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Effectiveness of three post-fire rehabilitation treatments in the Colorado Front Range

J. W. Wagenbrenner,[1] L. H. MacDonald[2]* and D. Rough[2]

[1] *USDA Forest Service, Rocky Mountain Research Station, Forestry Sciences Laboratory, 1221 S. Main St., Moscow, ID 83843, USA*
[2] *Department of Forest, Rangeland, and Watershed Stewardship, Colorado State University, Fort Collins, CO 80523-1472, USA*

Abstract:

Post-fire rehabilitation treatments are commonly implemented after high-severity wildfires, but few data are available about the efficacy of these treatments. This study assessed post-fire erosion rates and the effectiveness of seeding, straw mulching, and contour felling in reducing erosion after a June 2000 wildfire northwest of Loveland, Colorado. Site characteristics and sediment yields were measured on 12 burned and untreated control plots and 22 burned and treated plots from 2000 to 2003. The size of the hillslope plots ranged from 0·015 to 0·86 ha.

Sediment yields varied significantly by treatment and were most closely correlated with the amount of ground cover. On the control plots the mean sediment yield declined from 6–10 Mg ha^{-1} in the first two years after burning to 1·2 Mg ha^{-1} in 2002 and 0·7 Mg ha^{-1} in 2003. Natural regrowth caused the amount of ground cover on the control plots to increase progressively from 33% in fall 2000 to 88% in fall 2003. Seeding had no effect on either the amount of ground cover or sediment yields. Mulching reduced sediment yields by at least 95% relative to the control plots in 2001, 2002, and 2003, and the lower sediment yields are attributed to an immediate increase in the amount of ground cover in the mulched plots. The contour-felling treatments varied considerably in the quality of installation, and sediment storage capacities ranged from 7 to 32 m^3 ha^{-1}. The initial contour-felling treatment did not reduce sediment yields when subjected to a very large storm event, but sediment yields were significantly reduced by a contour-felling treatment installed after this large storm. The results indicate that contour felling may be able to store much of the sediment generated in an average year, but will not reduce sediment yields from larger storms.

KEY WORDS post-fire rehabilitation; erosion; ground cover; straw mulch; seeding; contour felling

INTRODUCTION

Erosion rates from undisturbed forests are generally low, with typical sediment yields from small forested catchments in the western USA ranging from 0·02 to 1·2 Mg ha^{-1} $year^{-1}$ (Patric *et al*., 1984; MacDonald and Stednick, 2003). In the Colorado Front Range the mean sediment yield from four 1 m Gerlach traps on unburned hillslopes was only 0·3 Mg ha^{-1} $year^{-1}$ (Moody and Martin, 2001). On unburned 1 m^2 plots a simulated rainfall of 76 mm h^{-1} generated a mean sediment yield of only 0·7 Mg ha^{-1} (Benavides-Solorio and MacDonald, 2001, 2002).

Intense wildfires can increase the amount of runoff and erosion in forested areas by several orders of magnitude (e.g. Helvey, 1980; Morris and Moses, 1987; Robichaud *et al*., 2000; Benavides-Solorio and MacDonald, 2001, 2002, 2005). These increases are attributed to a series of changes in the underlying hydrologic processes. In coniferous forest and chaparral ecosystems, moderate- and high-severity fires can induce a water-repellent layer at or below the soil surface, and this can greatly reduce the infiltration rate (DeBano, 1981; Imeson *et al*., 1992). The loss of ground cover by burning increases rain-splash erosion, may

* Correspondence to: L. H. MacDonald, Department of Forest, Rangeland and Watershed Stewardship, Colorado State University, Fort Collins, CO 80523-1472, USA. E-mail: leemac@cnr.colostate.edu

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induce soil sealing, decreases surface roughness, and reduces the time to initial runoff (DeBano *et al*., 1998; Johansen *et al*., 2001). By removing most or all of the vegetative, litter, and duff cover, high-severity wildfires reduce water losses through interception and transpiration, and this can further increase runoff.

These changes in runoff processes increase the volume and rate of runoff, which greatly increases the risk of flooding and the resultant threat to life and property downstream (Tiedemann *et al*., 1978; Robichaud *et al*., 2000). The changes in runoff induce an even larger increase in surface and channel erosion and a corresponding degradation of water quality (Tiedemann *et al*., 1978; DeBano *et al*., 1998; Moody and Martin, 2001; Kunze and Stednick, 2006). The downstream delivery of this sediment can impair aquatic habitats, damage in-stream structures, and reduce reservoir storage capacities (Graham, 2003).

In the USA, land managers often attempt to reduce the adverse effects of high-severity wildfires by applying emergency post-fire rehabilitation treatments (e.g. USDA Forest Service, 1995, 2000a, 2002). The most frequent treatments include grass seeding, mulching with straw, and contour felling (Robichaud *et al*., 2000). Land managers generally believe that these treatments are effective in reducing sediment yields, but few studies have rigorously tested the effectiveness of these treatments (Barro and Conard, 1987; MacDonald, 1989; Robichaud *et al*., 2000).

Grass seeding is the most commonly applied treatment because it is inexpensive and can be readily applied over large areas by aircraft. The goal is to increase revegetation rates and thereby increase infiltration, reduce rain splash, increase surface roughness, and reduce post-fire runoff and erosion rates. Previous studies have shown that seed germination is strongly influenced by seed density (California Division of Forestry, 1959; Krammes and Hill, 1963) and the amount and timing of rainfall (Corbett and Green, 1965; Barro and Conard, 1987; Amaranthus, 1989; Gross *et al*., 1989). Studies on the effectiveness of seeding have tended to measure changes in cover rather than erosion rates (e.g. California Division of Forestry, 1957; Orr, 1970; Tiedemann and Klock, 1973; Dean, 2001). Of the 19 seeding studies reviewed by Robichaud *et al*. (2000), only eight measured first-year erosion rates, and only one of these studies documented a reduction in erosion due to seeding.

Straw mulch is commonly used to increase ground cover on disturbed sites and reduce erosion rates (Meyer *et al*., 1970; Goldman *et al*., 1986). While straw mulch has been used in severely burned areas since at least the 1980s (USDA Forest Service, 1995), there are few inquiries on its ability to reduce post-fire erosion. One study in Spain evaluated the effectiveness of mulching in a semi-arid pine forest that had been burned by a wildfire (Bautista *et al*., 1996). Straw mulch was applied at a rate of 2 Mg ha^{-1} to three 16 m^2 plots while three plots were left untreated. Over a 19-month period the mean sediment yield from the untreated plots was 1·1 Mg ha^{-1} versus 0·1 Mg ha^{-1} from the mulched plots (Bautista *et al*., 1996). After the Cerro Grande Fire in New Mexico the application of straw mulch with seed reduced sediment yields in six 30-m^2 plots by 70% in the first year and 95% in the second year (Dean, 2001).

In contour felling, burned trees are cut down and the delimbed boles are placed on the contour to trap runoff and sediment (Figure 1). In most cases a small trench is dug upslope of the logs, and the excavated soil is placed between the log and the ground to prevent underflow. Infiltration may be enhanced if the trenches extend through a fire-induced water-repellent layer, and some hydrologists believe that the enhanced infiltration and water storage capacity in these trenches can reduce runoff rates. Storage capacities of up to 152 m^3 ha^{-1} have been reported from contour-felled hillslopes in the San Jacinto Mountains in California (Wohlgemuth *et al*., 2001), but more typical values range from the 4·9 m^3 ha^{-1} reported from the Wenatchee National Forest in Washington (Robichaud, 2000) to 67 m^3 ha^{-1} in central Colorado (P. Robichaud, USDA Forest Service, unpublished data, 2004). The effect of contour felling on post-fire sediment yields is uncertain, as the treated areas in both the California and the Washington studies had higher sediment yields than the untreated areas in the first year after burning. In the California study this was attributed to thinner soils and a correspondingly lower water-holding capacity in the treated watershed (Wohlgemuth *et al*., 2001). In the Washington study the difference was attributed to a higher intensity rainstorm on the treated watershed relative to the control watershed (Robichaud, 2000).

Figure 1. A contour-felled log. The trench upslope of the log is created by excavating the soil and piling it against the log to prevent underflow

These post-fire treatments can be quite expensive due to the large areas being treated and the costs of labour, materials, and transportation. Approximately US\$72 million was spent on post-fire rehabilitation after the 170 km^2 Cerro Grande Fire in New Mexico (Morton *et al*., 2003) and US\$18 million after the 560 km^2 Hayman Fire in Colorado (Graham, 2003). US\$786 000 was spent for rehabilitation after the 42 km^2 Bobcat wildfire, which was the primary study area for this paper, and the per hectare costs ranged from US\$220 for seeding to about US\$1000 for straw mulching and contour felling (USDA Forest Service, 2000d). Although millions of dollars per year are being spent on post-fire emergency rehabilitation treatments, there are few data on the efficacy of these treatments (Robichaud *et al*., 2000) or the underlying processes that control the effectiveness of a given treatment.

Goal and objectives

The goal of this project was to evaluate the effectiveness of three common post-fire rehabilitation treatments in burned areas along the Colorado Front Range. The basic design was to compare site characteristics and hillslope sediment production rates from treated and untreated control plots over a 4 year period. Sediment production rates were related to site characteristics and rainfall rates. The specific objectives were to: (1) determine whether seeding, mulching, or contour felling affected the amount of ground cover and vegetative regrowth relative to the untreated control plots; (2) determine whether any of the treatments reduced sediment yields relative to the untreated control plots; (3) relate the measured sediment yields to rainfall and site characteristics; (4) quantify the installation quality of several contour-felling treatments, and assess how this can affect runoff and sediment yields.

METHODS

Study areas

Three recent wildfires in the Colorado Front Range were selected for study. All of the erosion plots were established on the June 2000 Bobcat Fire. This burned 42 km^2 of primarily ponderosa pine forest about 20 km northwest of Loveland, Colorado (Figure 2). Additional sites to evaluate contour felling were established on the Eldorado Fire, which burned 4·5 km^2 west of Boulder in September 2000, and the Hi Meadows Fire, which burned nearly 44 km^2 southwest of Denver in June 2000 (Figure 2).

Nearly 50% of the area in the Bobcat Fire was burned at high severity as defined by Wells *et al*. (1979) and mapped by the USDA Forest Service (2000a). The areas burned at high severity were targeted for emergency rehabilitation treatments as they had the highest risk for increased runoff and erosion (USDA Forest Service, 2000a). The most extensive treatment was grass seeding using a mixture of slender wheatgrass (*Elymus*

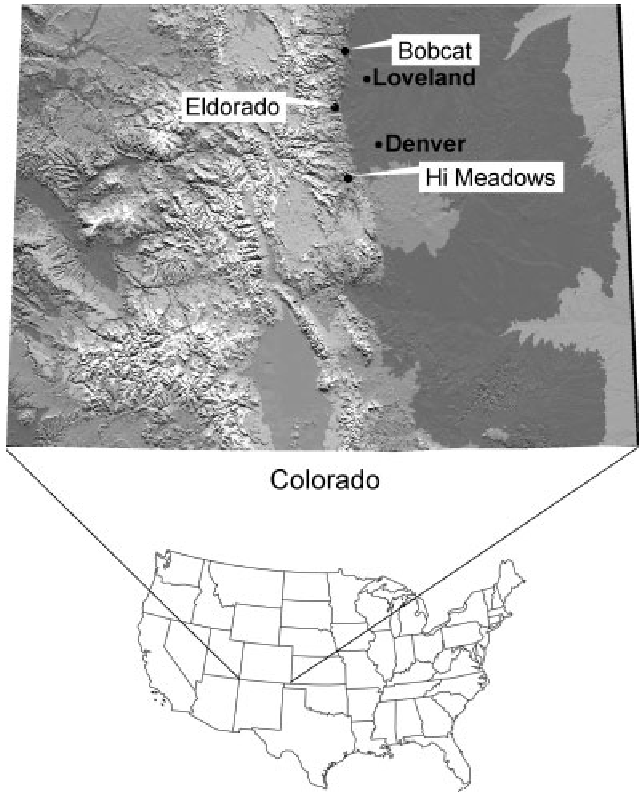

Figure 2. Location of the three wildfires used in this study

trachycaulus), mountain brome (*Bromus marginatus*), and a commercial mix of sterile grass seed (Regreen®). The target seed density was 430 m^{-2} or 34 kg ha^{-1}, and seeds were spread over 1050 ha by either aerial or hand application. The second treatment was mulching, and weed-free wheat straw was spread manually over approximately 50 ha at a rate of 2·2 Mg ha^{-1}. Contour felling was applied on 170 ha with a target density of 300–450 metres of logs per hectare (USDA Forest Service, 2000a,b). The straw mulch and contour-felled logs were generally installed in areas of special concern (USDA Forest Service, 2000a).

The three study sites in the Bobcat Fire (Bobcat, Galuchie, and Spruce sites) were selected because of the treatments applied, the presence of suitable swales for the installation of plots, and accessibility (Figure 3). The elevation of these sites ranges from 2100 to 2500 m, and the dominant pre-fire vegetation was ponderosa pine (*Pinus ponderosa*) with some intermixed lodgepole pine (*Pinus contorta*). All three sites are underlain by schist and gneiss (Cannon and Gleason, 2000). Soils generally were gravelly sandy loams with up to 20% rock outcrop (USDA Forest Service, 2000c).

In both the Eldorado and Hi Meadows Fires we selected two sites to evaluate the sediment storage capacity and installation quality of contour felling. The elevations of these study sites were between 2200 and 2400 m and slopes were 33–43%. The soils in both the Eldorado and Hi Meadows sites are stony or gravelly sandy loams (WPNRC, 2000; Gartner, 2003). All four sites were in ponderosa pine forests that had burned at high severity.

Experimental design and application of treatments

Thirty-four hillslope plots were established on the three Bobcat Fire sites. The plots were topographically defined and had contributing areas of 0·015 to 0·86 ha. Silt fences were installed at the outlets of the plots

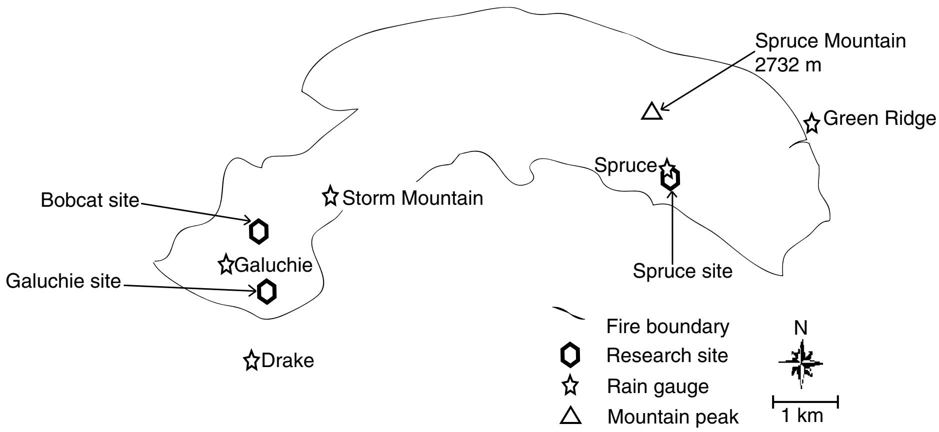

Figure 3. Study sites and rain gauges in and around the Bobcat Fire

Table I. Number of study plots by treatment for each site on the Bobcat Fire along with the mean contributing area, mean slope, and number of plots by aspect. The number of plots on planar hillslopes and the standard deviations for the contributing areas and slopes are shown in parentheses

Treatment	Number of plots			Contributing area (ha)	Slope (%)	Aspect		
	Bobcat	Galuchie	Spruce			N	S	E
Control	3 (1)	2	7 (3)	0·19 (0·22)	35 (13)	5	4	3
Seeded	0	0	4	0·24 (0·19)	28 (3)	2	2	0
Old mulch	2 (1)	0	2	0·15 (0·08)	23 (5)	2	2	0
New mulch	0	0	3	0·14 (0·04)	54 (17)	3	0	0
Old contour felling	2	2	0	0·47 (0·19)	29 (6)	2	2	0
New contour felling	0	0	7 (7)	0·03 (0·01)	20 (7)	4	3	0
Overall total or mean	7 (2)	4	23 (10)	0·19 (0·20)	31 (13)	18	13	3

to measure sediment yields from natural rainfall and snowmelt. Twelve plots were burned and untreated controls and 22 plots were in burned areas treated by the USDA Forest Service or were treated following its specifications (USDA Forest Service, 1995). The 22 treated plots included four seeded plots (two aerial-seeded and two hand-seeded), seven mulched plots, and 11 contour-felling plots (Table I). The sediment yields for 2000 were based on data from 16 plots that were installed prior to a very large storm on 16 August 2000. These included nine plots on the Bobcat and Galuchie sites (three control plots, two mulched plots, and four contour-felled plots) and seven plots on the Spruce site (one aerial seeded, one mulched, two controls, and three plots that had not yet been treated and were therefore classified as controls for this storm). By September 2000 all of the plots and treatments in the Spruce site had been installed except for two untreated controls and three mulch plots; these were established in May 2001. One additional control plot was established at both the Bobcat and Galuchie sites in May 2001.

Because the storm on 16 August 2000 greatly affected the sediment storage capacity of the contour-felling treatment, the contour-felled plots installed prior to this storm are termed 'old contour felling'. Similarly, the movement and decomposition of the straw mulch means that the mulched plots installed in August 2000 are termed 'old mulch', and the mulched plots installed in May 2001 are termed 'new mulch' (Table I). The aerial- and hand-seeded plots were lumped because these two groups had no significant differences in plot characteristics, or the type and amount of ground cover at any point during the study.

Precipitation

Nearly all of the erosion from burned areas in the Colorado Front Range is due to high-intensity summer thunderstorms (Benavides-Solorio, 2003), so our precipitation data focus on the period from 1 May to 30 September. Precipitation in and around the Bobcat Fire was measured by five recording rain gauges (Figure 3). The rainfall measured in 2000–03 was compared with the 20-year record from a gauge at Drake. The lag in obtaining and installing some of the rain gauges means that the rain gauge at Storm Mountain was used to characterize the precipitation at the Bobcat and Galuchie sites from 6 July to 7 September 2000, and the Green Ridge gauge was used to characterize precipitation at the Spruce site until the Spruce gauge was installed on 5 July 2001.

Total rainfall, storm duration, maximum 30 min intensity (I_{30}), rainfall erosivity (Brown and Foster, 1987), and a time-weighted linear 10-day antecedent rainfall index were computed for each storm that produced sediment as identified by field visits. Storms were separated by periods of at least 1 h with no precipitation. The return periods for the largest storms were determined from a rainfall frequency atlas for Colorado (Miller *et al.*, 1973).

Sediment collection

Silt fences (Dissmeyer, 1982; Robichaud and Brown, 2002) were used to measure the sediment produced from the 34 hillslope plots. Twenty-two silt fences were located in swales and 12 were on planar hillslopes (Table I). The planar hillslope plots generally had smaller contributing areas. Multiple silt fences were installed on the seven largest plots to increase the sediment storage capacity. After each storm, any large organic debris (e.g. cones or branches) was removed and discarded, and the sediment captured behind each fence was removed and weighed. For each fence, the measured sediment weight was adjusted by the water content determined from a 500–1000 g composite sample (Gardner, 1986). The adjusted weight was divided by the contributing area to obtain event-based unit area sediment yields. These event-based sediment yields were summed for August–December 2000 and each successive calendar year to determine annual sediment yields.

Plot characterization

The contributing area of each plot was first flagged and then surveyed using a Trimble Pathfinder® Pro XR global positioning system. Hillslope gradients were measured with a clinometer. The aspect of each plot was measured and classified into one of the four cardinal directions.

Surface cover was measured at 79 to 305 points within each plot using a transect method (Parker, 1951). The surface cover was classified at each point as bare soil, ash, live vegetation, litter, straw, standing dead tree, woody debris, or rock. Surface cover was first measured in fall 2000, and the measurements were repeated in both spring and fall in 2001, 2002, and 2003. Ground cover is defined as the sum of all surface cover types except bare soil and ash. In fall 2000, the number of grass seeds and seed hulls was counted on five or six $0{\cdot}09$ m^2 sub-plots within each of the seeded plots.

Quality assessment and infiltration in contour-felling plots

The quality of the contour-felling treatment was assessed from seven 30-log samples in the Bobcat, Eldorado, and Hi Meadows Fires. Each log was assessed to determine whether it was on contour and had continuous ground contact. Since many of the logs had been bucked into shorter lengths, the installation quality was assessed for each section, and the length of each log that could store water or sediment was termed the effective length L. The potential log storage per unit area S_L (m^3 ha^{-1}) was calculated by

$$S_L = \frac{1}{A}\sum_{i=1}^{n}\frac{Ld}{2}\left(x - \frac{\pi d}{4}\right) \tag{1}$$

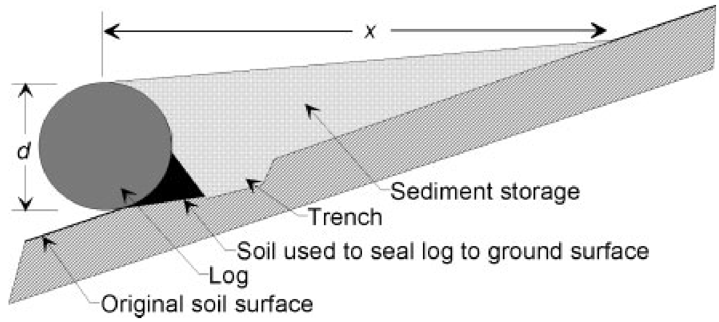

Figure 4. Cross-section of a contour-felled log showing the measurements used to quantify the storage capacity. The schematic shows a log with no remaining storage capacity

where A (ha) is the area over which measurements were made, n is the number of contour-felled logs in the area, L (m) is the effective length of the ith log, d (m) is the diameter of the ith log, and x (m) is the distance from the top of the ith log to the hillslope (Figure 4). The density of logs was the sum of the overall lengths of the logs divided by A.

Paired infiltration measurements were made in the trenches behind the contour-felled logs and on the burned hillslope adjacent to the logs. A rectangular infiltrometer, 20 cm wide and 50 cm long, was driven at least 5 cm into the ground. Water was ponded until the ground surface was covered and the infiltration rate was measured at 2 min intervals for 30–90 min (Bouwer, 1986). The final infiltration rate was the mean of the last 10 measurements. Six pairs of measurements were made at the Spruce site in fall 2000, early summer 2001, and fall 2001.

The reduction in runoff due to contour felling can be calculated by

$$\Delta Q = S_L A_H + 100 A_T \left(\int_0^D I_T \, dt - \int_0^D I_H \, dt \right) \tag{2}$$

where ΔQ (m^3) is the maximum potential change in runoff due to contour-felled logs, A_H (ha) is the hillslope area, A_T (ha) is the area of the trenches behind the contour-felled logs, I_T (cm h^{-1}) is the infiltration rate in the trenches, I_H (cm h^{-1}) is the infiltration rate on the adjacent hillslopes, D (h) is the duration of the storm, and t is the time in hours. For this paper, we calculated the reduction in runoff for a 1 ha hillslope using a numerical approximation of Equation (2) and the mean of the measured values for S_L, I_T, and I_H. To calculate A_T, we assumed that the trenches were 0·3 m wide and that I_T would occur over the mean effective length.

Statistical analyses

The 2000–03 ground cover and live vegetative cover data and the event-based and annual sediment yields from 2001 to 2003 were treated as repeated measures in mixed models with ‘site’ as a random variable, ‘treatment’ as a fixed variable, and ‘plot’ as the subject of repeated measures (Littell *et al*., 1996). The number of days since fire containment was used as the period of the repeated measures for ground cover, live vegetative cover, and event-based sediment yields. The year was the period of the repeated measures for annual sediment yields. Aspect was tested as a covariate for ground cover and the 2001–03 sediment yields, and slope was tested as a covariate for the 2001–03 sediment yields. The mean ground cover for each plot for each year was substituted for treatment in a separate analysis of the 2001–03 sediment yields, since treatment and ground cover were not independent. The sediment yields were log-transformed because their distributions were approximately lognormal (Ott, 1993).

Event-based comparisons between sites were not possible because the rainfall was so spatially varied. The Spruce site was used to test whether the event-based sediment yields were significantly related to rainfall I_{30}, rainfall erosivity, and the antecedent rainfall index. This site was selected because it had the largest number of plots and treatments and the same amount of rainfall could be assigned to each plot. When multiple storms occurred before the sediment could be removed, the measured sediment was associated with the total rainfall, total erosivity, and maximum I_{30} of the sediment-producing storms and with the antecedent rainfall index for the first storm.

The difference in seed density between the aerial- and hand-seeded plots was tested using a *t*-test, and seeding method was used as a treatment in a repeated measures analysis of the live vegetative cover in the seeded plots. Multiple comparisons were tested using least-squares differences on the least-squares means if the overall effect was significant (Ott, 1993). A repeated measures analysis was conducted on the infiltration rates to determine trends over time and the significance of the difference in infiltration rates between the trenches and the adjacent burned hillslopes (Littell *et al.*, 1996). The significance level for all statistical tests was 0·05 unless indicated otherwise.

RESULTS

Precipitation

Data from the Drake gauge indicate that the 20-year median rainfall from 1 May to 30 September is 198 mm. There was only 160 mm of rainfall over this period in 2000, or about 20% below normal. The total rainfall at Drake in May–September 2001 was 236 mm, or nearly 20% above normal. Data from the Drake gauge are incomplete for 2002 and 2003, but data from the rain gauges in the Bobcat Fire indicate that summer 2002 was exceptionally dry and that summer rainfall in 2003 was close to or slightly above the long-term median.

Between August 2000 and October 2003 there were 13 rain storms that produced sediment at the Bobcat and Galuchie sites and 18 storms that produced sediment at the Spruce site (Table II). Although the median rainfall for these storms was approximately 10 mm at each rain gauge, there was tremendous spatial variability in the magnitude of individual storm events. The largest storm occurred on 16 August 2000, when 48 mm was recorded at the Storm Mountain gauge in 2 h, and the estimated recurrence interval for this event is 5–10 years (Miller *et al.*, 1973). For this same storm, the Green Ridge gauge, which is less than 10 km to the east, recorded only 7 mm of rainfall (Table II). The median I_{30} for the sediment-producing storms was 10–12 mm h^{-1}, and the maximum I_{30} at the Bobcat and Galuchie sites was 48 mm h^{-1} for the storm on 16 August 2000. At the Spruce site, the maximum I_{30} was 35 mm h^{-1} for a 19·6 mm storm on 15 May 2003 (Table II).

The spatial variability in the large storms meant that there was more variability in the rainfall erosivity values between sites and between years than in the number of sediment-producing storms (Table II). At the Bobcat and Galuchie sites, the highest erosivity was in summer 2000, as the 48-mm storm on 16 August 2000 produced 430 MJ mm ha^{-1} h^{-1}, or 97% of the annual total for the sediment-producing storms. The total erosivity at the Galuchie gauge in 2001 was 259 MJ mm ha^{-1} h^{-1}, and in 2002 and 2003 the total erosivities were only 54 MJ mm ha^{-1} h^{-1} and 52 MJ mm ha^{-1} h^{-1} respectively (Table II). At the Spruce site, the total erosivity of the sediment-producing storms varied from just 15 MJ mm ha^{-1} h^{-1} in summer 2000 to 613 MJ mm ha^{-1} h^{-1} for four sediment-producing storms in summer 2003. Each of these four storms had a higher erosivity than all of the other storms except for the 16 August 2000 storm as recorded at the Storm Mountain rain gauge (Table II).

Plot characteristics and seed density

The contributing areas for the plots ranged from 0·015 to 0·86 ha, and averaged 0·19 ha (Table I). The mean slope was 31%, although values ranged from 11 to 69% (Table I). Most of the plots had a northerly or southerly aspect, and none of the plots had a westerly aspect. Each of the treatments except the new mulch had at least two plots with a northerly aspect and two plots with a southerly aspect (Table I).

Table II. Date, amount of rainfall, storm duration, I_{30}, rainfall erosivity, and antecedent rainfall index for the sediment-producing storms. The starting time is shown if more than one storm occurred on the same day. The yearly summaries for each site include the total precipitation, mean storm duration, mean I_{30}, total erosivity, and mean antecedent rainfall index for the sediment-producing storms

Date	Rainfall (mm)	Duration (h:min)	I_{30} (mm h^{-1})	Erosivity (MJ mm ha^{-1} h^{-1})	Antecedent rainfall index (mm)
Bobcat and Galuchie sites					
16 Aug 2000	48·0	2:41	48	430	2·8
19 Sep 2000	12·6	4:22	13	14	2·0
8 Jul 2001	5·0	0:13	5	12	4·7
11 Jul 2001	6·2	0:32	6	14	7·0
24 Jul 2001	8·4	1:35	8	16	0·1
9 Aug 2001	28·8	6:02	29	83	8·6
15 Aug 2001	7·6	0:58	8	25	23·5
16 Aug 2001	15·8	2:24	16	100	30·0
7 Sep 2001	7·6	1:49	8	9	2·1
3 Jun 2002	17·8	6:17	13	38	0·2
19 Jun 2002	3·0	0:33	6	3	1·3
8 Sep 2002	8·8	2:13	10	13	1·1
29 Aug 2003	16·8	4:15	18	52	5·6
2000	60·6	3:32	31	444	2·4
2001	79·4	1:56	11	259	10·9
2002	29·6	3:01	10	54	0·9
2003	16·8	4:15	18	52	5·6
Spruce site					
16 Aug 2000	7·0	0:52	8	8	1·8
19 Sep 2000	11·0	2:27	6	7	0·0
4 Jun 2001	9·0	5:02	4	4	12·7
8 Jul 2001	5·8	0:17	12	18	6·1
24 Jul 2001	3·2	1:30	4	2	1·8
9 Aug 2001	27·4	3:41	15	63	8·4
15 Aug 2001, 12:10	7·8	0:45	12	17	20·3
15 Aug 2001, 19:25	6·6	0:37	12	15	26·8
16 Aug 2001	6·4	0:28	13	15	33·0
7 Sep 2001	4·8	1:22	7	5	0·4
3 Jun 2002	16·2	6:18	10	26	0·5
19 Jun 2002	2·8	0:33	5	4	0·8
8 Sep 2002	14·8	2:06	16	41	1·8
12 Sep 2002	8·6	0:24	17	33	27·5
15 May 2003	19·6	1:45	35	167	14·6
17 Jun 2003	25·4	2:06	26	133	1·6
18 Jun 2003	25·8	3:19	28	154	25·8
29 Aug 2003	38·0	4:55	23	159	2·7
2000	18·0	1:40	7	15	0·9
2001	71·0	1:43	10	139	13·7
2002	42·4	2:20	12	104	7·7
2003	108·8	3:01	28	613	11·2

In September 2000 the mean seed density for the four seeded plots was 210 m^{-2}, or about half of the target seed density of 440 m^{-2}. The mean seed density of 96 m^{-2} in the two aerially seeded plots was significantly less than the mean seed density of 330 m^{-2} in the two hand-seeded plots. This difference is at least partly due to the timing of the seeding and the measurements, as the aerial seeding was completed prior to the large storm on 16 August 2000, whereas the hand seeding was done after this event. Field observations indicated that much of the aerially applied seed was washed downslope by the runoff from this storm, and this may account for the lower number of seeds in the aerially seeded plots.

Surface cover

In the first 3 months after burning there was very little ground cover or vegetative regrowth, except in the mulched plots (Figure 5). In fall 2000, the mean ground cover in the control plots was 33%, and this was comprised primarily of post-fire needle cast, burned woody debris, and rocks. The mean amount of live vegetative cover in the control plots was only 1%. In fall 2000, only the old mulch plots had significantly more ground cover (74%) than the control plots. The contour-felled plots had more than twice as much woody debris as the controls, but there was no significant difference in the total ground cover because woody debris was such a small component of the total cover.

By spring 2001 the ground cover in the control plots had increased significantly to 42%. The amount of ground cover continued to increase in each measurement period until fall 2003, when the mean value was 88% (Figure 5). The increase in ground cover over time was significant for each treatment except the new mulch. The old and new mulch treatments were the only treatments with significantly more ground cover than the controls (Figure 5), and these differences were significant through fall 2002. By spring 2003, none of the treatments had significantly more ground cover than the controls.

The measured increases in ground cover were due to significant increases in the amount of live vegetative cover. The only treatment with significantly more live vegetative cover than the controls was the old mulch treatment, and this was true from fall 2001 to fall 2003. There were no significant differences in the amount of live vegetative cover between the hand-seeded plots and the aerial-seeded plots, despite the more than

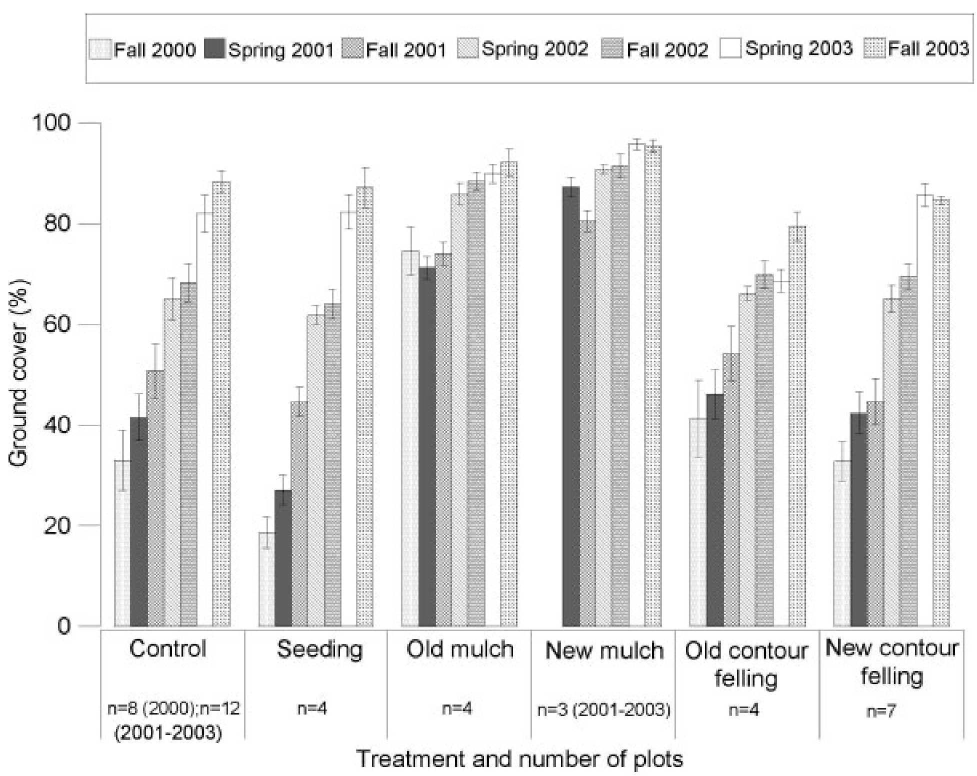

Figure 5. Mean ground cover by treatment over time. Bars represent one standard error. The number of plots for each treatment is for 2000–03 unless indicated otherwise

threefold difference in seed density. Aspect did not significantly affect the amount of ground cover or live vegetative cover for any of the treatments.

In the mulched plots, live vegetative cover gradually replaced straw as the dominant ground cover. For example, from fall 2000 to spring 2001 the amount of straw in the old mulch plots decreased from 51% to 38%, while the amount of live vegetative cover increased from 4% to 17%. By fall 2003, the mean straw cover had dropped to 0% for the old mulch treatment and 8% for the new mulch treatment, while the amount of live vegetative cover was 74% and 61%, respectively. Field observations indicate that the decline in the amount of straw was due to both decomposition and the removal of straw by wind and overland flow.

Sediment yields

All of the sediment collected over the study period was generated by rainstorms from May to September; no sediment was generated by snowmelt runoff in 2001, 2002, or 2003. As might be expected, the large storm on 16 August 2000 generated more sediment than any other storm, because this had the highest rainfall erosivity and only the mulched plots had more than 40% ground cover. The silt fences were overtopped in each plot except for the three old mulch plots and one of the four old contour-felled plots. The measured mean sediment yields in 2000 were 6·2 Mg ha^{-1} for the control plots, 3·9 Mg ha^{-1} for the seeded plot, 8·8 Mg ha^{-1} for the old mulched plots, and 5·8 Mg ha^{-1} for the old contour-felled plots (Table III). Because of the overtopping, these are minimum values for all treatments except the old mulch.

There were seven or eight sediment-producing storms at each site in 2001 (Table II). The mean sediment yield for the control plots was 9·5 Mg ha^{-1}, or 50% higher than in 2000. Mean sediment yields were significantly lower than the controls for both of the mulch treatments and the new contour-felling treatment (Table III). Although five silt fences overtopped in summer 2001, excluding these data does not substantially alter the mean sediment yields or the results of the significance tests between treatments. However, the overtopping does mean that the mean sediment yields were underestimated for the controls and the old contour-felling treatment in both 2000 and 2001, and for the seeding treatment in 2000.

There were only three to four storms that produced sediment in 2002 (Table II) and the total erosivities at each site were relatively low. This, plus the increase in the amount of ground cover, meant that the mean sediment yields for each treatment were significantly lower in 2002 than in 2001. For the control plots, the mean sediment yield was 1·2 Mg ha^{-1}, or just 13% of the value from 2001. Only the old and new mulch treatments had significantly lower sediment yields than the controls, and these values were less than 0·03 Mg ha^{-1} (Table III).

There was a further decline in mean sediment yields for each of the treatments between 2002 and 2003 (Table III). For the control plots, the mean sediment yield in 2003 was significantly lower at 0·7 Mg ha^{-1}, or

Table III. Mean sediment yields and the standard error (SE) for the means by treatment and year. Different letters indicate a significant difference in sediment yields within a column. A '+' indicates a minimum value due to at least one silt fence overtopping, and NA indicates not applicable

Treatment	No. of plots		Sediment yield (Mg ha^{-1} year^{-1})							
			2000		2001		2002		2003	
	2000	2001–03	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Control	8	12	6·2^{+}	1·3	9·5^{+a}	1·9	1·2^{a}	0·8	0·7^{a}	0·7
Seeding	1	4	3·9^{+}	NA	12·0^{a}	5·5	1·2^{ab}	1·1	0·3^{a}	0·2
Old mulch	3	4	8·8	3·2	0·5^{c}	0·2	0·02^{bc}	0·007	0·001^{a}	0·001
New mulch	0	3	NA	NA	0·02^{d}	0·004	0·006^{c}	0·002	0·000^{a}	0·000
Old contour felling	4	4	5·8^{+}	2·2	5·7^{+ab}	1·6	0·03^{abc}	0·01	0·02^{a}	0·01
New contour felling	0	7	NA	NA	2·8^{b}	0·6	0·2^{ab}	0·02	0·07^{a}	0·04

less than 60% of the 2002 value, despite the sixfold increase in rainfall erosivity at the Spruce site (Table II). Significant declines also were recorded for the seeding, old mulch, and new contour-felling treatments. None of the treatments had significantly lower sediment yields than the controls, and this is attributed to the much lower sediment yields in the control plots and the high relative variability in sediment yields among the plots within each treatment.

Factors affecting sediment yields

Ground cover was a strongly significant covariate for sediment yields in 2001–03 ($p < 0{\cdot}001$). Plots with less than 50% ground cover always had sediment yields of at least 1·0 Mg ha^{-1} year^{-1}, even when rainfall was well below normal (Figure 6). The converse was not always true: in 10 cases, high rainfall erosivities caused plots with at least 62% ground cover to have annual sediment yields higher than the assumed background sediment yield of 0·3 Mg ha^{-1} year^{-1}. These cases included the three old mulch plots in summer 2000, two old mulch and two control plots in summer 2001, and one seeded and two control plots in summer 2003.

Slope was not a significant covariate for annual sediment yields. There were no significant differences in sediment yields between north and south aspects for the control, mulch, or old contour-felling treatments. Aspect was a significant covariate for sediment yields for seeding and new contour felling, but the difference between aspects was small. In contrast to other studies (Benavides-Solorio and MacDonald, 2005), there were no significant differences in unit area sediment yields between the control plots located in swales and the control plots on planar hillslopes.

The event-based sediment yields were not significantly related to total rainfall, I_{30}, rainfall erosivity, or the antecedent rainfall index. This lack of significance may be caused by the larger, confounding effect of the decline in sediment yields over time and the resultant variability in the effect of rainfall. For example, a storm on 24 July 2001 resulted in a mean sediment yield of 0·3 Mg ha^{-1} from the control plots at the Bobcat and Galuchie sites, whereas a larger storm on 3 June 2002 (Table II) produced only 0·007 Mg ha^{-1}. The control plots at the Spruce site exhibit a similar reduction in event-based sediment yields between 2001 and 2002. This means that the significant declines in sediment yields from 2001 to 2002 and from 2002 to 2003 should be attributed to the natural recovery of the burned areas rather than to a reduction in rainfall.

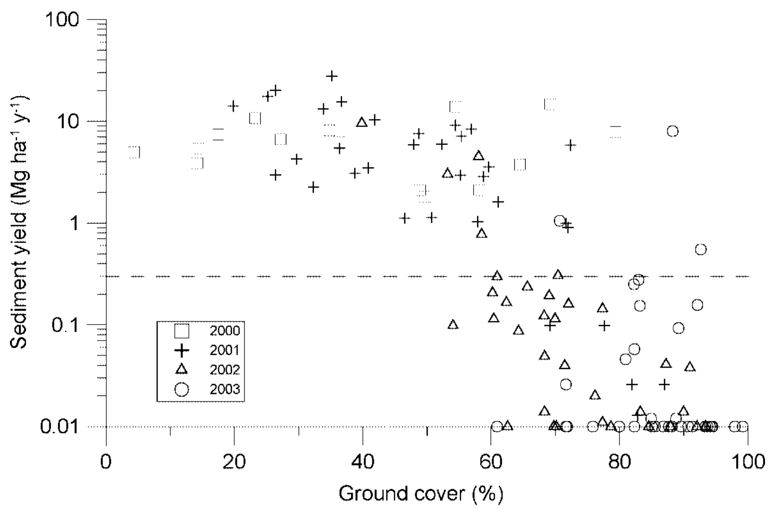

Figure 6. Plot of annual sediment yields versus ground cover for 2000–03. Each point represents one year of data from one plot ($n = 117$). The 29 plots with little or no sediment were assigned values of 0·01 Mg ha^{-1} year^{-1}. The dashed line represents the assumed background sediment yield of 0·3 Mg ha^{-1} year^{-1}

Installation quality and effectiveness of contour felling

The density of the contour-felled logs, installation quality, and sediment storage capacity (S_L) varied considerably within and among the three fires. The mean density of logs for all seven sites was 680 m ha^{-1}, although values ranged from 150 m ha^{-1} at the Galuchie site to 1300 m ha^{-1} at the Hi Meadows HST-2 site (Table IV). Within the Bobcat Fire, only the Spruce site exceeded the target density of logs of 300–450 m ha^{-1} (USDA Forest Service, 2000a). The overall mean log length was 5·0 m, but this ranged from 2·9 m at the Eldorado G-1 site to 6·6 m at the Spruce site (Table IV). The overall mean log diameter d was 0·23 m, and site-averaged values ranged from 0·18 to 0·27 m.

Logs were classified as ineffective when they had been placed or moved off contour, did not have good contact with the ground surface, or both. Of the 210 logs assessed, 32% were classified as partially or completely ineffective (Table IV). Nearly half of the ineffective logs were due to the logs being off-contour, one-fifth were due to poor ground contact, and one-third of the ineffective logs were both off-contour and had poor ground contact (Table IV).

Some segments of the ineffective logs were still able to store runoff and sediment, and some of the logs that were largely effective had ineffective portions at one or both ends. The more precise measurements along each log showed that only 43% of the total length of the contour-felled logs could be classified as effective for storing runoff and sediment. Site values ranged from just 17% at the Hi Meadows HST-2 site to 81% at the Spruce site in the Bobcat Fire (Table IV).

The variability in the quality of the installation of the logs contributes to the wide variability in potential storage volumes (Table IV). The overall mean S_L was 16 m^3 ha^{-1}, and the range was from 6·8 m^3 ha^{-1} at the Bobcat site to 32 m^3 ha^{-1} at the Hi Meadows HST-3 site (Table IV). Since effective length was the largest control on the sediment storage capacity of individual logs ($R^2 = 0{\cdot}69$, $p < 0{\cdot}0001$, $n = 210$), it follows that effective log length per unit area explains 57% of the variability in site storage capacity ($p = 0{\cdot}048$). The site-scale storage capacity was not significantly correlated with total log length per unit area, mean log diameter, log failure rate, or mean slope. The lack of significance for these factors is probably due to the small number of sites and the high variability in the measured components among sites.

Infiltration in contour-felling plots

In fall 2000, the mean infiltration rate in the trenches (I_T) was 18 cm h^{-1} versus 8·2 cm h^{-1} for the adjacent hillslopes (I_H), and this difference was significant (Figure 7). In 2001, the mean I_T progressively

Table IV. Log characteristics, installation quality, and the maximum potential site storage capacity by site for the contour-felling treatment. Total effectiveness is the length of the logs at each site that are capable of capturing sediment, and this is expressed as a percentage of the total log density

Fire: site	Log density (m ha^{-1})	Mean log length (m)	Mean hillslope (%)	Log installation defect rates				Total effectiveness	
				Off-contour (% of logs)	Not in complete contact (% of logs)	Off-contour and not in complete contact (% of logs)	Total defect rate (% of logs)	Effective log density (% of log density)	Site storage capacity (m^3 ha^{-1})
Bobcat: Bobcat	160	5·6	13	23	0	3	27	51	6·8
Bobcat: Galuchie	150	4·4	10	17	7	3	27	51	7·2
Bobcat: Spruce	540	6·6	20	0	7	3	10	81	18·0
Eldorado: B-1	940	3·2	10	0	10	17	27	41	12·0
Eldorado: G-1	860	2·9	9	10	7	7	23	63	29·0
Hi Meadows: HST-3	780	5·8	9	27	7	7	40	42	32·0
Hi Meadows: HST-2	1300	6·2	20	30	7	33	70	17	9·0
Overall mean	680	5·0	13	15	6	10	32	49	16·3

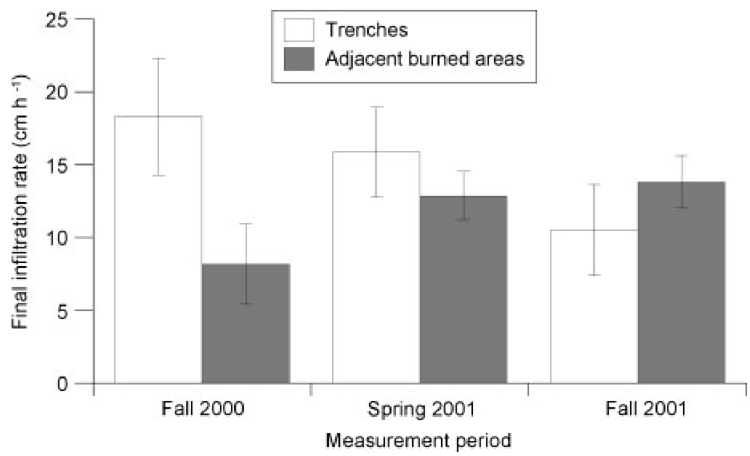

Figure 7. Mean infiltration rates over time in the trenches above the contour-felled logs and on the adjacent hillslopes. Bars represent one standard error

decreased and the mean I_H progressively increased (Figure 7), and this means that there were no significant differences in infiltration between the trenches and the hillslopes in summer and fall 2001. The decrease in I_T was probably due to the accumulation of fine sediment and organic matter in the trenches, whereas the increase in I_H was probably due to the breakdown of the fire-induced water-repellent layer (MacDonald and Huffman, 2004). These results suggest that the trenches behind the contour-felled logs can only enhance unit area infiltration rates immediately after burning and before they fill with sediment.

When the fall 2000 infiltration rates are extrapolated to the hillslope scale using the mean S_L and Equation (2), the maximum potential decrease in runoff ΔQ for a 1 h storm is 26 m^3, or 2·6 mm over a 1 ha hillslope. This value represents 26% of the median rainfall for the storms that produced sediment, or 10% of the 2-year, 1-hour storm. ΔQ will decline as the trenches above the logs are filled with sediment and there is progressively less difference between I_T and I_H. The importance of ΔQ also will diminish with increasing storm size.

DISCUSSION

Effect of seeding and mulching on ground cover and sediment yields

The mean seed density in the four seeded plots was only 210 m^{-2}, which is at the low end of the range recommended by the USDA Forest Service (1995). The seed was applied in summer 2000, but little germination was observed until the following spring. The lack of germination is supported by the fact that there was no significant change in the amount of live vegetative cover in the seeded plots between fall 2000 and spring 2001. Neither aerial nor hand seeding increased the ground cover relative to the controls, and there was no significant relationship between seed density and live vegetative cover. These results show that seeding had no detectable effect on the amount of ground cover.

Other researchers have used the amount of ground cover to indicate the effectiveness of seeding or other treatments in reducing post-fire erosion. Robichaud *et al*. (2000) suggested that 60% ground cover should be sufficient to protect a treated watershed from erosion. The data reported here generally support this threshold, as all of the plots with sediment yields at or below the presumed background rate of 0·3 Mg ha^{-1} $year^{-1}$ (Moody and Martin, 2001) had at least 54% ground cover.

For the first 2 years after burning, the mulched plots had significantly more ground cover than the controls and significantly lower sediment yields. In 2001, the sediment yields from the old and new mulched plots were less than 5% of the sediment yields from the control plots. This reduction is slightly greater than the

91% reduction observed from three mulched plots in a burned pine forest in Spain (Bautista *et al*., 1996), substantially higher than the approximately 30% reduction as a result of mulching in semi-arid shrublands in northeast Spain (Badia and Marti, 2000), and similar to the values measured from smaller plots after the Cerro Grande Fire in New Mexico (Dean, 2001). In absolute terms, the mean sediment yields from the old mulch plots in 2002 and 2003 were less than the presumed background level of 0·3 Mg ha^{-1}, and the sediment yields for the new mulch plots were less than 0·03 Mg ha^{-1} in 2001, 2002, and 2003. These results show that mulching is generally effective at reducing post-fire erosion rates, and this can be attributed to both the immediate increase in ground cover and the more rapid regrowth in the old mulch plots in the first year after burning. Other studies have documented that mulching provides more favourable conditions for plant germination and growth (Barfield *et al*., 1983; Goldman *et al*., 1986), and our data indicate that this also is true for severely burned areas.

Event-based comparisons showed that sediment yields for similar storms were much lower in 2002–03 than in 2000–01. We attribute the much lower sediment yields in 2002–03 to the increase in total ground cover. The importance of ground cover in reducing post-fire sediment yields is increasingly well documented (e.g. Benavides-Solorio and MacDonald, 2001, 2002; Pannkuk and Robichaud, 2003; Benavides-Solorio and MacDonald, 2005). The observed decline in annual sediment yields cannot be attributed to decreasing soil water repellency, as the fire-induced soil water repellency in the Bobcat fire was undetectable within a year after burning (MacDonald and Huffman, 2004), whereas sediment yields did not decline until the third summer after burning.

Effectiveness of contour felling

In 2000, the old contour-felling treatment and the control plots had similar mean sediment yields, even though the contour-felled plots had a mean sediment storage capacity of 7 m^3 ha^{-1}. The lack of any treatment effect is at least partly due to the very large storm on 16 August 2000, as the sediment generated by this storm filled the storage behind the logs and overtopped the silt fences in three of the four contour-felled plots and all of the control plots. Visual observations indicate that the surface runoff from this storm initiated rills at the downslope end of the logs that were off-contour. The lack of any sediment storage after this storm and the continued rilling explain why the old contour-felling treatment did not significantly reduce sediment yields relative to the controls in 2001–03.

The contour-felling treatment installed at the Spruce site in September 2000 had a lower log failure rate and an S_L of 18 m^3 ha^{-1}, or 2·6 times the mean S_L of the Bobcat and Galuchie sites. Since the contour-felled plots at the Spruce site were not subjected to the large storm on 16 August 2000, this storage capacity was largely unfilled at the beginning of the summer thunderstorm season in May 2001. As a result, the new contour-felling treatment reduced 2001 sediment yields by 71% relative to the controls, and this difference was significant. In 2002 and 2003 the mean sediment yields from the new contour-felling treatment were 83–91% less than the controls, but the low sediment yields and high between-plot variability meant that these differences were not significant.

If the mean bulk density of the eroded sediment is assumed to be 1·5 Mg m^{-3}, then the mean storage capacity of the contour-felled logs at the Spruce site is approximately 24 Mg ha^{-1}, or more than twice the mean sediment yield from the control plots in 2001. Since 2001 was a relatively wet year, the implication is that contour felling in the Colorado Front Range may be able to capture most of the sediment generated in the first year after burning, assuming average summer rainfall. In general, the effectiveness of contour felling in reducing sediment yields will depend on the density, size, and quality of installation of the contour-felled logs, as well as the magnitude and timing of the subsequent storm events.

Contour felling is relatively labour intensive and expensive at about US\$1000 ha^{-1}, but relatively small modifications could greatly reduce the failure rate. At the Spruce site, earth berms were constructed upslope from the ends of the trenches on about half of the logs. These berms prevented runoff from flowing around the ends of the logs, and this greatly improved the effectiveness of the logs that were slightly off-contour. This simple addition could potentially increase the mean storage capacity by up to 30%, which is the maximum off-contour failure rate, and this would increase the sediment storage capacity by up to 5 m^3 ha^{-1}. This increase in storage capacity would increase the likelihood that contour felling could reduce post-fire sediment yields.

Contour felling will be much less likely to reduce peak runoff rates because the volume of runoff is so much greater than the volume of eroded sediment. The calculated mean storage capacity of 2·6 mm could be increased to a maximum of about 5 mm if the site with the highest potential storage capacity is assumed to have a 0% failure rate. This storage capacity could reduce the amount of runoff from small- or moderate-sized storms, but the reduction in runoff will become progressively less important in the larger storms. Both S_L and I_T will also diminish rapidly as the trenches fill with eroded sediment, and this will reduce the ability of contour felling to reduce post-fire runoff rates. The implication is that any effort to predict the effectiveness of contour felling must be done on a probabilistic basis, as this treatment might be effective in one year, such as the new contour-felling treatment in 2001, but not when a site is subjected to a very large storm event, as happened with the old contour-felling treatment in summer 2000.

CONCLUSIONS

Natural recovery was relatively rapid, as the total ground cover in the untreated control plots increased by 55% between 2000 and 2003, and this recovery was mainly due to the increasing amounts of live vegetation. Mean sediment yields in the control plots exceeded 6 Mg ha^{-1} in the first two summers after burning, declined to 1·2 Mg ha^{-1} by the third summer after burning, and dropped to just 0·7 Mg ha^{-1} by the fourth summer after burning. The event-based data indicate that this decline was not caused by a reduction in rainfall, and the event-based and annual sediment yields were most closely correlated with the amount of ground cover. Both the event and annual data show that sediment yields approach background levels once there is at least 60% ground cover.

The seeding treatment had no detectable effect on total ground cover, the rate of vegetative recovery, or sediment yields. This lack of effectiveness can be attributed to the ineffectiveness of seeding rather than the low seed densities. In contrast, the mulched plots always had significantly more ground cover than the controls, as the mulch immediately increased the mean ground cover to nearly 80% and facilitated vegetative regrowth. Unit-area sediment yields from the mulched plots were less than 5% of the value from the control plots in 2001, 2002, and 2003. However, mulching did not reduce sediment yields in 2000 because of the large amount of sediment produced from the 5–10 year storm. This indicates that mulching, which was the most effective of the three treatments, may not be effective in reducing sediment yields in the largest storm events.

For the contour-felling treatment there was considerable variation between sites in the density of logs, quality of installation, and resultant sediment storage capacity. On average, 32% of the logs were off-contour, not in good contact with the ground, or both. Mean sediment yields from the old contour-felled plots were not significantly different from the control plots, and the sediment yields from the new contour-felled plots were significantly less than the controls only in 2001, when all of the log storage capacity was available to retain sediment. The results suggest that contour felling can reduce runoff rates and sediment yields from small- or moderate-sized storms, but is not effective in larger storms or after the storage capacity has filled with sediment. Improved design and installation could increase the potential effectiveness of contour felling.

The dependence of sediment production on ground cover means that the most effective treatments will be those that immediately increase the amount of ground cover and facilitate vegetative regrowth. The natural recovery in ground cover on the untreated plots means that the relative effectiveness of any treatment will decline over time. Since the effectiveness of the mulching and contour-felling treatments varies with storm size, efforts to predict treatment effectiveness must be probabilistic rather than deterministic.

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REFERENCES

Amaranthus MP. 1989. Effect of grass seeding and fertilizing on surface erosion in two intensely burned sites in southwest Oregon. In *Proceedings of the Symposium on Fire and Watershed Management.* USDA Forest Service General Technical Report PSW-GTR-109, Berkeley, CA; 148–150.

Badia D, Marti C. 2000. Seeding and mulching treatments as conservation measures of two burned soils in the central Ebro valley, NE Spain. *Arid Soil Research and Rehabilitation* **13**: 219–232.

Barfield BJ, Warner RC, Haan CT. 1983. *Applied Hydrology and Sedimentology for Disturbed Areas.* Oklahoma Technical Press: Stillwater, OK.

Barro SC, Conard SG. 1987. *Use of ryegrass seeding as an emergency revegetation measure in chaparral ecosystems*. USDA Forest Service General Technical Report GTR-PSW-102, Berkeley, CA.

Bautista S, Bellot J, Vallejo VR. 1996. Mulching treatment for postfire soil conservation in a semiarid ecosystem. *Arid Soil Research and Rehabilitation* **10**: 235–242.

Benavides-Solorio JD. 2003. *Post-fire runoff and erosion at the plot and hillslope scale, Colorado Front Range*. PhD dissertation. Colorado State University: Fort Collins, CO.

Benavides-Solorio JD, MacDonald LH. 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. *Hydrological Processes* **15**: 2931–2952. DOI: 10·1002/hyp.383.

Benavides-Solorio JD, MacDonald LH. 2002. Erratum for 'Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range'. *Hydrological Processes* **16**: 1131–1133. DOI: 10·1002/hyp.5017.

Benavides-Solorio JD, MacDonald LH. 2005. Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. *International Journal of Wildland Fire* **14**(4): 457–474.

Bouwer H. 1986. Intake rate: cylinder infiltrometer. In *Methods of Soil Analysis: Part 1*, Klute A (ed.). American Society of Agronomy: Madison, WI; 825–844.

Brown LC, Foster GR. 1987. Storm erosivity using idealized intensity distributions. *Transactions of the American Society of Agricultural Engineers* **30**(2): 379–386.

California Division of Forestry. 1957. *Emergency revegetation of burned watersheds*. California Department of Natural Resources Annual Report, Sacramento, CA.

California Division of Forestry. 1959. *Emergency revegetation of burned watersheds*. California Department of Natural Resources Annual Report, Sacramento, CA.

Cannon SH, Gleason JA. 2000. *Emergency assessment of flood and debris-flow hazards from the Bobcat Fire, Larimer County, Colorado.* http://www.dnr.state.co.us/geosurvey/pubs/fires/maps/Bobcatreport.pdf [25 March 2001].

Corbett ES, Green LR. 1965. *Emergency revegetation to rehabilitate burned watersheds in southern California*. USDA Forest Service Research Paper PSW-22, Berkeley, CA.

Dean AE. 2001. Evaluating effectiveness of watershed conservation treatments applied after the Cerro Grande Fire, Los Alamos, New Mexico. MS thesis, University of Arizona: Tuczon, AZ.

DeBano LF. 1981. *Water repellent soils: a state of the art*. USDA Forest Service General Technical Report PSW-GTR-46, Berkeley, CA.

DeBano LF, Neary DG, Ffolliott PF. 1998. *Fire's Effects on Ecosystems.* Wiley: New York.

Dissmeyer GE. 1982. *How to use fabric dams to compare erosion from forestry practices*. USDA Forest Service Forestry Report SA-FR 13, Atlanta, GA.

Gardner WH. 1986. Water content. In *Methods of Soil Analysis: Part 1*, Klute A (ed.). American Society of Agronomy: Madison, WI; 493–507.

Gartner JD. 2003. *Erosion after wildfire: the effectiveness of log erosion barrier mitigation*. MA thesis, University of Colorado: Boulder, CO.

Goldman SJ, Jackson K, Bursztynsky TA. 1986. *Erosion and Sediment Control Handbook.* McGraw-Hill: New York.

Graham RT. 2003. *Hayman Fire case study*. USDA Forest Service General Technical Report RM-GTR-114, Ogden, UT.

Gross E, Steinblums I, Ralston C, Jubas H. 1989. Emergency watershed treatments on burned land in southwest Oregon. In *Proceedings of the Symposium on Fire and Watershed Management.* USDA Forest Service General Technical Report PSW-GTR-109, Berkeley, CA; 109–114.

Helvey JD. 1980. Effects of a north central Washington wildfire on runoff and sediment production. *Water Resources Bulletin* **16**(4): 627–634.

Imeson AC, Verstraten JM, van Mulligen EJ, Sevink J. 1992. The effects of fire and water repellency on infiltration and runoff under Mediterranean type forest. *Catena* **19**: 345–361.
Johansen MP, Hakonson TE, Breshears DD. 2001. Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands. *Hydrological Processes* **15**: 2953–2965. DOI: 10·1002/hyp.384.
Krammes JS, Hill LW. 1963. *''First aid" for burned watersheds*. USDA Forest Service Research Note PSW-29: Berkeley, CA.
Kunze MD, Stednick JD. 2006. Streamflow and suspended sediment yield following the 2000 Bobcat Fire, Colorado. *Hydrological Processes* **20**: in press.
Littell RC, Milliken GA, Stroup WS, Wolfinger RD. 1996. *SAS® System for Mixed Models.* SAS Institute: Cary, NC.
MacDonald LH. 1989. Rehabilitation and recovery following wildfires: a synthesis. In *Proceedings of the Symposium on Fire and Watershed Management*. USDA Forest Service General Technical Report PSW-GTR-109, Berkeley, CA; 141–144.
MacDonald LH, Huffman EL. 2004. Post-fire soil water repellency: persistence and soil moisture thresholds. *Soil Science Society of America Journal* **68**: 1729–1734.
MacDonald LH, Stednick JD. 2003. *Forests and water: a state-of-the-art review for Colorado*. Colorado Water Resources Research Institute completion report no. 196, Colorado State University, Fort Collins, CO.
Meyer LD, Wischmeier WH, Foster GR. 1970. Mulch rates required for erosion control on steep slopes. *Soil Science Society of America Proceedings* **34**: 928–931.
Miller JF, Frederick RH, Tracey RJ. 1973. *Precipitation-Frequency Atlas of the Western United States, Volume III—Colorado*. US Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service: Silver Spring, MD.
Moody JA, Martin DA. 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms* **26**: 1049–1070.
Morris SE, Moses TA. 1987. Forest fire and the natural soil erosion regime in the Colorado Front Range. *Annals of the Association of American Geographers* **77**(2): 245–254.
Morton DC, Roessing ME, Camp AE, Tyrrell ML. 2003. *Assessing the environmental, social, and economic impacts of wildfire*. GISF Research Paper, Yale University Global Institute of Sustainable Forestry, New Haven, CT.
Orr HK. 1970. *Runoff and erosion control by seeded and native vegetation on a forest burn: Black Hills, South Dakota*. USDA Forest Service Research Paper RM-60, Fort Collins, CO.
Ott RL. 1993. *An Introduction to Statistical Methods and Data Analysis*, fourth edition. Wadsworth: Belmont, CA.
Pannkuk CD, Robichaud PR. 2003. Effectiveness of needle cast at reducing erosion after forest fires. *Water Resources Research* **39**(12): 1333–1342. DOI: 10·1029/2003WR002318.
Parker KW. 1951. *A method for measuring trend in range condition on National Forest ranges*. US Department of Agriculture, administrative report.
Patric JH, Evans JO, Helvey JD. 1984. Summary of sediment yield data from forested land in the United States. *Journal of Forestry* **82**: 101–104.
Robichaud PR. 2000. Fire and erosion: evaluating the effectiveness of a post-fire rehabilitation treatment, contour felled logs. In *Proceedings of Watershed Management 2000 Science and Engineering Technology for the New Millennium*, Fort Collins, CO.
Robichaud PR, Brown RE. 2002. *Silt fences: an economical technique for measuring hillslope soil erosion*. USDA Forest Service General Technical Report RM-GTR-94, Fort Collins, CO.
Robichaud PR, Beyers JL, Neary DG. 2000. *Evaluating the effectiveness of postfire rehabilitation treatments*. USDA Forest Service General Technical Report RM-GTR-63, Fort Collins, CO.
Tiedemann AR, Klock GO. 1973. *First year vegetation after fire, reseeding, and fertilization on the Entiat Experimental Forest*. USDA Forest Service Research Note PNW-195, Portland, OR.
Tiedemann AR, Helvey JD, Anderson TD. 1978. Stream chemistry and watershed nutrient economy following wildfire and fertilization in eastern Washington. *Journal of Environmental Quality* **7**(4): 580–588.
USDA Forest Service. 1995. *Burned area emergency rehabilitation handbook*. Forest Service Handbook No. 2509·13, Washington, DC.
USDA Forest Service. 2000a. *Bobcat Fire burned area emergency rehabilitation assessment*. USDA Forest Service Arapaho–Roosevelt National Forest, Fort Collins, CO.
USDA Forest Service. 2000b. *Burned area emergency rehabilitation—Bobcat Fire accomplishments to date*. USDA Forest Service Arapaho–Roosevelt National Forest, letter to Regional Forester, Fort Collins, CO.
USDA Forest Service. 2000c. *Map of draft soils interpretation for Drake quadrangle*. USDA Forest Service Arapaho–Roosevelt National Forest, Fort Collins, CO.
USDA Forest Service. 2000d. *Burned area emergency rehabilitation—Bobcat Fire, Arapaho–Roosevelt National Forest Approval of Initial BAER request*. Letter to Regional Forester, USDA Forest Service Washington Office, Washington, DC.
USDA Forest Service. 2002. *Hayman Fire burned area emergency rehabilitation assessment*. USDA Forest Service Pike National Forest: Pueblo, CO.
Wells CG, Campbell RE, DeBano LF, Lewis CE, Fredriksen RL, Franklin EC, Froelich RC, Dunn PH. 1979. *Effects of fire on soil, a state-of-knowledge review*. USDA Forest Service general technical report WO-7, Washington, DC.
Wohlgemuth PM, Hubbert KR, Robichaud PR. 2001. The effects of log erosion barriers on post-fire hydrologic response and sediment yield in small forested watersheds, southern California. *Hydrological Processes* **15**: 3053–3066. DOI: 10·1002/hyp.391.
WPNRC. 2000. *Boulder County Parks and Open Space Eldorado Fire area rehabilitation plan*. WP Natural Resources Consulting, Inc, Fort Collins, CO.

