

## Measurement of post-fire hillslope erosion to evaluate and model rehabilitation treatment effectiveness and recovery

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**Abstract.** The increasing size and severity of wildfires in the western United States has caused a corresponding increase in post-fire emergency erosion control activities. Hillslope treatments, such as broadcast seeding, mulching and installed barriers, are applied to reduce runoff and erosion, as well as downslope sedimentation. However, there are few data to determine if these post-fire treatments are practical and effective. Direct measurement of hillslope erosion, particularly in the remote settings where wildfires occur, is time consuming and costly. Rainfall simulation, sediment fences and paired catchment studies have been adapted for measuring post-fire erosion in the mountainous forest regions of the western USA. The use of paired catchments to measure hillslope erosion and evaluate treatment effectiveness is illustrated by an ongoing experiment of six contour-felled log erosion barrier research sites. Deciding which type of treatments to use, as well as the locations and timing of application, requires treatment cost and effectiveness to be weighed against potential damage from unmitigated erosion. To assist in this process, a web-based Erosion Risk Management Tool has been developed that incorporates variability in rainfall, burn severity and soil properties, as well as treatment options to provide probabilistic erosion estimates for 4 years after a fire.

**Additional keywords:** Burned Area Emergency Response; emergency stabilization; mitigation; paired watersheds; sediment; silt fence; wildfire.

### Introduction

Fire is a natural and important disturbance mechanism in many ecosystems. However, fire suppression in the western United States, beginning in the early 1900s, has altered natural fire regimes in many areas (Agee 1993) resulting in a significant increase in the number, size and severity of wildfires (Joint Fire Science Program 2004). Fire suppression can allow fuel loading and forest floor material to increase, resulting in fires of greater intensity and extent than might have occurred otherwise (Norris 1990). High severity fires are of particular concern because they not only consume or deeply char all the vegetation, but also affect the physical properties of soil (DeBano *et al.* 1998). Altered watershed response to rainfall can cause increased runoff, erosion and downstream sedimentation, which can threaten human life and damage property (Robichaud *et al.* 2000). During the past 15 years, as wildfire size and severity have dramatically increased, the population living in the wildland–urban interface (forested lands surrounding urban areas) has also increased (Stewart *et al.* 2003). The protection of life and property is a significant challenge, not only for wildland fire suppression efforts, but also for mitigation of the increased erosion, downstream

sedimentation, flooding and debris flows that often occur after these fires (DeBano *et al.* 1998).

The US Department of Agriculture Forest Service and other land management agencies have spent tens of millions of dollars on post-fire emergency watershed stabilization measures intended to minimize flood runoff, peakflows, onsite erosion, offsite sedimentation, mud and debris flows, and other hydrologic damage to natural habitats as well as to roads, bridges, reservoirs and irrigation systems (General Accounting Office 2003). After consumption and charring of vegetation, increased erosion and flooding are the most visible and dramatic physical consequences of fire.

The growing costs and the public demand for emergency post-fire rehabilitation have prompted economic and scientific studies to determine the most cost-effective approaches to mitigate the effects of fire on human lives and property, water supplies, water quality, soil productivity and endangered species and habitat. In the late 1990s, the program responsibilities of Burned Area Emergency Response (BAER – a federal authority that directs and funds the evaluation of burn severity and post-fire rehabilitation) were expanded to include monitoring of treatment effectiveness.

Yet the US General Accounting Office recently reported that post-fire mitigation treatments used to reduce runoff and erosion have not been rigorously evaluated to determine if they are meeting treatment objectives (General Accounting Office 2003). Most emergency post-fire rehabilitation efforts have been evaluated qualitatively in written reports with some photographic support, but few quantitative data have been collected (Robichaud *et al.* 2000). Recent scientific efforts have focused on developing and implementing methods that assess the effectiveness and the limitations of specific post-fire rehabilitation treatments through direct measurement of hillslope erosion.

The objectives of this paper are to describe: (1) some post-fire watershed hydrologic responses that influence the methods used to measure post-fire erosion and affect erosion mitigation treatment effectiveness; (2) research methods developed to study post-fire treatment effectiveness through direct measurement of hillslope erosion; (3) post-fire hillslope erosion mitigation treatments most commonly used and their known effectiveness; (4) a sample of preliminary data from a current treatment study; and (5) the use of post-fire erosion measurement data to model potential post-fire erosion and treatment effectiveness. BAER treatments are applied to burned hillslopes, stream channels and roads (Robichaud *et al.* 2000). However, this paper will focus on hillslope treatments because the research methods, preliminary results and erosion prediction models being presented relate specifically to hillslope erosion, and hillslope treatments are regarded as a first line of defense against post-fire erosion and unwanted sediment deposition.

#### **Post-fire watershed responses: factors that influence erosion measurement methods and treatment effectiveness**

Watersheds with good hydrologic conditions (>75% of the ground covered with vegetation and plant litter) and adequate rainfall sustain stream baseflow conditions for much or all of the year and produce little sediment. Under these conditions, 2% or less of the rainfall becomes surface runoff, and erosion is low (Bailey and Copeland 1961). Fire can destroy accumulated forest floor material and vegetation, altering infiltration by exposing soils to raindrop impact or creating water-repellent soil conditions (DeBano *et al.* 1998). When severe fire produces hydrologic conditions that are poor (<10% of the ground surface covered with plants and plant litter), surface runoff can increase more than 70% and erosion can increase by three orders of magnitude (DeBano *et al.* 1998).

Within a watershed, sediment and runoff responses to wildfire are often a function of burn severity and the occurrence of hydrologic events. Even severely burned areas will have minimal soil loss in the absence of rainfall. However, when a major rainfall event follows a large, high burn severity fire, a significant hydrological response and erosion are likely.

In particular, high-intensity, short-duration rainfall, which is relatively common in the central Rocky Mountains (Farmer and Fletcher 1972), has been associated with high stream peakflows and significant erosion events after fires (DeBano *et al.* 1998; Neary *et al.* 1999; Moody and Martin 2001). After the Buffalo Creek Fire in the Colorado Front Range, Moody and Martin (2001) measured 30-min maximum rainfall intensities ( $I_{30}$ ) that were  $>60 \text{ mm h}^{-1}$ . Short-duration rainfall events of such intensity tend to exceed the average infiltration rates of many soils causing streamflow to be dominated by overland flow (Moody and Martin 2001). The thunderstorms that produce these rainfall intensities may be quite limited in area, but can produce severe localized flooding and erosion. Because erosion rates vary by rainfall intensity, amount and duration, it is more useful to relate post-fire erosion amounts to specific rainfall events, rather than a general precipitation parameter such as annual rainfall.

Post-fire soil erosion amounts vary not only with rainfall, but also with burn severity, topography, soil characteristics and amount of vegetative recovery. Sediment yields in the first year after a fire range from very low in flat terrain without major rainfall events, to extreme in steep terrain affected by high-intensity thunderstorms. Published sediment yields after wildfires vary from 0.01 to over 110  $\text{Mg ha}^{-1} \text{ year}^{-1}$  in the first post-fire year (Robichaud *et al.* 2000), decrease by an order of magnitude the following year, and recover, with no measurable erosion, by the fourth year (Robichaud and Brown 2000). Consequently, if erosion mitigation is required, treatments need to be applied immediately after fire suppression and effectiveness monitoring needs to begin at the same time.

Recovery rates vary by climate and geographic area as well as by size and severity of the burn. DeBano *et al.* (1996) found that following a south-western USA wildfire, sediment yields from a low burn severity fire recovered to normal levels after 3 years, but moderate and high burn severity watersheds required 7 and 14 years, respectively. Therefore, monitoring rehabilitation treatment effectiveness through the recovery process requires several years.

#### **Methods for evaluating and monitoring hillslope treatment effectiveness**

Post-fire runoff and sediment yields are often estimated from related data, because direct measurement of runoff and erosion is usually expensive, complex and labor-intensive (Robichaud *et al.* 2000). If runoff and erosion are to be measured directly to determine post-fire rehabilitation treatment effectiveness, this research demands both a quick response, in order to measure the potentially largest erosion events that occur in the first post-fire year, and a commitment of several years so that treatment effects can be evaluated through the initial recovery period and compared with the natural recovery process that occurs in burned but untreated control areas.

Robichaud and Brown (2002, 2003) have developed and implemented rapid-response approaches to compare treatment effectiveness by monitoring sediment yield and runoff response. Small watershed impoundments and sediment fence sites are established within weeks following a forest fire and are monitored for 3–5 years. This rapid response allows measurements to be made during the first post-fire year when runoff and erosion are likely to be greatest, and allows for continued monitoring through the initial recovery process. In addition to trapping and measuring the sediment from a hillslope, treatment effectiveness has been examined using rainfall simulation experiments that measure plot-scale infiltration, and interrill and rill erodibility (Robichaud 2000a; Pierson *et al.* 2001). In order to run the first trials before any recovery has occurred, the rainfall simulation experiments require the same rapid response approach and, like the sediment collection experiments, are repeated for 3–5 years to monitor changes in infiltration and erodibility during the initial recovery process. Regardless of which research techniques are used, site characteristics, including soil physical properties, water repellency characteristics and ground cover measurements, are recorded in addition to rainfall and erosion data to compare the erosion rate and recovery processes between treated and untreated sites (Robichaud and Brown 2002).

#### Paired catchments

A paired catchment experiment uses two adjacent catchments that are closely matched for size, slope, aspect, elevation, soil characteristics and burn severity. Catchments are large enough to include at least one natural drainage channel with a single exit point for water and sediment. One catchment has a post-fire rehabilitation treatment applied and one is left untreated as a control. With adjacent catchments, there is a greater chance that isolated thunderstorms will affect both areas with similar rainfall characteristics. The sizes of these catchments (2–12 ha) are large enough to generate sufficient runoff and sediment to compare treatment effectiveness, yet small enough that total runoff and sediment loads are measurable. Generally, catchments have high sediment delivery ratios with little eroded material stored in depositional areas that could decrease the measured erosion rate. Catchment size areas are most useful for validation of runoff and sediment yield models (Mutchler *et al.* 1988).

Near the outlet of each catchment, a sediment impoundment structure is aligned within the main catchment channel and installed (Fig. 1). Each structure is adapted to fit the various contours of the individual catchments, but generally a sheet metal barrier with a V-notch weir is partially buried in a shallow (0.4–0.7 m) hand-dug trench and supported with wood posts and metal bracing. Concrete is poured into the trench on both sides of the sheet metal, embedding the base of the sheet metal wall to give it solid support and inhibiting undercutting by impounded water (Fig. 1). On the outside



**Fig. 1.** Typical paired catchment sediment basin after removal of sediment. (a) Sheet metal barrier wall; (b) sediment basin area; (c) debris collection rack; (d) V-notch weir; (e) magnetic/electronic stage sensor; (f) ultrasonic depth sensor; and (g) tipping-bucket rain gauge.

of the sheet metal wall, concrete is poured into shallow pits where the angled metal supports enter the ground and below the V-notch weir to form a splash zone. Chain link fencing is attached inside the impoundment structure to form a ‘trash rack’ that protects the V-notch weir from large debris (Fig. 1) (Robichaud and Brown 2003).

Instruments for measuring water and sediment depths are installed in each impoundment structure and wired directly into a data logger. Flow depth is measured with a magnetic float that slides along a vertical stainless steel rod placed inside a 10-cm diameter slotted polyvinyl chloride pipe to create an electronic stage sensor, which is mounted on the inside of the sheet metal wall (Fig. 1). The volume of runoff can be determined using these flow depth measurements with the 90° V-notch weir. An ultrasonic distance sensor is attached to one end of an L-shaped pipe and mounted on one of the barrier wall support posts with the sensor centered over the impoundment area and directed downward to measure the distance from the sensor to the bottom of the sediment storage basin (Fig. 1). These continuous distance measurements, recorded by the data logger, are used to determine the depth of the sediment and water mix, the sediment, or the snow. Each study site has a complete weather station, connected to the data logger, that provides continuous precipitation, wind, temperature, solar radiation and relative humidity data.

The sediment collected in the impoundment basins is dug out, weighed and sampled manually after each rain event to relate intensity, amount and duration to runoff and sediment yield. Data loggers, powered by photovoltaic panels, store and transmit data via cell phone or radio. Daily telemetric data transmissions allow several widespread installations to be closely monitored (<http://forest.moscowfsl.wsu.edu/engr/weather>, verified 7 October 2005) so that sediment



**Fig. 2.** Locations of fires where paired catchment sites have been installed in western USA.

removal and equipment repair can be scheduled as needed. Measurements of runoff, sediment loads, rainfall, soil characteristics and ground cover are done for all paired catchments. In addition, some post-fire rehabilitation treatments require specific data for analyzing effectiveness. For example, contour-felled log erosion barriers (LEBs) are surveyed for their sediment-holding capacity, position and effectiveness (based on quality of the installation) and, after each runoff event, sediment accumulation and causes of individual LEB failure are determined.

Rapid response after a wildfire requires advanced preparation of the materials, equipment and labor needed to install the impoundment structures, measurement equipment and electronic monitoring systems. Immediately after a fire is controlled, suitable catchments for these studies are identified by considering physical characteristics, post-fire emergency rehabilitation treatment implementation areas and accessibility. To take advantage of the study sites, four to six technicians, equipment trucks and at least one equipment container trailer are transported to the study site for 4–8 days of construction to complete a paired catchment installation. Using this rapid response technique, ten paired-watershed sites have been installed over the past 6 years (Fig. 2) to measure and evaluate LEBs, straw mulch and hydromulch treatment effectiveness (Table 1).

#### *Sediment fences*

Sediment fences, constructed of geotextile silt fence fabric, provide a less expensive method to directly measure hillslope erosion (Robichaud and Brown 2002) (Fig. 3). Using the installation procedure described in Robichaud and Brown



**Fig. 3.** Typical sediment fence where accumulated sediment is being removed.

(2002), two or three people can install several sediment fences in a day using hand tools and relatively small amounts of materials. Consequently, this technique is useful for erosion measurements in remote sites.

Sediment fences are best located on uniform slopes with minimal obstructions or in small swales (<0.5 ha in size). For research purposes, multiple fences may be installed adjacent to one another across a slope with test treatments randomly applied to each plot. This is a useful way to test new erosion treatment products and techniques. To monitor the effectiveness of post-fire rehabilitation treatments applied over large areas, sediment fences can be installed within treated areas. However, in order to compare treatment effectiveness, care must be taken to match sediment fence plot slope, aspect, elevation, area, hillslope position and burn severity between the various treatments and the untreated controls. A contributing area for each sediment fence is defined by a natural or constructed barrier across the upslope plot edge to trap or divert runoff and sediment away from the study plot area and out of the sediment fence. Well-installed fences can withstand

**Table 1. Paired catchment installations to evaluate post-fire rehabilitation treatment effectiveness**

Fire name, location	Fire year	Rehabilitation treatment		Treatment catchment area (ha)	Control catchment area (ha)
		Description	Application rate (logs ha <sup>-1</sup> or t ha <sup>-1</sup> )		
North 25, Washington	1998	Contour-felled log erosion barriers	43 logs	9.0	11.0
Mixing, California	1999	Contour-felled log erosion barriers	131 logs	1.2	1.1
Valley Complex, Montana	2000	Contour-felled log erosion barriers	113 logs	3.0	4.2
Fridley, Montana	2001	Contour-felled log erosion barriers	70 logs	11.8	13.3
Hayman, Colorado	2002	Contour-felled log erosion barriers	110 logs	3.1	3.0 <sup>B</sup>
		Salvage logged <sup>A</sup>	NA	2.9	
Hayman, Colorado	2002	Aerial straw mulch	2.25 t	3.2	4.5 <sup>B</sup>
		Aerial hydromulch	2.25 t	5.2	
Cannon, California	2002	Contour-felled log erosion barriers	78 logs	12.5	8.6
Kraft Springs, Montana	2002	Salvage logged <sup>A</sup>	NA	3.7	2.8
Roberts, Montana	2003	Aerial straw mulch	2.25 t	2.3	2.1
Cedar, California	2003	Hydromulch, applied in contour strips for 50% surface coverage	2.25 t	2.6	1.5 <sup>B</sup>
		Hydromulch, applied over entire area for 100% surface coverage	2.25 t	2.1	

<sup>A</sup>Not a post-fire rehabilitation treatment. The erosion rate from the salvage-logged site is being compared to the erosion rate from the control site to determine effects of post-fire timber harvesting.

<sup>B</sup>A burned, untreated catchment, placed between two treated catchments, serves as the control for both treatments.

**Table 2. Sediment fence installations to evaluate post-fire rehabilitation treatment effectiveness**

Fire name, location	Fire year	Treatments	Total sediment fence plots/treatment replications
North 25, Washington	1998	Seed, fertilizer, seed and fertilizer, control	32/8
Valley Complex, Montana	2000	Straw wattle, contour-felled log, hand trench, control	16/4
Hayman, Colorado	2002	Straw mulch, wood straw, contour raking, control; treatments repeated on two slope classes	32/4
Indian, Arizona	2002	Shredded wood strands, straw pellets, straw mulch, control	4/1
Myrtle Creek, Idaho	2003	Straw mulch, hydromulch, natural pine needle cast, control	24/6
Roberts, Montana	2003	Surfactant, control	12/6
Hot Creek, Idaho	2003	Straw mulch, multi-log erosion barriers, control	18/6
Cedar, California	2003	Hydromulch – full surface coverage, hydromulch – contour strips for 50% surface coverage, control; treatments repeated on 2 soil types	60/10

the force of creeping snow during the winter months even on slopes >60%.

Continuous-recording tipping-bucket rain gauges are installed adjacent to the sediment fence plots in an open-canopy area for each research site. These low-cost rain gauges have internal data loggers that are manually downloaded during site visits. As with paired catchment basins, sediment impounded by sediment fences is removed, weighed and sampled manually after each rainfall event so that rainfall characteristics can be directly related to the sediment yield. However, because there is no transmission of data from the study site, it is more difficult to determine when sediment fences have accumulated sediment needing to be removed or if sediment fences or rain gauges need repair. In addition, no runoff data are collected, and the smaller plot sizes allow only rill and interrill erosion processes to be measured. These shortcomings are compensated by the low cost and

ease of installation, which allows for a larger number of treatment replications within a study. The analysis techniques described in Robichaud and Brown (2002) include the use of the Friedman test, a nonparametric test for significance difference between groups, because sediment yield data are often non-normal highly skewed distributions.

A number of researchers have used or are currently using sediment fences to determine erosion rates at the hillslope scale (e.g. Dean 2001; Spigel 2002; Wagenbrenner *et al.* in press). Eight sediment fence sites, located in Washington, Montana, Colorado, Arizona, California and Idaho, have been established to evaluate post-fire rehabilitation treatments that include the application of seed, fertilizer, seed with fertilizer, straw mulch, surfactants, hydromulch, wood straw, shredded wood strands, straw pellets, LEBs, straw wattles, multi-log constructed erosion barriers, hand trenching and contour raking (Table 2).

### *Rainfall simulation*

Rainfall simulation techniques have been used to measure rill and interrill erosion, runoff, infiltration and erodibility in agricultural, rangeland, forest and other managed conditions (Renard *et al.* 1979). Although rainfall simulation studies do not directly measure the erosion rate, the measured soil parameters (infiltration and erodibility) are directly linked to soil erosion potential and are essential parameters in the post-fire erosion models being developed. In addition, these soil parameters change in response to wildfire and then recover over time (Pierson *et al.* 2001). To measure the full range of fire effects and to capture the recovery process, rainfall simulation experiments must be initiated immediately after the fire and continued for several years. Measurements can be taken on burned plots and compared to unburned plots or they can be done on burned plots that have been treated with post-fire rehabilitation treatments and compared to untreated burned plots (Robichaud 2000a; Pierson *et al.* 2001).

Rainfall is applied with overhead sprayers at various intensities to exceed natural infiltration rates. Interrill erodibility and infiltration are determined from samples of runoff and sediment, which are usually taken at 1- or 2-min intervals throughout the simulation. To measure rill erodibility, water is pumped through a flow meter and applied as overland flow on pre-wetted plots that are generally 2 m wide  $\times$  9 m long. The flow rate is varied and rill formation is measured. Both types of experiments require road access within 300 m of the study site, specialized equipment, a water source and several trained technicians.

### *Comparing erosion data*

Erosion rates are measured in mass of eroded sediment per unit area (1 ha) per unit time (1 year), or mass of sediment transported across a unit hillslope contour (1 m) per unit time (1 day), the latter being referred to as a sediment flux rate. Comparing erosion rates between two different studies is complicated by variability in rainfall, soil type, topography and other site differences. In addition, the variability introduced by measuring erosion rates at different scales (e.g. comparing erosion rates determined from paired catchment measurements with hillslope sediment fence measurements) is difficult to assess. Erosion from plot scales usually has interrill and rill components, and erosion measured at the catchment scale will include those two processes as well as some channelized flow. As a result, the erosion rates measured at the catchment scale may be greater (due to downcutting or widening of the flow path) or less (due to sediment redistribution within the catchment) than the erosion rate measured at the plot scale. Of the ten paired catchment sites (Table 1) being monitored in our studies, only two (Fridley and Hayman) have had observable channel downcutting and widening after high-intensity rainfall events. In addition, because the paired catchments are located in steep areas (35%

or greater mean slopes), there is little sediment storage within the catchments.

### **Emergency post-fire hillslope rehabilitation treatments being used and studied**

Hillslope post-fire rehabilitation treatments, intended to reduce surface runoff and keep soil on the hillslope, can generally be categorized into three groups: (1) seeding for vegetative regrowth and invasive weed control; (2) ground covers or mulches; and (3) barriers and trenches that physically hold runoff and sediment. Within these groups, there are several techniques and products to choose from, and more are being developed and tested. However, the effectiveness of any hillslope rehabilitation treatment depends on the actual rainfall amounts and intensities – especially in the first 1–3 years after the fire. For example, on the 2000 Bobcat Fire in the northern Colorado Front Range, dry straw mulch, seeding and LEBs did not significantly reduce sediment yields in the first year after the fire. During the first post-fire summer, an intense rain event ( $I_{30} = 48 \text{ mm h}^{-1}$ ) overwhelmed all the applied treatments, resulting in the same or greater sediment yields on treated plots as on untreated control plots. Some treatments did reduce sediment yields in the second year after burning, when rainfall occurred over several smaller events (Wagenbrenner *et al.* in press).

### *Seeding*

Historically, broadcast seeding of grasses, usually from aircraft, has been the most common post-fire rehabilitation treatment. Rapid vegetation establishment has been regarded as the most cost-effective method to promote water infiltration and reduce hillslope erosion (Noble 1965; Rice *et al.* 1965; Miles *et al.* 1989). Because of the difficulty and expense involved in measuring hillslope erosion directly, most evaluations of seeding effectiveness have been reported in terms of ground cover or canopy cover produced, rather than any direct measurement of erosion reduction (Robichaud *et al.* 2000; Beyers 2004). The studies reviewed by Robichaud *et al.* (2000) suggest that seeding does not assure higher plant cover during the critical first year after burning. For example, Robichaud *et al.* (2000) examined nine seeding studies in conifer forests that provided quantitative ground cover data. In the first growing season after the fire, about half of the studies reported <30% ground cover and only 22% reported at least 60% ground cover. In other words, the 60–70% ground cover needed for erosion reduction (Robichaud *et al.* 2000; Pannkuk and Robichaud 2003) was attained in less than one-fourth of the treated areas during the first growing season. Better cover, and thereby better erosion mitigation, can be expected in the second and subsequent years. However, several studies from various areas in the western USA show that second- and, in some cases, third- and fourth-year erosion rates were not affected by seeding (Roby 1989;

Van de Water 1998; Wohlgemuth *et al.* 1998; Wagenbrenner *et al.* in press). Beyers (2004), in a recent review of post-fire seeding effectiveness, reported that when post-fire seed growth provides enough cover to substantially reduce erosion (60–70%), it generally suppresses revegetation by naturally occurring species.

### Mulching

Mulch is material spread over the soil surface to protect it from rain impact and reduce overland flow. Many materials, including paper, wood chips, wheat and rice straw, jute, and natural and synthetic fabrics, have all been used as mulch. Mulch mixed with grass seed is frequently applied to improve the germination of seeded grasses by increasing infiltration and enhancing soil moisture retention (Robichaud *et al.* 2000). In the past, seed germination from grain or straw mulch was regarded as a bonus as this increased the cover on a site; however, the introduction of the straw species, noxious weeds and other non-native plants are now considered drawbacks to the use of straw mulch. In addition, the mat of mulch on the soil surface, depending on factors such as thickness, type of material and percentage of surface covered, may inhibit native herb and shrub germination (Beyers 2004).

Straw mulch is effective – it has been shown to reduce erosion rates after wildfires by 50–94% (Bautista *et al.* 1996; Faust 1998). In a comparative study continued for two rainy seasons after the 2000 Cerro Grande Fire in New Mexico, the plots treated with aerial seed and straw mulch yielded 70% less sediment than the control plots in the first year and 95% less in the second year. Ground cover transects showed that aerial seeding without added straw mulch provided no increase in ground cover relative to untreated plots (Dean 2001). In the second year after the 2000 Bobcat Fire in Colorado, Wagenbrenner *et al.* (in press) reported sediment yields from mulched hillslopes that were significantly less than those from both untreated and seeded-only slopes.

The use of helicopters to spread dry mulch is relatively new in post-fire emergency rehabilitation. Straw bales suspended in cargo nets break apart as they fall and spread further upon impact, resulting in a fairly even distribution of straw mulch with ~70% ground cover when applied at a rate of 2.4 Mg ha<sup>-1</sup> (Fig. 4). Owing to the cost and logistics of straw mulching, it is usually used to protect high-value resources, such as reservoirs, water quality, habitat, roads, structures and sensitive cultural sites, from upslope erosion.

The use of hydromulch for post-fire rehabilitation is an example of new efforts to take advantage of the general success of hydromulches as a treatment on bare soil after road and building construction. There are numerous combinations of tackifier, polymers, bonded fiber, seeds, etc., used in hydromulch, which, when mixed with water and applied to the soil surface, form a matrix that can reduce erosion and foster plant growth. Hydromulch is commonly applied with truck-mounted spray equipment and has been shown to reduce



Fig. 4. Aerial application of straw mulch on a research catchment in the high-severity burned area of the 2002 Hayman Fire (Colorado, USA).

erosion by up to 97% in unburned applications (San Diego State University 2002). It has only been applied in a limited number of post-fire situations. For example, after the 2002 Hayman Fire in Colorado, 600 ha of aerial hydromulching was applied to steep, inaccessible areas that drain directly into the South Platte River and the reservoir system that provides 90% of Denver's municipal drinking water (Robichaud *et al.* 2003a). Large-scale application to burned hillslopes for post-fire rehabilitation requires helicopters fitted with slurry tanks and access to a nearby staging area, making aerial application of hydromulch more expensive than dry mulching treatments (Fig. 5).

In some burned areas, natural mulch may provide adequate ground cover making the 'no treatment' option a practical choice. After a wildfire, there is a mosaic of low, moderate and high burn severity conditions within the burned area (DeBano *et al.* 1998). Low and moderate burn severity areas produce less runoff and erosion than high burn severity areas (Benavides-Solorio and MacDonald 2001). In conifer forests, low and moderate burn severity sites often have trees that are lightly charred and partially consumed by fire, leaving dead needles in the canopy. These needles fall to the ground



**Fig. 5.** Aerial application of hydromulch on a research catchment in the high-severity burned area of the 2002 Hayman Fire (Colorado, USA).

and provide a natural mulch ground cover. Pannkuk and Robichaud (2003) found a 60–80% reduction in interrill erosion and a 20–40% reduction in rill erosion due to a 50% ground cover of dead needles. Thus, prudent use of post-fire rehabilitation treatments would exclude areas where needles are present to provide sufficient ground cover.

#### *Erosion barriers*

Straw wattles (Fig. 6), straw bales, LEBs (Fig. 7) and other natural and engineered structures have been used to provide mechanical barriers to overland flow, promote infiltration and trap sediment, and thereby reduce sediment movement on burned hillsides. LEBs have been used widely in areas where fires leave dead trees that can be felled, placed along the contours of burned hillslopes and staked in place, and the gaps between the logs and soil surface filled with additional soil to prevent underflow (Robichaud 2000b). Some recent installations have included the construction of soil berms at the end of the logs to increase their storage capacities.

Miles *et al.* (1989) monitored LEBs after the 1987 South Fork Trinity River fires in California and considered sediment trapping efficiency to be low and cost to be high for this treatment. Dean (2001) found that plots treated with both LEBs and straw mulch with seed yielded 77% less sediment in the first post-fire year and 96% less in the second year; however, these results were not significantly different from the straw mulch with seed treatment alone. Preliminary data from on-going studies suggests that LEBs can be effective for low- to moderate-intensity rainfall events. However, during high-intensity rainfall events, their effectiveness is greatly reduced (Robichaud 2000b). The effectiveness of LEBs also decreases over time as the sediment storage areas behind the logs become filled and the barriers can no longer trap mobilized sediment (Robichaud 2000b; Wagenbrenner *et al.* in press).



**Fig. 6.** A straw wattle erosion barrier is tested during a rainfall simulation experiment following the 2000 Valley Complex Fire (Montana, USA).



**Fig. 7.** Fire crews install a contour-felled log erosion barrier in a research catchment after the 1999 Mixing Fire (California, USA).

#### **Preliminary contour-felled log erosion barrier treatment effectiveness data**

Some data from the first and second post-fire years are available from six paired catchment sites where LEBs are being studied. These preliminary results generally show the greatest erosion during the first year following a fire (Table 3). At the North 25, Mixing and Fridley sites, similar or greater erosion was measured from the catchments treated with LEBs than from untreated control catchments. A first-year, high-intensity rainfall event ( $70 \text{ mm h}^{-1}$ , maximum 10-min intensity) completely filled the Fridley catchment sediment storage basins and the data (overflow amounts were estimated) show that treatment had no discernable effect on the erosion rate. In contrast, Bitterroot, Hayman and Cannon sites



**Table 3. Preliminary results from paired catchment studies of contour-felled log erosion barrier (LEB) treatment effectiveness**

Fire name, location	Year	Mean annual sediment yield	
		LEB treated (Mg ha <sup>-1</sup> )	Untreated (Mg ha <sup>-1</sup> )
North 25, Washington	1999	1.1	0.64
	2000	0	0
Mixing, California	2000	0.4	0.03
	2001	0.09	1.8
Valley Complex, Montana	2001	0.15	0.64
	2002	0.48	0.93
Fridley, Montana	2002	6.1	6.7
	2003	0.16	0.3
Cannon, California	2002	0.11	0.13
	2003	0.003	0.005
Hayman, Colorado	2003	11	24

showed about a 50% reduction of erosion on the LEB-treated catchments compared to the untreated catchments during the first year. Generalizing from the data collected to date, the expected first-year erosion reduction from LEBs is ~20–50% in areas exposed to moderate- to high-intensity rainfall events, and unlikely to be higher than 70% for any rainfall event. Once the LEBs are filled to capacity, any additional runoff causes sediment-laden water to flow around and over the logs. Their effectiveness is likely to be a function not only of rainfall intensity and amounts and the sediment-holding capacity of the barriers as installed, but also of soil type, topography and ground cover.

### Post-fire erosion prediction models

Some of the post-fire infiltration, erodibility and erosion rate data are being used to parameterize and validate web-based post-disturbance erosion prediction models. These models, based on Water Erosion Prediction Project (WEPP) technology (Flanagan and Livingston 1995), include Disturbed WEPP (Elliot *et al.* 2001a; Elliot 2004) and the Erosion Risk Management Tool (ERMiT) (Elliot *et al.* 2001b, 2001c; Robichaud *et al.* 2003b). To facilitate broad access and ease of use, these models as well as the climate models that generate input files, are available at <http://forest.moscowfsl.wsu.edu/fswapp/> (verified 7 October 2005).

Disturbed WEPP provides estimates of annual hillslope erosion given various management scenarios, including prescribed fire and wildfires. However, Disturbed WEPP does not account for the spatial and temporal variability of fire effects on soil and erosion processes (Robichaud and Miller 1999). ERMiT provides probabilistic estimates of single-storm post-fire hillslope erosion by incorporating variability in rainfall characteristics, burn severity and soil characteristics into each prediction (Robichaud *et al.* 2003b). ERMiT users specify: (1) climate parameters (based on location with adjustments made through Rock : Clime (Elliot 2004)); (2) vegetation type (forest, range, chaparral); (3) soil type

(clay loam, silt loam, sandy loam, loam) and rock content; (4) topography (slope length and gradient); and (5) burn severity class (low, moderate, high). These input choices are similar to other WEPP-based interfaces (Elliot 2004). However, the model-generated variabilities and probabilistic output are unique to ERMiT.

Probabilities for the ERMiT climate parameters are determined by CLIGEN (Nicks *et al.* 1995), which is accessed through Rock : Clime and generates a 100-year climate record for the selected site. Years with the 5th, 10th, 20th, 50th and 75th largest runoff events are selected for further analysis. These rain events represent the 20-, 10-, 5-, 2- and 1½-year return interval runoff events and have occurrence probabilities of 7.5, 7.5, 20, 27.5 and 37.5%, respectively. Only these years are used with the model-generated combinations of spatial variation in burn severity and soil characteristics (Elliot *et al.* 2001b, 2001c).

Based on data from rainfall simulation experiments (Robichaud 1996; Brady *et al.* 2001; Pierson *et al.* 2001), four spatial arrangements of overland flow elements, with assigned probabilities, are used for the burn severity class selected. Within each of these spatial arrangements, five distributions of soil characteristics, with a 10, 20, 40, 20 and 10% probability of occurring, are used for the soil texture selected. The soil characteristics change with each post-fire year to reflect site recovery. ERMiT runs the 20 combinations of spatial distributions and soil characteristics for 4 years producing 80 possible soil erosion rates and their associated probabilities. Predicted erosion in the second, third and fourth years is based on these initial runs with ground cover amounts doubling each year (generalized field observations) until the site recovers.

The Erosion Risk Management Tool also can provide probabilistic estimates of the erosion reduction to be expected for three treatments – seeding, straw mulching and LEBs. Data from rain simulation, sediment fence and paired catchment studies are being used to calibrate the erosion reduction and sediment trapping efficiency (sediment stored by a LEB divided by sediment leaving the hillslope) of these treatments. Based on these data, straw mulch lowers predicted first-year erosion rates due to increased ground cover by more than the other treatments. Predicted erosion rates for LEBs vary with rainfall intensity (less erosion reduction occurs with high-intensity rainfall events) as well as with estimated sediment storage capacity already filled.

Validation of ERMiT predictions are under way by various users. New data from treatment effectiveness studies and post-fire erosion measurements will expand and refine the number of post-fire rehabilitation treatments that can be modeled in ERMiT. Land managers who have used the model find the probability-based erosion predictions particularly useful when applied to risk-based management decisions, such as where to apply post-fire rehabilitation treatments to mitigate potential erosion.

## Conclusions

Post-fire rehabilitation efforts continue to be a major land management activity due to the increase in the number, size and intensity of wildfires in the western USA during the past decade. The threat of future wildfire damage to resources and property is creating a demand for demonstratively effective erosion mitigation strategies as well as improved modeling tools on which to base treatment decisions. Hillslope treatments, designed to reduce runoff and erosion at their sources, have the most potential to provide the required protection to valued resources, such as water quality, habitat, roads and structures. However, the measurement of hillslope erosion, a necessary component of treatment effectiveness assessments, can be expensive and time consuming. The use of sediment fences to measure hillslope erosion is less expensive and easier to install and manage than most other alternatives. Because the highest erosion rates are generally observed the first year after the fire, and are often an order of magnitude greater than in the second year, post-fire erosion measurement requires rapid mobilization of equipment, materials and labor to capture the first, and potentially largest, post-fire erosion events.

Monitoring post-fire rehabilitation treatment effectiveness is providing quantified data that can be used to determine whether post-fire rehabilitation treatments are meeting their objectives. Preliminary analysis of results suggests that treatment performance may be closely related to rainfall characteristics (intensity, amount and duration) and length of time since the fire. In preliminary analysis of LEB effectiveness data, these barriers appear to slow runoff and trap more of the eroded sediment onsite during low-intensity rainfall events than during high-intensity rainfall events.

Post-fire rehabilitation treatments cannot prevent erosion, but they can reduce overland flow amounts, site soil loss and sedimentation for some rainfall events. Therefore, the risk of post-fire damage to water quality, habitat, roads and other structures cannot be eliminated, but it can be reduced. It is useful to do risk assessments – balancing the increased risk of erosion, flooding, etc., against the risk reduction expected from specific treatments – when making post-fire treatment decisions. The need to protect the valued resources in and around burned areas has motivated efforts to improve the effectiveness of post-fire rehabilitation treatments, develop post-fire erosion prediction models and evaluate new rehabilitation treatment technologies.

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