired watersheds (Robichaud, 2000a), or the treated watershed produced more runoff and sediment than the control (Wohlgemuth *et al*., 2001). The lack of effectiveness of the contour-felled log erosion barriers was attributed to rainfall with greater intensity (Robichaud, 2000a) or shallower soils and a resultant lower water-holding capacity (Wohlgemuth *et al*., 2001) in the treated watersheds. In a 3-year study after the 2000 Bobcat Fire in Colorado, the calculated storage capacity of the contour-felled log erosion barriers was greater than the sediment produced in an average year (Wagenbrenner *et al*., 2006). However, this qualified success is highly dependent on the magnitude and timing of the rain events affecting the hillslopes, as well as the size, density, and quality of the contour-felled log installation. Gartner (2003) examined the effectiveness of the contour-felled log erosion barrier treatment at several spatial scales after the 2000 Hi Meadows Fire in Colorado and found that the treatment reduced sediment yields at the hillslope ($\sim$400 m^2) and catchment (16 ha) scales but not at the subcatchment (1–5 ha) or plot (1–5 m^2) scales. Following the 2000 Cerro Grande Fire in New Mexico, Dean (2001) measured postfire reductions in sediment yields of 77% in 2000 and 96% in 2001 from a combination treatment of seed, straw mulch, and contour-felled log erosion barriers, but there was no determination of the contributions of each treatment to the measured reductions.

Several qualitative monitoring reports suggested that erosion barriers could be effective at slowing runoff and trapping sediment if they were installed correctly, did not fail, and had sufficient sediment-holding capacity to remain effective until the postfire erosion rates stabilized (Robichaud *et al*., 2000). Generally, positive reports of machine-dug contour trenching (a type of erosion barrier) effectiveness included reduction in peak flows for short-duration, high-intensity thunderstorms (DeByle, 1970), improved revegetation but no reduction in water yield (Doty, 1970), and an 80% reduction in first-year sediment yields (Costales and Costales, 1984).

Measuring erosion from natural rainfall requires adjustments to account for the variability and random nature of the rain events. Even when hillslope plots are near one another, natural rainfall can vary between them (Spigel and Robichaud, 2007). Also, in periods of low precipitation, sufficient rainfall to produce measurable erosion may not occur. This can be especially challenging when measuring erosion after fires, because the 'average' rainfall-induced erosion during the first one to three postfire years is critical for determining and modelling the recovery process or predicting postfire rehabilitation treatment effectiveness (Elliot *et al*., 2001). To provide equivalent and sufficient rainfall inputs, rainfall simulators have been developed and used in laboratory and agricultural field experiments and, more recently, to measure and monitor fire effects, such as increased runoff and erosion rates (Robichaud, 1996; Benavides-Solorio and MacDonald, 2001, 2002; Pierson *et al*., 2001). However, rainfall simulators are limited in their ability to duplicate the characteristics of natural rainfall, such as the range in drop sizes and kinetic energy (Meyer and Harmon 1979; Meyer, 1994; Foltz *et al*., 1995). To measure the effects of concentrated flow on a hillslope, simulated inflow experiments may be used. Inflow rates are selected to mimic a selected rainfall intensity, runoff ratio, and contributing area above the inflow point. Results from these tests can be used to predict the hillslope response to overland flow at that location (Laflen *et al*., 1991).

An opportunity to measure the effectiveness of erosion barriers in mitigating postfire runoff and erosion occurred after the 2000 Valley Complex Fire burned 86 000 ha in the Bitterroot Valley of western Montana (Figure 1). Within the fire area, the burn severity classification was 38% high, 22% moderate, and 40% low or unburned, and 2370 ha of land burned at high severity received postfire treatments (including 198 ha of contour-felled logs and 297 ha of straw wattles) (USDA Forest Service, 2000).

Hillslope plots in an area burned by the Valley Complex Fire were used to measure: (1) runoff rates and sediment yields from simulated rainfall and inflow; (2) sediment yields from natural rainfall to determine typical postfire sediment yields for this region and changes in sediment yields over time; and (3) the effects of contour-felled logs, straw wattles, and contour trenches on runoff rates and sediment yields.

METHODS

Experimental design and site description

A randomized complete block design was used with four treatments (contour-felled logs, straw wattles, contour trenches, and untreated controls) and four replicates on 16 bounded plots (A–Q) measuring 5 m× 20 m. A single erosion barrier spanned the width of each plot and was installed approximately 18 m from the top of each plot (Figure 1) using standard specifications and installation density of 100 barriers per hectare (USDA Forest Service, 2000).

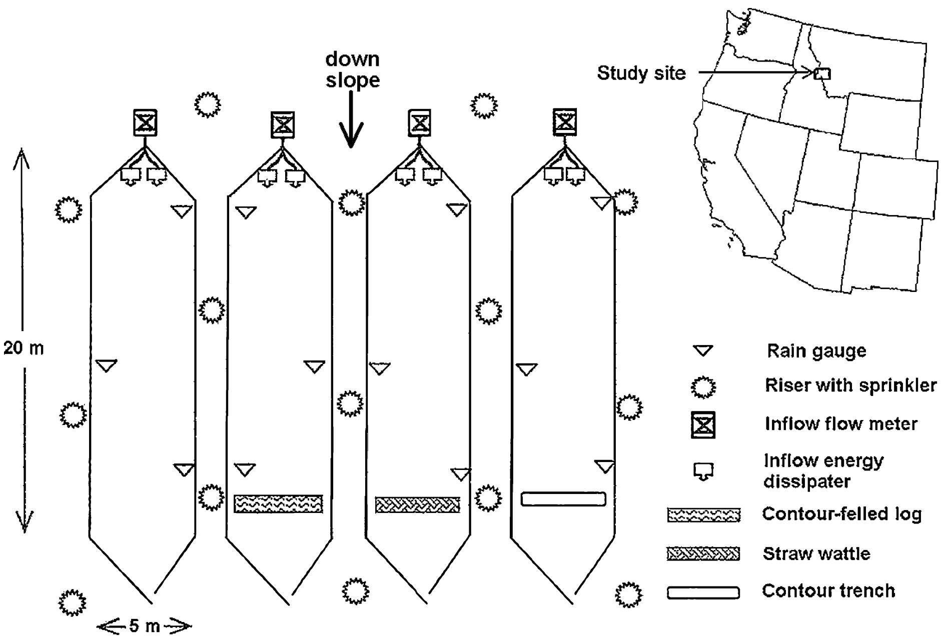

Figure 1. A map of the western USA with the study site located, and a diagram of four plots showing the general placement of the rain/inflow apparatus as it was used for each run of the experiment. The 16 plots were divided into four sets and simulations were conducted simultaneously on four adjacent plots as shown

The plots were established 2 weeks after the 2000 Valley Complex Fire in an area that burned at high severity. The 16 plots were located across a steep hillslope with a mean slope of 57% (range 52–61%), an east aspect, and an elevation of 1618 m. The soil was classified as a *superactive loamy-skeletal, mixed, typic haplustalf* (Macmeal soil series) (USDA Natural Resources Conservation Service, 2006) with a surface texture of gravelly sandy loam and parent material of weathered fine-grained granite (K. McBride, Bitterroot National Forest, personal communication, 5 January 2002). Prior to the wildfire, the dominant vegetation was Douglas fir (*Pseudotsuga menziesii*) with an understory of ninebark (*Physocarpus malvaceus*) and pinegrass (*Calamagrostis rubescens*). The 26-year mean annual precipitation at the Saddle Mountain snow telemetry station (elevation 2400 m), 5 km south of the study site, is 925 mm, and only 18% of this falls between June and September (Natural Resources Conservation Service, 2005).

Simulated rainfall and inflow experiment

In August 2000, a simulated rainfall and inflow experiment was conducted on the 16 plots. No natural rainfall had occurred since the fire and the soil was dry. The soil water repellency was determined using the water drop penetration time (WDPT) test (Krammes and DeBano, 1965; Doerr, 1998) prior to the start of the simulated rainfall at 10 points within each plot. WDPT measurements were made at the soil surface and at 10 mm intervals below the surface down to 50 mm. The proportion of water-repellent soil within a plot was the percentage of water-repellent test results with WDPT tests greater than 5 s (following DeBano (1981)). In addition, the depth with maximum soil water repellency was determined for each plot using WDPT test results from each point and depth and averaging them over each plot. Ocular estimates of ground cover were made on three 1 m^2 representative areas, which were used to apportion the plot into categories of ground cover: none (bare soil); gravel ($>$19 mm); cobble; litter; basal vegetation; and woody debris. Samples of the top 3 cm of soil were taken to measure antecedent moisture content and particle size distribution (Gardner, 1986; Gee and Bauder, 1986). The median particle size D_{50} and the 84th (D_{84}) and 16th (D_{16}) percentiles were used to compare surface and eroded sediment distributions. Three wedge-type rain gauges were placed in each plot to measure the rainfall distribution from the simulator (Figure 1).

Each contour-felled log and straw wattle erosion barrier was measured to determine the overall length, diameter, and slope from end-to-end (Figure 2). The storage volume of each erosion barrier was calculated by measuring the width and depth of the storage space and assuming a triangular cross-section for the length of the erosion barrier. The amount of ground contact between the erosion barrier and the hillslope was visually estimated.

Rain with a 60 min average intensity of 26 mm h^{-1} was applied simultaneously to four plots for 1 h using a CSU-type rainfall simulator (Holland, 1969) (Figure 1). The median raindrop diameter for a CSU-type simulator was reported as 1·2 mm (Neff, 1979) versus 2·2 mm for natural rainfall at the same rate (Laws and Parsons, 1943). Also, the elevation of the nozzles in the current study was approximately 80% of that needed to attain terminal velocity for this drop size (Laws, 1941). Because of these physical differences, the erosive energy was less than that of natural rainfall at the same rate.

For the last 15 min of the rainfall experiment, inflow of 48 L min^{-1} (29 mm h^{-1} if applied to the whole plot) was added to each plot (Elliot *et al.*, 1989). The simulated

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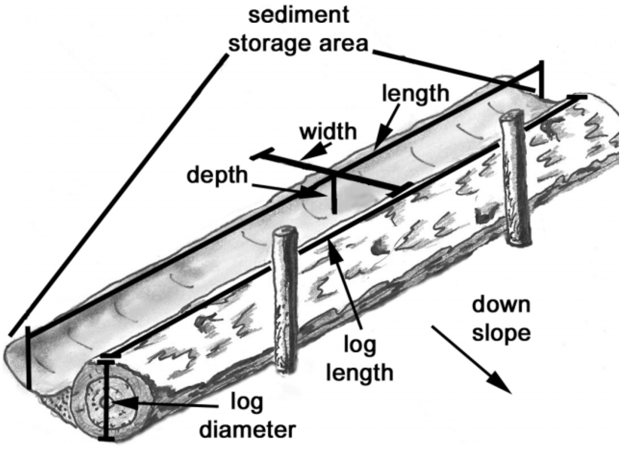

Figure 2. Schematic of measurements made on straw wattles and contour-felled logs to calculate the sediment storage capacity of each erosion barrier

Figure 3. A photograph of the rainfall simulation experiment in progress. Three plots are visible in the photograph: the nearest plot is treated with a contour-fell log, the middle plot is untreated, the far plot is treated with a straw wattle

inflow was distributed through two energy dissipaters spaced approximately 2 m apart at the top of each plot (Figure 1). During the first 30 min of each simulation, runoff samples were collected at the outlet of each plot for approximately 45 s of every minute. After 30 min, samples were collected every other minute until runoff stopped.

The runoff volume and dry sediment weight were measured for each sample (Gardner, 1986) and then summed to get totals for each plot. Total runoff and sediment produced were calculated by integrating the sampled rates over the duration of the simulation. After each simulation was completed, the depth and width of all rills were measured at 4 m and 15 m from the top of the plot and used to determine the total rill cross-sectional area in each plot. The sediment stored by each erosion barrier was removed, dried, and weighed.

During the first simulations (plots A–D), the water pressure in the supply to the simulator's nozzles (Figure 3) dropped for approximately 15 min because of problems with the secondary storage tanks and supply hoses; consequently, rainfall was applied for an additional 15 min before the final 15 min rainfall-plus-inflow period began. For analysis of these four plots, the measurements from the rainfall-only period were truncated at 45 min, at which point the rainfall-plus-inflow measurements were appended.

Runoff from untreated control plot I and contour trench plot K was observed flowing into burned out root holes and gaps between rocks within the plots. Because the lack of runoff at the plot outlet was the result of these observable differences in the surface characteristics of the plots rather than rehabilitation treatments being tested, the results from these two plots were not included in the analysis.

Natural rainfall erosion study

In October 2000 sediment fences were installed at the outlet of each plot to capture sediment produced by natural rainfall (Robichaud and Brown, 2002). The plots received no measurable precipitation between the simulation experiments and the installation of the sediment fences. Ground cover estimates were repeated in August 2001, September 2002, and July 2003. An area-weighted canopy cover value also was estimated on these occasions by visually partitioning each plot into areas of similar cover and estimating the proportion of each area covered by vegetation (following O'Brien and Van Hooser (1983)). WDPT tests were repeated in half of the plots in 2003.

Natural precipitation at the site was measured using a recording tipping-bucket rain gauge. Rain events were separated by a 6 h period with no rainfall, and the total rainfall, duration, and 10 min and 30 min maximum rainfall intensities (I_{10} and I_{30} respectively) were calculated for each event. When more than one rain event occurred between site visits, the event with the greatest I_{10} was used to represent the sediment-producing events. For three sediment-producing events with missing data, the Laird Creek rain gauge, 14 km northwest of the site, was used to calculate the rainfall characteristics. Return periods for the rain events were calculated using a precipitation–frequency atlas (Miller *et al.*, 1973).

Sediment collected in the fences was periodically removed, weighed, and sampled. Sediment samples were dried to determine the water content, particle size distribution, and dry sediment weight. When sediment accumulation was less than 3 kg, all of the accumulated sediment, rather than a sample, was processed. Event sediment yields within each calendar year were summed to produce annual sediment yields.

After three rain events in 2001 the amount of accumulated sediment in the erosion barriers was estimated visually and observations of the functionality of the erosion barriers were made. The estimated volume of stored sediment was converted to mass using a bulk density of 1400 kg m^{-3}. The efficiency E (%) of the erosion barrier treatments was calculated as

$$E = \frac{M_B}{M_B + M_F} \times 100 \qquad (1)$$

where M_{B} (kg) is the cumulative sediment stored by the erosion barrier and M_{F} (kg) is the cumulative sediment removed from the sediment fence.

Statistical analysis

A series of mixed model analyses were conducted. Each analysis had treatment as a fixed effect and replicate as a random effect (Littell *et al.*, 1996). If the overall F-test for treatment was significant, then differences among treatments were tested using least-significant differences. The dry sediment mass and runoff were divided by the plot area to determine area-weighted sediment yields, runoff rates, and peak runoff rates. These values, as well as peak sediment concentrations, were log-transformed before analysis, since their distributions were approximately log–normal (Ott, 1993). For all tests, $\alpha = 0{\cdot}05$. Covariates evaluated in each analysis included plot slope, ground cover, and occurrence of water repellency prior to the rainfall simulation.

The total sediment yield and runoff produced for each simulation were calculated for the rain-only portion of the simulation (0–45 min), the rainfall-plus-inflow portion (45 min to the end of runoff), and for a combination of both. These variables, as well as the time to runoff, rill cross-sectional area, peak sediment concentration, peak runoff rate, time to peak runoff, and sediment stored in the erosion barrier, were then tested for differences among treatments and effect of the covariates.

In the natural rainfall experiment, event-based and annual sediment yields were treated as repeated measures with the plot as the subject and the number of days or years since the fire as the repeated period. For the event-based sediment yield models, covariates also included total rainfall, I_{10}, I_{30}, canopy cover, and the total rill cross-sectional area, total runoff, and total sediment yield from the rainfall simulations. Similar analyses were used to test for differences in ground and canopy cover among treatments and years and for differences in particle size distributions between the composite soil samples and the sediment samples.

RESULTS AND DISCUSSION

Rainfall and inflow simulation

During the rainfall-only portion of the rainfall simulation experiments, runoff was produced in all but two of the 16 plots (contour-felled plot B and contour trench plot E); however, the runoff rates and sediment concentrations were low (Figures 4 and 5), and no differences in time to initial runoff, total runoff, or sediment yields between treatments were measured during this portion of the experiment. The low runoff and sediment yields during the rainfall-only portion of the simulation experiment were the result of the low energy of the rain from the CSU-type simulator (Neff, 1979), since the nominal application rate was equivalent to a 25-year 1 h storm and natural storms of this intensity produced greater erosion rates in the current natural erosion study as well as in another nearby study (Spigel and Robichaud, 2007). The interruption in rainfall during the first simulations (plots A–D) produced a lower mean total rainfall in these four

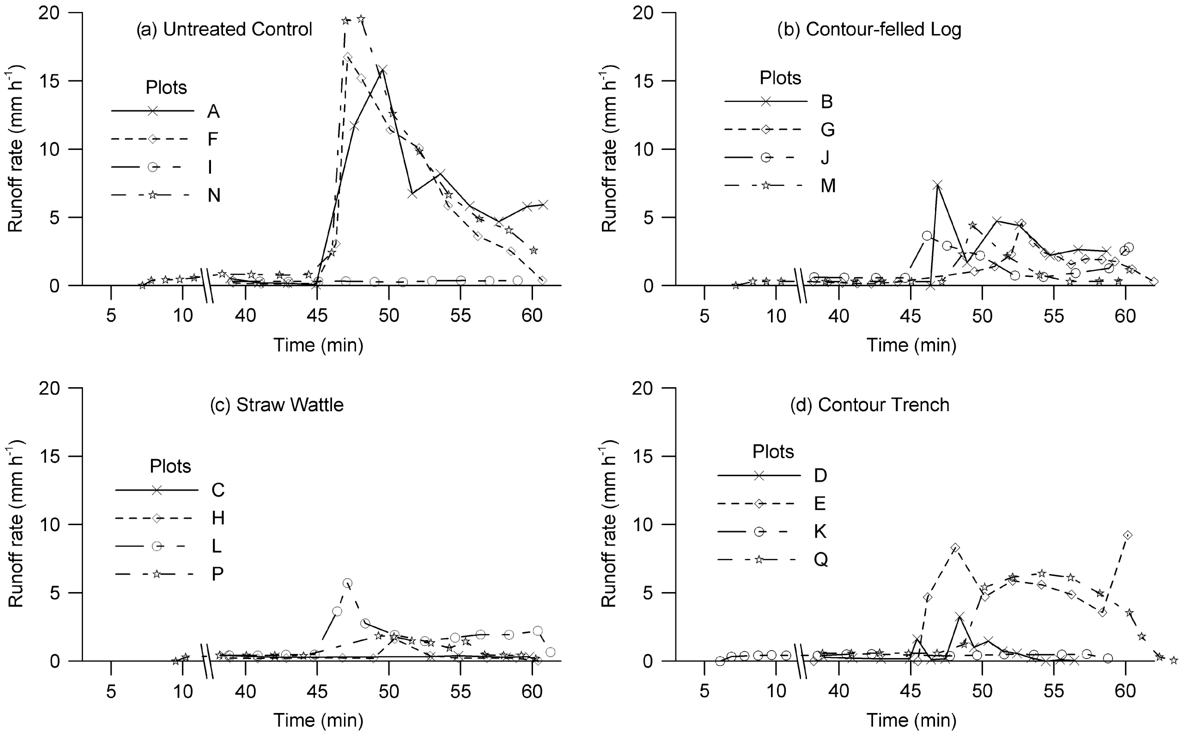

Figure 4. Hydrographs for the 16 rainfall and inflow simulations, separated by treatment: (a) untreated control; (b) contour-felled log; (c) straw wattle; (d) contour trench. At time equals 45 min, an overland flow of 48 L min^{-1} was added at the top of each plot. No changes in runoff rate were observed between minutes 12 and 37 where there is a break in the X axis

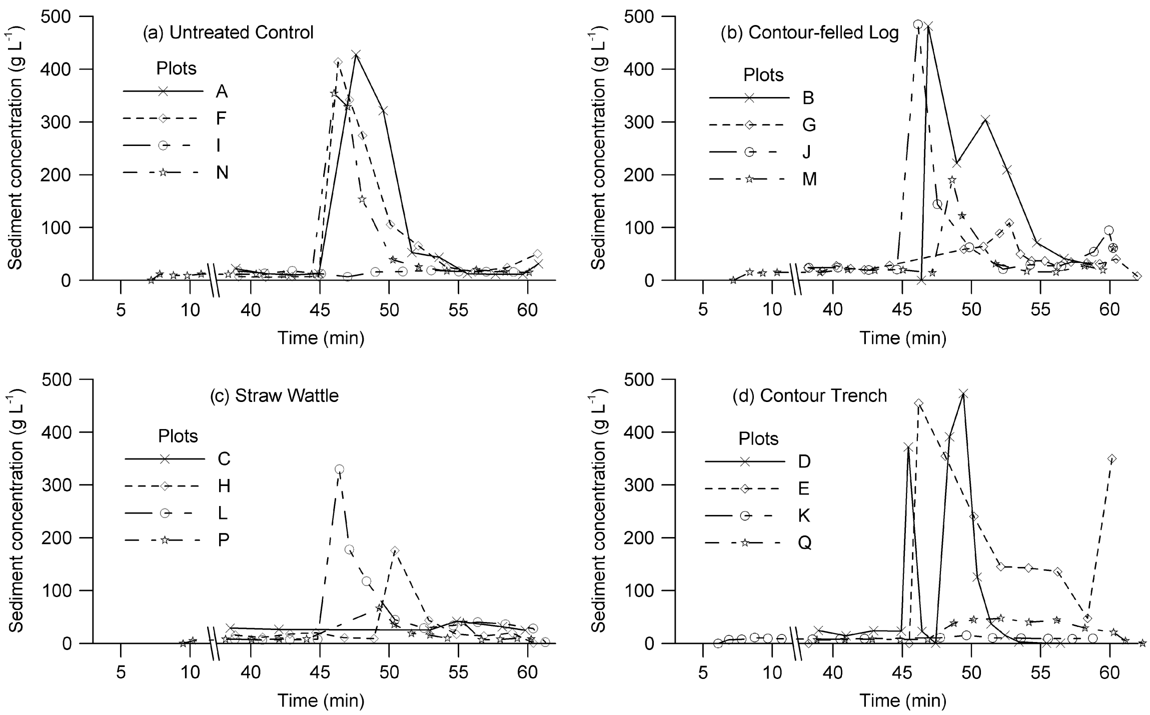

Figure 5. Sedigraphs for the 16 rainfall and inflow simulations, separated by treatment: (a) untreated control; (b) contour-felled log; (c) straw wattle; (d) contour trench. At time equals 45 min, an overland flow of 48 L min^{-1} was added at the top of each plot. No changes in sediment concentration were observed between minutes 12 and 37 where there is a break in the *X* axis

plots (18·8 mm) than the other 12 plots (26·7 mm). However, even though this lower rainfall probably produced a lower antecedent soil moisture condition in plots A–D than in the other plots for the rainfall-plus-inflow segment of the experiment, the runoff and sediment produced during both the rainfall-only and the rainfall-plus-inflow portions of these simulations were within the ranges measured in the other 12 plots. Thus, no adjustments in the analysis were made for differences in applied rainfall.

After 45 min of wetting, the simulated rainfall-plus-inflow began, and there was a large increase in runoff in all but three plots (straw wattle plot C and the two discarded plots, I and K; Figure 4). The runoff that occurred during the rainfall-plus-inflow period generally peaked quickly and then receded, and did not stabilize for any plot during the remainder of the simulation (e.g., Figure 4a, plot F). The sediment concentrations followed a similar pattern, spiking when inflow began and then receding to a level that was generally greater than the sediment concentrations from the rain-only period (Figure 5). High-intensity rainfall simulations on burned plots produced similar responses in sediment concentration in a study in Colorado (Benavides-Solorio and MacDonald, 2001), and this response indicates rapid flushing of available sediment and winnowing of fine particles. Maximum sediment concentrations were as high as 485 g L^{-1}, whereas the overall mean maximum concentration was 295 g L^{-1} (Table I). In addition, results of the significance tests were the same for the 15 min rainfall-plus-inflow portion of the experiment and the full 60 min simulation. Consequently, only results from the rain-only or the full 60 min simulation are reported.

The mean total runoff from the untreated control plots was 2·0 mm (or 6% of the total rainfall-plus-inflow applied), which was significantly greater than the 0·58 mm for the contour-felled log plots and the 0·40 mm for the straw wattle plots, but not significantly different than the 1·3 mm from the contour trench plots (Table I). The reduction in runoff during the rainfall-plus-inflow portion of the simulation experiment may have been due to storage of runoff and increased infiltration in the trenches above the contour-felled logs and straw wattles. Wagenbrenner *et al.* (2006) showed that infiltration in the trenches above contour-felled logs was greater than in adjacent burned areas in the first summer after burning. Although the contour trenches provided some storage capacity (0·026 m^3) for runoff and sediment, the capacity was lower than for the contour-felled logs (0·098 m^3) and straw wattles (0·057 m^3) (Table I), and not sufficient to significantly reduce the runoff or sediment yield when compared with the untreated control plots.

The mean peak runoff rate for the untreated control plots was 17 mm h^{-1}, and this value was significantly greater than the mean peak runoff rates for the treated plots: 5·0 mm h^{-1} for the contour-felled logs; only 2·4 mm h^{-1} for the straw wattle plots; and 6·3 mm h^{-1} for the contour trench plots (Table I). The storage volume of the treatments was a significant covariate for the peak runoff rate. The contour-felled logs had a mean storage capacity of 0·098 m^3; this was nearly double the storage capacity of the straw wattles (0·057 m^3) and nearly four times the value for the contour trenches (0·026 m^3). The storage volumes created by the erosion barriers reduced peak runoff rates by allowing runoff to pool, thereby reducing the runoff velocities.

Table I. Mean parameter values by treatment for 60-min simulation experiment. Standard deviations are shown in parentheses. Different letters within a row indicate significant differences at $\alpha = 0{\cdot}05$

	Untreated control[a]	Contour-felled log	Straw wattle	Contour trench[a]
WDPT (s)	71 (103)	51 (89)	66 (101)	60 (101)
Soil depth with maximum water repellency (mm)	9 (11)	12 (14)	6 (7)	9 (10)
Occurrence of soil water repellency in top 50 mm (%)	93	88	90	100
Simulated rainfall (mm)	26·4 (13·1)	29·3 (4·0)	26·9 (8·5)	23·3 (5·6)
Runoff (mm)	2·0 (0·46)a	0·58 (0·15)bc	0·40 (0·23)c	1·3 (0·95)ab
Peak runoff rate (mm h^{-1})	17 (1·9)a	5·0 (1·7)c	2·4 (2·2)c	6·3 (3·0)b
Peak sediment concentration (g L^{-1})	398 (39)	316 (196)	172 (115)	325 (241)
Rill cross sectional area (cm^2)				
at 4 m	68 (16)	59 (29)	67 (15)	69 (30)
at 15 m	71 (36)	62 (20)	66 (9)	66 (41)
Sediment collected (kg)	22 (9·4)a	5·8 (4·5)ab	2·1 (2·0)b	25 (35)a
Sediment yield (Mg ha^{-1})	2·2 (0·9)a	0·58 (0·45)ab	0·21 (0·20)b	2·5 (3·5)a
Erosion barrier storage capacity[b] (kg)	—	137	80	36
Sediment trapped in erosion barrier (kg)	—	10 (1·3)	8 (5·0)	10 (4·3)
Erosion barrier storage capacity used[b] (%)	—	7	10	28

[a] Means, standard deviations, and significance tests do not include data from plots I (untreated control) or K (contour trench).
[b] The erosion barrier storage capacity was calculated on the basis of an assumed bulk density of 1400 kg m^{-3}.

The reduction in runoff over time during the rainfall-plus-inflow portion of the simulation experiment on the untreated plots, and to a lesser degree in the treated plots (Figure 4), may be related to a reduction in soil water repellency. Over all the plots, the top 50 mm of soil had a 93% occurrence of soil water repellency, with the highest degree of water repellency at an average depth of 9 mm (Table I). Soil water repellency decreases with increased soil moisture (Robichaud and Hungerford, 2000; Huffman *et al*., 2001; MacDonald and Huffman, 2004) and continued wetting (Robichaud, 2000b), and infiltration rates tend to increase as soil water repellency decreases. There was no difference in antecedent soil moisture among the plots, and the overall mean soil moisture was only 1·4%. However, the first 45 min of low-energy simulated rainfall may have increased soil moisture sufficiently to reduce soil water repellency and, with the onset of the simulated inflow, increased infiltration (Figure 4). During a postfire rainfall simulation study in Montana, Robichaud (2000b) measured a similar reduction in runoff over time on a high-severity burned site. The reductions in runoff (from 65 to 40 mm h^{-1}) were observed after 30 min of simulated rainfall with a mean rainfall intensity of 94 mm h^{-1}.

The mean total sediment yield for the untreated control plots was 2·2 Mg ha^{-1}, compared with 0·58 Mg ha^{-1} for contour-felled log plots, 0·21 Mg ha^{-1} for straw wattle plots, and 2·5 Mg ha^{-1} for contour trench plots. Only the straw wattles significantly ($p = 0{\cdot}005$) reduced sediment yield compared with the control (Table I). The sediment storage capacity of the contour-felled logs was nearly double that of the straw wattles. However, the contour-felled logs did not significantly reduce sediment yields because the rills nearer the ends of the contour-felled logs were observed to carry water and sediment around the ends of the barriers. Only 7% of the available storage capacities of the contour-felled logs and 10% of the straw wattles were used (Table I). In the contour trench plots, rills carried water and sediment into the contour trenches and quickly formed small sediment deposits ('mini-deltas') that filled about 28% of the trench storage capacity. These deposits diverted subsequent flow of runoff and sediment to the ends of the trench, where they quickly overfilled the storage capacity of the trenches. Since the only downslope barrier to flow was the loosened, highly erodible soil created by the construction of the trench, the trench overflow picked up a large amount of available sediment, resulting in a slightly larger total erosion rate for the contour trench plots than for the control plots (Table I).

There was no difference in the D_{16}, D_{50}, or D_{84} of the eroded sediments among treatments during the rain and inflow simulation, and there was no difference in these particle size distribution parameters between any treatment and the soil from the pre-simulation surface sample. The sediment from the simulations had an overall mean D_{16} of 0·11 mm, a mean D_{50} of 0·83 mm, and a mean D_{84} of 2·9 mm. Since pre-simulation samples were taken in the top 2 cm of the soil surface and the rill depths averaged 2 cm and did not exceed 5 cm, the eroded sediments and soil samples came from the same depth in the soil profile. Also, since little sediment was moved by the rain-only portion of the simulation, no armouring of the soil surface had taken place.

Erosion from natural rainfall

The annual precipitation for each year of the study was within 14% of the 26-year average (925 mm) at the Saddle Mountain snow telemetry site. Periods of sediment accumulation were associated with 10 storms during the 3-year study (Table II). The maximum I_{10}, 42·7 mm h^{-1}, occurred on 15 July 2002, and I_{10} values

Table II. Data for 10 natural rainfall events associated with sediment yields, including date, total rainfall, duration, I_{10}, and I_{30} for each storm. Sediment was removed from the silt fences on the cleanout date indicated

Rainfall date	Total rainfall (mm)	Duration (min)	I_{10} (mm h^{-1})	I_{30} (mm h^{-1})	Cleanout date
3 Jun 01	29·0	2075	13·7	12·2	6 Jun 01
15 Jul 01	6·6	1210	19·8	7·1	21 Jul 01
21 Jul 01	15·7	540	39·6[b]	22·9	26 Jul 01
30 Jul 01[a]	22·1	1050	7·6	2·8	2 Aug 01
14 Sep 01	3·8	49	13·7	6·6	20 Oct 01
27 Mar 02	2·8	25	13·7	5·6	8 May 02
15 Jul 02	7·6	13	42·7[b]	15·2	23 Jul 02
24 Aug 02[a]	7·4	115	21·3	11·2	3 Sep 02
25 May 03[a]	4·1	465	7·6	4·6	29 May 03
10 Jun 03	5·6	295	30·5	10·7	30 Jul 03

[a] Data from Laird Creek gauge.
[b] 2–5-year return period for 10-min duration (Miller *et al.*, 1973).

Table III. Annual sediment yields for each plot and treatment. Standard deviations are shown in parentheses. Different letters between years indicate significant differences at $\alpha = 0{\cdot}05$

Plot	Treatment	Sediment yield (Mg ha^{-1} year^{-1}) 2001	2002	2003
A	Untreated control	24	0·5[a]	0·05
F	Untreated control	66	0·4[a]	0·03
I	Untreated control	9	1·3	0·17
N	Untreated control	16	0·3	0·04
B	Contour-felled log	21	0·4[a]	0·07
G	Contour-felled log	12	0·3[a]	0·20
J	Contour-felled log	20	1·1	0·36
M	Contour-felled log	7	0·6	0·12
C	Straw wattle	38	0·3[a]	0·12
H	Straw wattle	64	0·3[a]	0·96
L	Straw wattle	4	1·7	0·12
P	Straw wattle	3	0·5	0·04
D	Contour trench	31	0·3[a]	0·15
E	Contour trench	44	0·2[a]	0·09
K	Contour trench	48	1·1	0·29
Q	Contour trench	4	0·3	0·01
Mean				
A, F, I, N	Untreated control	29 (25)	0·8 (0·7)	0·07 (0·07)
B, G, J, M	Contour-felled log	15 (7)	0·8 (0·4)	0·19 (0·13)
C, H, L, P	Straw wattle	27 (29)	1·1 (0·8)	0·31 (0·43)
D, E, K, Q	Contour trench	32 (20)	0·7 (0·5)	0·14 (0·12)
All		26 (21)a	0·9 (0·5)b	0·18 (0·23)c

[a] Inflow from above these plots occurred on 15 July 2002 and event sediment yields from these plots on this event were not included in the means or analysis.

ranged from 7·6 to 39·6 mm h^{-1} for other storms associated with sediment production. The storms on 21 July 2001 and 15 July 2002 had return periods of between 2 and 5 years for the 10 min duration, whereas all other storms had return periods of less than 2 years (Miller *et al.*, 1973) (Table II).

Unlike the simulation experiments, there were no significant differences in event-based or annual sediment yields among treatments during the natural rainfall experiment (Table III). However, there were significant declines in annual sediment yields from 2001 to 2002 and from 2002 to 2003 (Table III). There were no significant treatment effects on ground or canopy covers, and the overall mean ground cover was 4 to 5% in 2000 and 2001, increasing to 19% in 2002 and to 55% in 2003 (Table IV). No live vegetation remained in the plots immediately after the fire, so canopy cover was 0% on all plots in 2000. By 2001, the overall mean canopy cover increased to 21%, and this increased again to 39% in 2002 but did not change in value in 2003 (Table IV). As cover increased, the hillslope stabilized and sediment yields went down by an order of magnitude each year (Table III). These annual reductions in sediment yields are similar to trends reported in other postfire erosion studies (Table V). Although the significant downward trend in sediment yields was concurrent with significant

Table IV. Mean ground cover (gravel, cobble, litter, basal vegetation, or woody debris) and mean canopy cover for each treatment and year. Standard deviations are shown in parentheses. There were four plots for each treatment in each year. Different letters indicate a significant difference in overall means by year at $\alpha = 0{\cdot}05$

	Mean ground cover (%)				Mean canopy cover (%)			
Treatment	2000	2001	2002	2003	2000	2001	2002	2003
Untreated control	5 (6)	5 (4)	20 (10)	59 (10)	0 (0)	26 (6)	45 (9)	45 (7)
Contour-felled log	4 (3)	4 (2)	18 (7)	53 (6)	0 (0)	20 (6)	41 (14)	38 (5)
Straw wattle	5 (3)	4 (3)	21 (10)	58 (6)	0 (0)	21 (10)	30 (9)	39 (5)
Contour trench	4 (4)	4 (3)	19 (6)	53 (9)	0 (0)	18 (14)	40 (9)	38 (6)
Overall mean	5 (4)a	4 (3)a	19 (8)b	55 (8)c	0 (0)a	21 (9)b	39 (11)c	40 (6)c

Table V. Mean annual sediment yields measured on burned, untreated hillslope plots in postfire years one, two, and three

		Sediment yield ($\mathrm{Mg\ ha^{-1}\ year^{-1}}$)			
Location (fire name, year)	No. of plots	Year 1	Year 2	Year 3	Reference
Eastern Oregon (Twin Lakes, 1994)	6	1·9	0·1	0·03	Robichaud and Brown (2000)
North central Washington (North Twenty-five, 1998)	4	16	0·7	0·4	Robichaud *et al.* (2006)
Central Colorado (Bobcat, 2000)	12	11	1·2	0·5	Wagenbrenner *et al.* (2006)
Western Montana (Valley Complex, 2000)	4	29	0·6	0·1	This study

Table VI. Mean D_{16}, D_{50}, and D_{84} for surface composite samples and by year for the accumulated sediment samples. Standard deviations are in parentheses

Sample/year	No. of samples	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)
Surface composite/Aug 2000	4	0·14 (0·12)	2·0 (0·60)	4·3 (0·54)
Accumulated sediment/2001	17	0·15 (0·14)	0·9 (0·38)	3·1 (0·83)
Accumulated sediment/2002	9	0·19 (0·10)	1·2 (0·24)	3·9 (0·39)
Accumulated sediment/2003	5	0·29 (0·06)	1·5 (0·32)	4·2 (0·59)

increases in vegetative cover, other factors may have affected the sediment yields. Although the WDPT was not measured in every plot in 2003, the average occurrence dropped from 82% in 2000 to 20% in 2003. The lower water repellency would increase infiltration and reduce overland flow and associated erosion rates. These limited data support the evidence of a reduction in water repellency over time (MacDonald and Huffman, 2004; Doerr *et al.*, 2006).

The repeated measures analyses showed no differences between the particle size distribution of the antecedent soil samples and the eroded sediments or between the particle size distributions of the eroded sediments by treatment. However, the D_{16}, D_{84}, and D_{50} of the accumulated sediment samples did increase over time, suggesting the early flushing of fines and a coarsening of eroded sediments over time (Table VI). Coarser sediments require additional energy per unit mass to be eroded, resulting in a net reduction in sediment yield for similar rainfall energy (Simons and Senturk, 1992). This process of soil armouring, along with the increase in ground cover and decrease in soil water repellency, likely contributed to the measured decreases in annual sediment yield each year of the study.

Although treatment did not have an effect on event sediment yields, event sediment yields within each postfire year significantly increased with total rainfall and increasing I_{10}. Of the 10 periods of sediment accumulation, a rain event in 2001 with an I_{10} of 39·6 mm h^{-1} produced the largest overall mean sediment yield of 23 Mg ha^{-1}. The rain event with the largest I_{10} (42·7 mm h^{-1}) occurred 1 year later and produced a mean sediment yield of only 0·6 Mg ha^{-1}. In 2003, the largest rain event (I_{10} of 30·5 mm h^{-1}) produced an overall mean sediment yield of just 0·18 Mg ha^{-1} (Table II). These three storms, with relatively comparable I_{10} values, produced much smaller sediment yields in the three subsequent years. Thus, the reduction in sediment yields was not a result of differences in rainfall inputs over time, but rather a combination of several factors, such as decreased water repellency, increased ground cover, and soil armouring.

Observations of erosion barrier functioning were made following three storms in 2001. On 15 July, the first large rainfall event partially filled the erosion barriers (Table VII). The next, even larger rainfall event occurred on 21 July, and the additional eroded sediment filled most of the remaining storage capacity above the erosion barriers (Table VII). Although later storms had lower rainfall

Table VII. The estimated sediment trapped, proportion of sediment storage capacity used, trap efficiency, and observations of erosion barrier performance for each erosion barrier over three consecutive rainfall events on 15, 21, and 30 July 2001

	Contour-felled logs				Straw wattles				Contour trenches			
	B	G	J	M	C	H	L	P	D	E	K	Q
Erosion barrier storage capacity (kg)	187	127	112	123	75	77	95	68	36	36	36	36
Estimated sediment trapped in erosion barrier[a,b] (kg)												
15 July	35 ◔	65 ◑	55 ◑	25 ◔	55 ◕	40 ◑	40 ◑	15 ◔	25 ◕	25 ◕	30 ◕	30 ◕
21 July	55 ◔	125 ●	95 ◕	60 ◑	70 ●	45 ◑	40 ◑	35 ◑	30 ◕	30 ◕	n/e	n/e
30 July	n/e	125 ●	95 ◕	95 ◕	n/e	55 ◕	55 ◑	40 ◑	p/f	30 ◕	p/f	p/f
Trap efficiency of erosion barrier[a] (%)												
15 July	63	95	95	94	54	93	92	92	53	52	93	91
21 July	21	52	32	46	15	7	51	56	8	6	—	—
30 July	—	52	32	57	—	8	60	60	—	6	—	—
Observations of erosion barrier performance[c]												
15 July	E		E U	E	E T U	T	E	E	T	E	E	E
21 July	E	E T	E T	E T	E T U	E	T	E T	T	T		
30 July		E T	E					T				

[a] n/e: not estimated; p/f: plot border failure; −: not calculable

[b] Symbols for estimated proportion of storage filled. ◔: 0–25%; ◑: 26–50%; ◕: 51–75%; ●: 76–100%.

[c] Codes for erosion barrier performance. E: flowed around end(s); T: flowed over top, U: flowed underneath.

amounts and intensities (Table II), there was insufficient capacity remaining to store runoff and sediment, and the treatments were quickly overwhelmed. Observations after these storms indicate that sediment-laden runoff flowed around the ends, and in many cases over the tops of the barriers (Table VII). The flow around the ends of the structures was not related to the slope of the structures, since three of the eight contour-felled log and straw wattle erosion barriers had slopes of 0%, and none of the structures had slopes greater than 4%. The flow around the ends and the flow over the tops of the structures, therefore, was in response to runoff or sediment partially filling the structure storage capacity. Also, seven of the eight contour-felled logs and straw wattles had 100% ground contact, yet two of these structures had flow underneath (Table VII). Thus, the water that accumulated behind the log or straw wattle caused piping and undercut the loosened soil that had been used to fill the gap between the barrier and the ground surface.

Several factors have been shown to impact the efficacy of contour-felled logs and straw wattles at reducing runoff and sediment yields, including the size and number of the erosion barriers per unit area and the quality of installation (Robichaud *et al.*, 2000; Wagenbrenner *et al.*, 2006). Observations of runoff and sediment going around the ends of contour-felled logs, straw wattles, and contour trenches suggest that increasing the storage capacity of the barriers would improve their utility. The addition of end berms on contour-felled log erosion barriers at sites in Montana and Colorado increased the sediment storage capacity of the logs by 16% and 10% respectively (P. Robichaud, unpublished data, June 2005). A similar increase in straw wattle storage capacity could be accomplished by turning the end 1 m of the wattle upslope before staking it to the ground. Although the storage capacity of contour trenches could be increased by increasing their size, the disturbance of soil during trench construction would likely negate the effect of any increased storage. Increasing the number of erosion barriers per unit area would increase the site storage capacity and decrease the contributing area for each structure.

The mean sediment-trapping efficiency for the first storm of 2001 was 87% for contour-felled logs, 83% for straw wattles, and 72% for contour trenches (Table VII). However, these barriers captured little additional sediment after that first storm, and their efficiency declined appreciably as additional rain events occurred. By the end of 2001, the mean efficiencies had declined to less than 50% for contour-felled logs, 45% for straw wattles, and 10% for contour trenches (Table VII). In 13 of the 29 visual observations, runoff and sediment flowed over the top of the barrier; yet in only three of those observations were the barriers filled to capacity and five were at or below 50% full (Table VII). Given that the erosion barriers in this study were installed for research purposes, the installation likely was more careful than in general field installations. Yet, these erosion barriers were only partially effective in retaining runoff and sediment even when sediment storage capacity was available, and did little to reduce hillslope erosion processes. In postfire field installations, with hundreds of barriers installed by crews of varying skill, attentiveness, and supervision, it is likely that some of the barriers will be poorly installed, compromising the potential storage capacity. In a study on contour-felled log erosion barriers installed by field crews in Colorado, an average of 32% of the logs from seven sites, and as many as 70% of the logs from a single site, were either off-contour and/or had incomplete contact with the ground surface (Wagenbrenner *et al*., 2006).

CONCLUSIONS

The erosion barrier treatments have the capacity to reduce runoff compared with the untreated control plots. In the simulated rainfall and inflow experiment the contour-felled logs and straw wattles reduced the total runoff, whereas all three barrier treatments reduced the peak runoff rates. However, only the straw wattles reduced the sediment yields compared with the untreated controls; neither the contour-felled logs nor the contour trenches significantly reduced sediment yields.

During the 3-year natural rainfall erosion study, event sediment yields increased with increasing total rainfall and rainfall intensity during 10 sediment-producing rainfall events. The sediment yields declined significantly over the same period that the ground cover increased significantly. Despite the reduction in sediment yields by the straw wattles during the simulated rainfall and inflow experiment, none of the treatments reduced sediment yields from the natural rainfall events in the 100 m^2 plots.

By using controlled rainfall and inflow conditions during the simulation experiment, differences in runoff and sediment yield among treatments were measured. However, the measurements and observations made during the subsequent 3-year postfire period, where natural variations in rainfall characteristics and hillslope recovery provided a more realistic evaluation of treatment effectiveness, showed the erosion barriers provided no significant reduction in sediment yields. Thus, differences in treatment effectiveness that were observed in the controlled setting were not observed during the field test.

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