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Post-Fire Treatment Effectiveness for Hillslope Stabilization

Peter R. Robichaud, Louise E. Ashmun, and Bruce D. Sims





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Abstract

This synthesis of post-fire treatment effectiveness reviews the past decade of research, monitoring, and product development related to post-fire hillslope emergency stabilization treatments, including erosion barriers, mulching, chemical soil treatments, and combinations of these treatments. In the past ten years, erosion barrier treatments (contour-felled logs and straw wattles) have declined in use and are now rarely applied as a post-fire hillslope treatment. In contrast, dry mulch treatments (agricultural straw, wood strands, wood shreds, etc.) have quickly gained acceptance as effective, though somewhat expensive, post-fire hillslope stabilization treatments and are frequently recommended when values-at-risk warrant protection. This change has been motivated by research that shows the proportion of exposed mineral soil (or conversely, the proportion of ground cover) to be the primary treatment factor controlling post-fire hillslope erosion. Erosion barrier treatments provide little ground cover and have been shown to be less effective than mulch, especially during short-duration, high intensity rainfall events. In addition, innovative options for producing and applying mulch materials have adapted these materials for use on large burned areas that are inaccessible by road. Although longer-term studies on mulch treatment effectiveness are on-going, early results and short-term studies have shown that dry mulches can be highly effective in reducing post-fire runoff and erosion. Hydromulches have been used after some fires, but they have been less effective than dry mulches in stabilizing burned hillslopes and generally decompose or degrade within a year.

Keywords: BAER, contour-felled logs, hydromulch, LEB, straw mulch, PAM, wood shreds, wood strands

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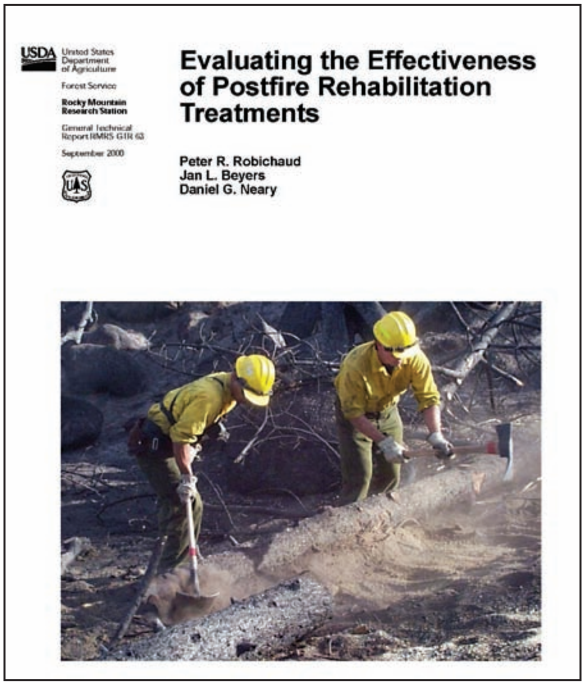
Preface

This report is a synthesis of post-fire emergency hillslope stabilization treatment effectiveness information that was written to provide guidance for future post-fire treatment selection and use. It builds on an earlier synthesis, *Evaluating the Effectiveness of Postfire Rehabilitation Treatments* (Robichaud and others 2000) (fig. 1). Since that publication, the effectiveness of emergency post-fire hillslope treatments have been evaluated in several scientific studies and treatment monitoring reports prepared by Burned Area Emergency Response (BAER) and Emergency Stabilization and Rehabilitation (ESR) teams. In addition, our knowledge of how environmental factors impact treatment effectiveness and the development of new post-fire hillslope treatment products and application techniques has grown. The objective of this document is to synthesize that new information in a format that is easily accessible by post-fire assessment teams and land managers.



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Rocky Mountain Research Station

General Technical Report RMRS-GTR-63

September 2000

Evaluating the Effectiveness of Postfire Rehabilitation Treatments

Peter R. Robichaud
Jan L. Beyers
Daniel G. Neary

Figure 1. Cover of RMRS-GTR-63 (Robichaud and others 2000).

Scope of Post-Fire Treatment Effectiveness for Hillslope Stabilization

This synthesis focuses on post-fire hillslope emergency stabilization treatments, including erosion barriers, mulching, chemical soil treatments, and combinations of these treatments. This is a narrow focus given the range of post-fire emergency responses typically implemented by BAER teams (see Napper 2006 for a comprehensive review of post-fire treatments). However, these hillslope treatments are usually the most expensive post-fire treatments used, which makes cost effectiveness an important factor in their selection. In addition, recent reports synthesize the current information for other post-fire emergency treatments. For example, a synthesis of broadcast seeding, one of the first and most extensively used post-fire hillslope treatments (Robichaud and others 2000), is discussed in papers being prepared by Jan Beyers (Pacific Southwest Research Station), Carolyn Hull Sieg (Rocky Mountain Research Station), Peter Fulé and colleagues (Northern Arizona University), and David Pyke (U.S. Geological Survey). Consequently, seeding is only included in this report when it was used in combination with other hillslope treatments. Post-fire stabilization treatments for roads are frequently implemented to facilitate the passage of potentially larger post-fire water flows that may damage roadways, culverts, bridges, etc. These treatments and their known effectiveness have been addressed in *A Synthesis of Post-Fire Road Treatments for BAER Teams* (Foltz and others 2009) and are not included in this synthesis.

Post-fire treatments to stabilize channels or deflect large channel flows are occasionally recommended after wildfires, but there are few quantified data on treatment performance, and those treatments are not discussed in this document. However, some hillslope treatment effectiveness studies have been done on swales, hillslope plots that contain two convergent hillslopes that form a zero-order channel, and small catchments that contain one or more low-order channels with a clearly defined outlet. In these studies, the measured eroded sediment is trapped at the base of the hillslope swale or at the outlet of the low-order catchment channel system and includes the eroded sediment from the hillslopes and channels within the contributing area. Those studies are included in this synthesis because hillslope stabilization treatments (as opposed to channel treatments) were evaluated.

We have synthesized the available post-fire hillslope treatment effectiveness research and monitoring data that apply to the United States. However, with few exceptions, the data are from studies done in the western United States. There are some post-fire hillslope treatment studies from Europe, particularly Spain and Portugal, but the majority of the relevant research is from the western United States where hillslope treatments have been implemented after large wildfires. Wildfires do occur in the central and eastern United States, but post-fire hillslope stabilization treatments are rarely implemented, and there are few or no available data on treatment effectiveness. Generally, post-fire recovery occurs more rapidly in these wetter climates than in the drier western forest. However, with climate change, the risk of larger and more severe wildfires is becoming increasingly important in areas like the southeastern piedmont forests (Crumbley and others 2007). The treatment effectiveness information that has been generated in the western United States will likely apply to other areas if post-fire treatments are warranted.

Side Bars

Side bars are the shaded boxes outside the main report narrative that contain unpublished treatment information that is more anecdotal than scientific. They are included to illustrate a decision-making process, describe an interesting observation, or show how environmental factors impacted the effectiveness of a treatment.

All photos are from the USDA Forest Service, unless otherwise noted.

Post-Fire Treatment Effectiveness for Hillslope Stabilization

Peter R. Robichaud, Louise E. Ashmun, Bruce D. Sims

Introduction

Wildfires continue to be a major land management concern in the United States and throughout the world. The number and severity of wildfires in the United States has increased during the past decade (National Interagency Fire Center 2009), and the rise is likely to continue, especially in the western United States where drought and other effects of climate change are exacerbating wildfire conditions (Brown and others 2004; Flannigan and others 2000; Miller and others 2009; Westerling and others 2006). At the same time, the number of people living in the wildland-urban interface continues to grow, putting human life and safety, infrastructure, homes, buildings, and natural areas that support livelihoods (grazing, timber, etc.) at risk from wildfire and secondary fire effects such as increased runoff, flooding, erosion, and debris flows (Stewart and others 2003). Mitigating these fire effects has resulted in increased use of post-fire treatments (Robichaud and others 2000; Robichaud 2005).

Realistic and verifiable assessments of post-fire treatment effectiveness are essential if post-fire assessment teams are to choose treatments that balance protection of public safety and values-at-risk with justifiable, cost-effective expenditures of public funds (GAO 2003, 2006). Managers also need to know how and why treatments work so they can determine the best treatment(s) for a specific location and decide how to adapt treatments to improve their effectiveness. For example, the formulation and application rate of mulches can be modified to enhance specific qualities such as longevity, adherence to soil, interlocking of mulch strands, etc. Burned Area Emergency Response (BAER) teams and Emergency Stabilization and Rehabilitation (ESR) teams may vary treatment components and implementation processes (for example, mulch type and formulation, seed content, and application rate) in response to the specific climate, soil, vegetation, and topography of the treatment area. Consequently, this synthesis of post-fire hillslope treatment effectiveness discusses treatment characteristics as they relate to the treatment performance, as well as the effectiveness of various treatments for emergency hillslope stabilization.

Post-Fire Treatment Types

Post-fire treatment activities are divided into three categories—emergency stabilization, rehabilitation, and restoration—that are differentiated by objectives, types, and timing of the processes (GAO 2006). Emergency stabilization treatments (such as mulching to prevent soil erosion, installation of water bars to facilitate water passage over roads, etc.) are conducted within one year of a fire to stabilize the burned area, protect public health and safety, and reduce the risk of additional damage to valued resources such as water supply systems, critical habitat, and infrastructure. The burned area assessment and emergency stabilization plans are implemented as soon as possible in an effort to place treatments before the first damaging rain events are likely to occur (Robichaud and others 2000).

Emergency stabilization activities may be followed by years of rehabilitation and restoration activities (GAO 2006). These longer-term activities can include repair of facilities needed for access and recreation (road and bridge repair, fencing, and facility repair or replacement) and mitigation of land damage that is unlikely to recover to a desired condition on its own (tree or grass planting, noxious weed control, and fuel reduction). BAER activities are restricted to assessing the need for and implementing emergency post-fire stabilization treatments "that provide essential and demonstrated protection at minimum cost while meeting emergency stabilization objectives" (USDA Forest Service Manual 2004, Section 2523.03); however, emergency stabilization treatments may have long-term impacts. Treatment types that are known to enhance, or at least not impede, natural recovery and potential restoration efforts should be favored when treatments are selected for emergency stabilization (Franklin and Agee 2003). Unfortunately, there are few studies on long-term effects of broadcast hillslope stabilization treatments, such as straw mulch or hydromulch, despite their growing use.

Post-Fire Treatment Effectiveness and Treatment Performance

For the purposes of this synthesis, we have differentiated "treatment effectiveness" from "treatment performance." Treatment effectiveness will describe how well a treatment meets emergency stabilization objectives. For example, if straw mulch was applied to burned hillslopes to reduce peak flow rates and sediment yields, the treatment effectiveness would be the reduction in those two variables that could be ascribed to the treatment. Measured peak flow rates and sediment yields from equivalent treated and untreated areas would be compared to make that determination (Robichaud 2005). Differences between the treated and untreated areas are generally expressed in percent difference and are often described as the "percent reduction due to treatment."[1] In contrast, treatment performance is related to the materials used in the treatment (for example, thickness of straw stalks and length of wood strands), installation features (for example, percent cover and depth of straw), and changes over time (for example, movement by wind and decay rate). Treatment performance characteristics can affect treatment effectiveness, which is why they are assessed and monitored in addition to treatment effectiveness. However, emergency hillslope treatment effectiveness information (generally, reduction in runoff, peak flows, and/or sediment yields) can be difficult to interpret when combined with measurements of treatment performance.

Although the need to measure treatment effectiveness has gained acceptance, there are limited data to determine if post-fire treatments are practical and effective. Field measurements of runoff and/or sediment yields in burned areas require a rapid response research protocol (Lentile and others 2007) and are generally expensive and labor-intensive. Such studies are challenging to fund and sustain over time. Nonetheless, quantitative treatment effectiveness data influence treatment decisions.

In the 1990s, contour-felled log erosion barriers (LEBs) were applied on 69 percent of the wildfires that included post-fire hillslope stabilization treatments. Land managers generally regarded these LEB treatments as effective and useful (Robichaud and others 2000). Throughout the 2000s, BAER treatment area and expenditures increased; yet, the use of LEBs decreased rapidly in the first two to three years of the decade. LEBs rarely have been installed since 2002. The transition away from LEBs for post-fire hillslope treatment is directly related to the dissemination of quantitative research results that verified their limited effectiveness (Robichaud 2005; Robichaud and others 2000, 2006, 2008a, b; Wagenbrenner and others 2006).

Post-Fire Hydrology and Erosion

Forested watersheds with good hydrologic conditions (precipitation infiltrates into soil and streamflow response to precipitation is relatively slow) and adequate rainfall generally sustain stream base flow conditions throughout the year and produce little sediment (DeBano and others 1998). Under these conditions, infiltration of snowmelt and rainfall is high (≤2 percent of the rainfall becomes overland flow) and associated erosion is low (Bailey and Copeland 1961). Fire impacts hydrological conditions by destroying accumulated forest floor material and vegetation that provide protection to the mineral soil and hold sediment on hillslopes. Fire often alters infiltration by exposing soils to raindrop impact and creating or enhancing water-repellent soil conditions (DeBano and others 1998, 2005; Doerr and others 2006). High soil temperatures can increase surface soil erodibility—an indication of soil's susceptibility to raindrop impact, runoff, and other erosive processes (Moody and Martin 2009a; Scott and others 2009). With the input of energy, available sediment can be eroded from hillslopes and channels, transported, and deposited downstream. Rainfall, runoff, wind, and gravity are the drivers (energy sources) of these erosion processes; like the forest soil, these drivers are affected by the loss of vegetation and forest floor material. Exposed hillslopes have increased raindrop impact, increased runoff with more power due to longer uninterrupted flow paths and less surface roughness, and increased wind speeds. These changes increase the amount of energy available for erosion and sediment transport (Moody and Martin 2009a).

Fire effects on hydrology can be briefly mitigated by the presence of ash. Forest fires may leave a dry, highly porous ash layer covering the burned mineral soil (Cerdà and Robichaud 2009). The ash layer absorbs rainfall, which increases the time to start of runoff and results in less runoff

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[1] Percent reduction can be misleading when the quantities being compared are small relative to the units of measure. For example, consider the following: The mean sediment yield from treated plots was 0.001 ton ac^{-1} (0.002 Mg ha^{-1}) or about 20 pounds of soil (~one-half of a 5-gallon bucket) from an acre. The mean sediment yield from untreated control plots was 0.01 ton ac^{-1} (0.02 Mg ha^{-1}) or about 200 pounds of soil [~5 full 5-gallon buckets] from an acre. In this case, the percent reduction due to treatment is 90 percent—likely a statistically significant treatment effect. However, the actual sediment yields from both the treated and the control plots are small and of little consequence in the context of post-fire hillslope stabilization.

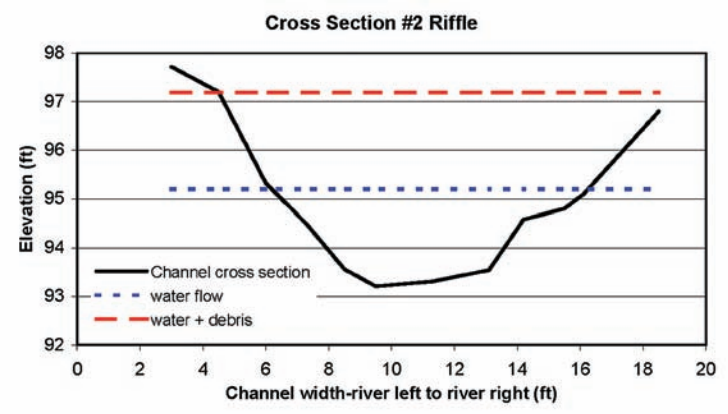
What to Expect—Predicting Post-Fire Response

Contributed by
Nick Gerhardt, Forest Hydrologist (retired)

A year after the 2005 Blackerby Fire in north-central Idaho, a rain event (1.5 inch [38 mm] of rain in 54 min) triggered a large hydrological response on a steep area burned at high severity. The runoff concentrated in the upper and mid reaches of the channels in predictably high volumes, and sediment and debris (rock and some woody materials) were quickly entrained in the flow. As the debris torrent entered the lower reaches, nearly all of the larger material (debris) was deposited, and the high density (sediment-laden) flood flow continued down the channel. The addition of sediment and debris to the concentrated runoff flow increased the flow volume multi-fold. Using measured channel cross sections of the debris torrent and using models to predict the runoff/flow volume, the proportion of water to sediment and debris was estimated (SB1-fig. 1).

Upslope from the culvert locations, cross-sectional areas were almost five times greater for the debris torrent (60.2 ft^2 [5.60 m^2]) when compared to the predicted water flow cross-sections (12.4 ft^2 [1.15 m^2]); volume estimates for the debris torrent (620 $ft^3\ s^{-1}$ [18 $m^3\ s^{-1}$]) were nearly an order of magnitude greater than the flow volume estimated for water alone (SB1-fig. 2). Protection of values-at-risk such as culverts, bridges, and stream-adjacent infrastructure is dependent on an adequate treatment response, and in turn, treatment decisions are dependent on accurate predictions of potential post-fire response.

SB1-figure 1. Cross-section measurements were used to model the storm flow and estimate the parameters of the post-fire debris flow in this channel.



SB1-figure 2. Channel cross-section diagram showing the base channel structure, estimated cross-sectional area of water flow in the channel (based on hydrological modeling), and measured cross-sectional area of the debris torrent (water flow plus debris).

compared to areas with little or no ash cover (Cerdà and Doerr 2008; Onda and others 2008; Woods and Balfour 2008). The effects of the ash on post-fire infiltration and runoff are generally short-lived (weeks to months) as ash is easily transported and is moved to valley bottoms with the first wind and rain events. Consequently, ash effects have little impact on the longer-term post-fire watershed responses that are of primary concern for post-fire treatment (Cerdà and Robichaud 2009).

When high severity fire results in poor hydrologic conditions (most precipitation does not infiltrate into the soil and streamflow response to precipitation is rapid), runoff and peak flows can increase by several orders of magnitude and can cause some of the most extreme impacts faced by land managers (DeBano and others 1998; Neary and others 2005a). Post-fire increases in flooding, channel incision, and debris flows are well documented (for example, Curran and others 2006; DeBano and others 1998; Lane and others 2006; Moody and Martin 2009a,b; Neary and others 2005a). In general, the more intense the watershed response the less effective post-fire treatments will be in mitigating those responses (fig. 2) (Robichaud and others 2008b). Thus, the factors discussed below impact both the potential post-fire watershed responses and the effectiveness of post-fire hillslope treatments.

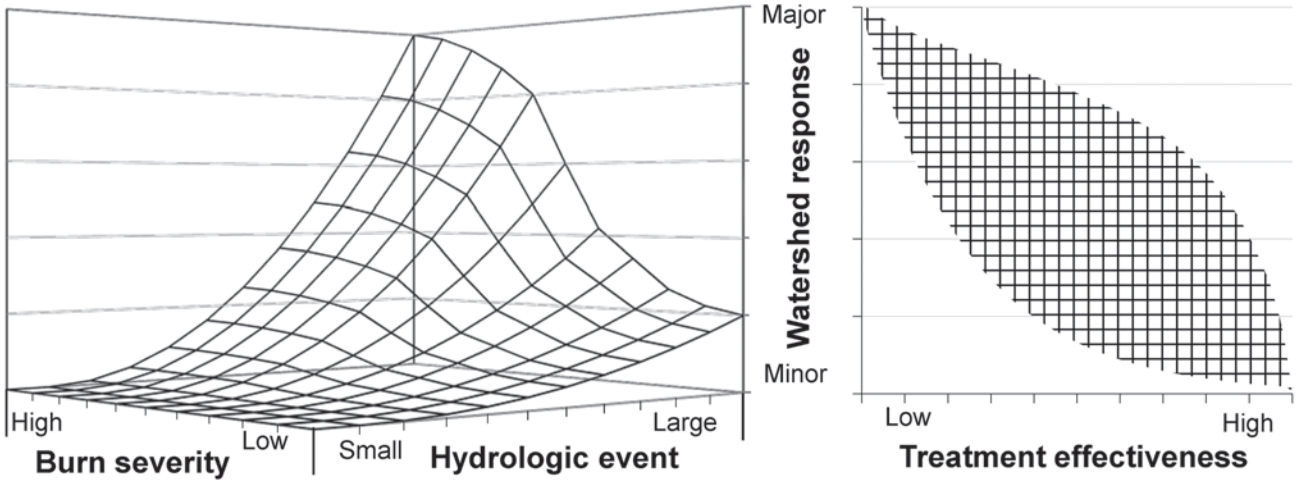


Figure 2. The three-dimensional chart on the left is a conceptual diagram (after Neary and others 2005b) that illustrates the relationships between burn severity (low to high), hydrological event (small to large), and watershed response (minor to major). The chart on the right uses the same vertical axis (watershed response) and adds a fourth dimension—treatment effectiveness (low to high)—that is represented by a cross-hatched area. Treatment effectiveness varies by treatment type but generally decreases as watershed response increases.

Factors That Impact Post-Fire Watershed Response and Treatment Effectiveness

The specific environmental characteristics that impact post-fire treatment effectiveness have been divided into two groups—factors that are not fire dependent (such as topography and rainfall characteristics) and factors that are directly related to the fire (such as soil burn severity and the time since the fire). The cumulative effect of these factors determines the severity of the watershed response and, as a consequence, impacts post-fire treatment effectiveness (Reid 2010).

Factors Unrelated to Fire:

- *Rainfall characteristics, especially rainfall intensity*—Intense, short-duration storms characterized by high rainfall intensity and low rainfall amounts have been associated with high stream peak flows and significant erosion events after fires (fig. 3) (DeBano and others 1998; Moody and Martin 2001; Neary and others 2005b; Robichaud 2005; Robichaud and others 2008a). In a recent publication, Moody and Martin (2009b) synthesized post-fire sedimentation rates for the western United States. Given the connection among rainfall amount, rainfall intensity, and sediment yields, Moody and Martin derived and mapped "rainfall regimes" in the western United States (fig. 4). The rainfall regimes were determined by a combination of rainfall types (based on Kincer 1919) and adjusted by the degree assigned to the two-year 30-minute (min) rainfall intensity ($I_{30}^{2\text{yr}}$) by the authors (table 1). Since the potential rainfall amounts, intensities, and seasonal patterns directly impact post-fire hillslope treatment effectiveness, it is essential to consider the potential rainfall regime of the burned area when selecting treatments.

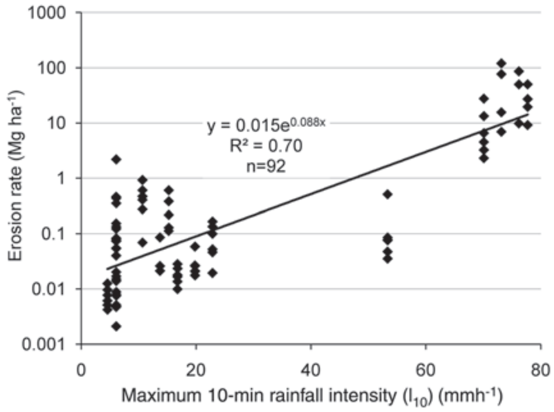


Figure 3. Post-fire year one event erosion rates (plotted on a logarithm scale) versus maximum 10-min rainfall intensity (I_{10}) as measured on hillslope study plots in the Bitterroot National Forest, Montana (after Spigel and Robichaud 2007).

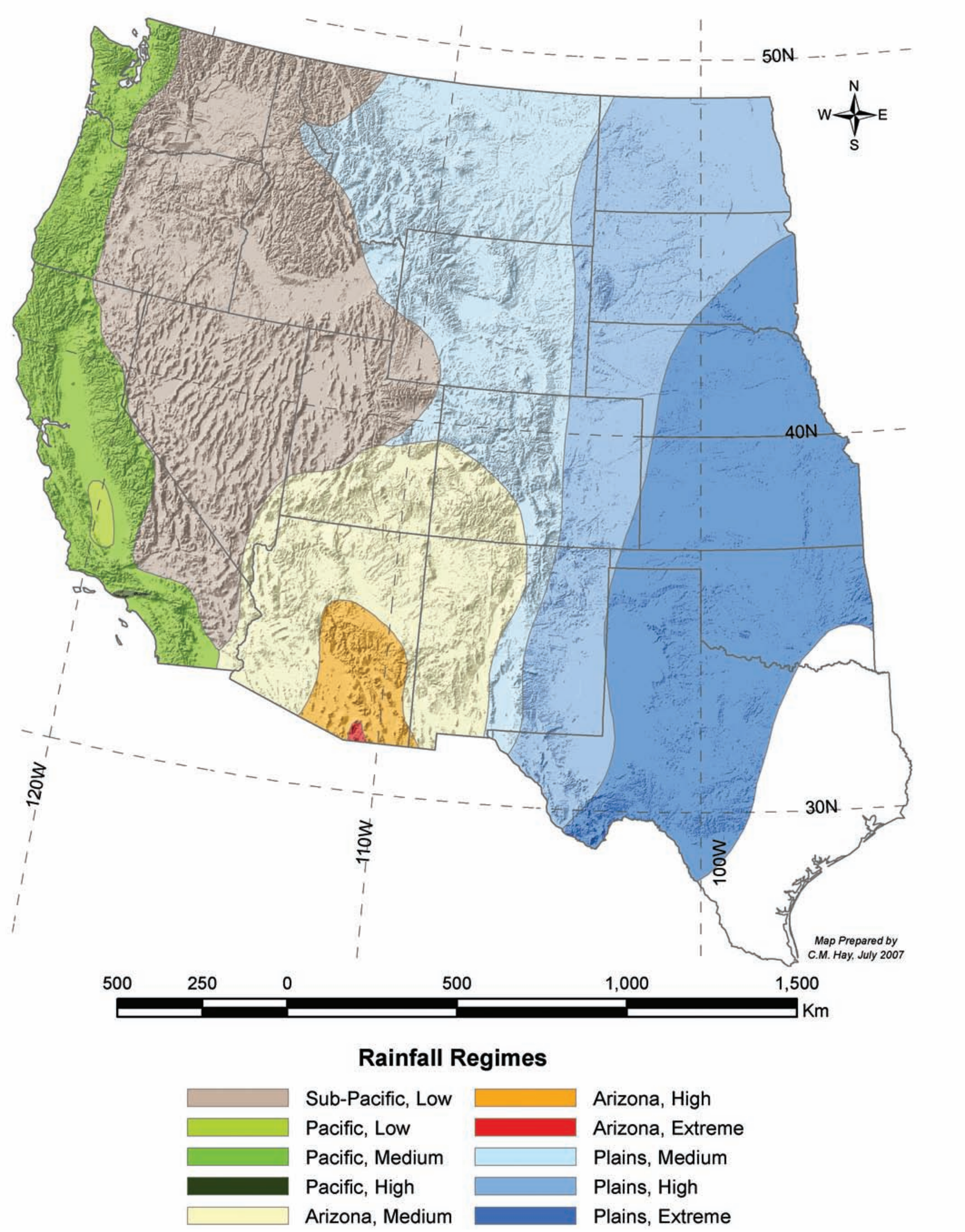


Figure 4. Rainfall regimes in the western United States as delineated by Moody and Martin (2009b; used with permission) (see table 1).

Table 1. Rainfall regimes, seasonal characteristics, intensity classification, and upper and lower 2-yr, 30-min rainfall intensity limits for each classification as delineated and described by Moody and Martin (2009b) for the western United States (see fig. 4).

Rainfall regime	Seasonal characteristics	Rainfall intensity classification	2-yr, 30-min rainfall intensity (I_{30}^{2yr}) (inch h^{-1} [mm h^{-1}])	
			Lower	Upper
ARIZONA	Winter and summer wet	EXTREME	>2.0 [52]	3.9 [100]
	Spring dry	HIGH	>1.4 [36]	2.0 [52]
	Fall moist	MEDIUM	>0.8 [20]	1.4 [36]
PACIFIC	Winter maximum	HIGH	>1.4 [36]	2.0 [52]
	Summer minimum	MEDIUM	>0.8 [20]	1.4 [36]
		LOW	>0.6 [15]	0.8 [20]
SUB-PACIFIC	Winter wet	LOW	>0.4 [10]	0.8 [20]
	Spring moist			
	Summer and fall dry			
PLAINS	Winter maximum	EXTREME	>2.0 [52]	3.9 [100]
	Summer minimum	HIGH	>1.4 [36]	2.0 [52]
		MEDIUM	>0.7 [19]	1.4 [36]

- *Topography*—The erosion rate generally increases as slope and hillslope length (flow path) increase. In addition, the drainage pattern (as determined by geologic terrain) can concentrate or dissipate erosive energy (Moody and Martin 2009a; Scott and others 2009). Longer flow paths and convergent hillslopes (swales) allow overland flow to concentrate into rill flow, which has higher erosive power and causes the majority of surface erosion (Libohova 2004).
- *Land use and management*—The magnitude of a watershed response to a hydrological event is dependent not only on natural factors (for example, rainfall and topography) but on anthropogenic activities such as road building, fuel reduction, and timber harvest. The cumulative effect of these activities and land use can increase the severity of runoff, flooding, and erosion following precipitation (Reid 2010).

Fire-Dependent Factors:

- *Burn severity*—(also referred to as "fire severity") is a qualitative measure of the effects of fire on ecosystem properties and is usually evaluated by the degree of soil heating and/or vegetation mortality (Agee 2007). Several factors that impact post-fire flooding and erosion response are included in the assessment of burn severity, and higher burn severity is associated with larger and more rapid watershed responses to rainfall (DeBano and others 1998; Moody and others 2008). Forest ecologists define burn severity by the degree of overstory plant mortality, where overstory mortality below approximately 30 percent is considered low severity, 30 to 70 percent is considered moderate severity, and greater than 70 percent is considered high severity (Agee 2007). Burned areas where vegetation patches burned at high severity are interspersed with patches burned at low severity may be rated "moderate burn severity" or "mixed severity" (Parsons and others 2010). Overstory plant mortality influences post-fire flooding and erosion by impacting the raindrop energy hitting the soil surface, hillslope sediment storage, overland flow routing, drag forces on surface wind, etc. However, the changes in soil properties due to soil heating and loss of protective ground cover (both included in "burn severity") are often more directly implicated in the increased watershed responses and are categorized separately as "soil burn severity" (Robichaud 2007).
- *Soil burn severity*—The fire effects of soil heating and the consumption of organic material on the soil surface and near-surface lead to changes in soil properties that generally reduce soil infiltration and increase soil erodibility (Benavides-Solorio and MacDonald 2001; Doerr and others 2006). (Other fire effects on soil, such as changes in nutrient composition and microbe communities, have little impact on post-fire emergency stabilization treatment effectiveness and are not discussed here.) The degree of soil burn severity is dependent on the peak temperatures and the duration of those temperatures within the soil. Observable post-fire ground parameters (for example, amount and condition of ground cover, ash color and depth, soil structure, presence of fine roots, and

soil water repellency) are often used to classify soil burn severity (Parsons and others 2010; Robichaud 2007). Although increased erosion is likely on steep slopes with moderate and high soil burn severity, the greatest erosion occurs in areas of continuous (not patchy) high soil burn severity (Moody and Martin 2009a; Robichaud 2005; Robichaud and others 2006). BAER teams, when evaluating the need for post-fire stabilization treatments, are particularly interested in the soil burn severity. The process used to produce most post-fire burn severity maps from pre- and post-fire satellite imagery can detect the fire-induced changes in vegetation more definitively than changes in the soil (Clark and Bobbe 2004). Since the need for hillslope stabilization treatments is more closely related to soil burn severity than to canopy mortality, post-fire assessment teams often need to correct and verify the soil burn severity map (Parsons and others 2010; Robichaud 2007). Factors that are most often associated with post-fire treatment effectiveness studies, such as percent ground cover, soil water repellency, and soil erodibility, are dependent on soil burn severity and are discussed below.

- *Amount of bare soil*—The amount of bare soil is an important factor used to map burn severity (Key and Benson 2006) and has been positively related to post-fire erosion rates (Benavides-Solorio and MacDonald 2005; Curran and others 2006). In addition, there is evidence that post-fire erosion is reduced when natural mulch, such as conifer needle cast, provides protective post-fire ground cover (Pannkuk and Robichaud 2003) or when hillslope treatments, such as straw mulch, provide immediate ground cover, thereby reducing raindrop impact and shortening overland flow paths (Wagenbrenner and others 2006).
- *Soil water repellency*—Fire-induced soil water repellency has been directly linked to soil burn severity (DeBano 2000; Doerr and others 2006; Robichaud and Hungerford 2000) and to reduced infiltration (Cerdà and Robichaud 2009; Robichaud 2000). Although the presence of fire-induced soil water repellency is generally confined to the top few inches of the soil, the presence and degree vary widely across the burned landscape. In addition, the effects of soil water repellency can vary over time, depending on soil moisture, with water repellency being most pronounced during dry conditions and reduced or absent following prolonged wet conditions (Doerr and others 2009). The amount of wetting needed to reduce or eliminate soil water repellency varies with burn severity as well as with soil type and degree of water repellency that exists prior to wetting (Doerr and others 2009). Since soil water repellency can be assessed more easily than infiltration rates, post-fire soil water repellency is often used to estimate the potential reduction in infiltration rates.
- *Soil erodibility*—The ability of soils to resist erosion is based on many factors but predominantly on soil texture, structure, and organic matter content (Hillel 1998). Soil texture refers to the relative proportions of the inorganic soil particles by size (sand, silt, and clay) and is usually unaffected by fire (DeBano and others 2005). Based on differences in particle mass, sand, sandy loam, and loam textured soils tend to be less erodible than silt, very fine sand, and certain clay textured soils. Soil structure is the arrangement of primary soil particles into aggregates. In the upper soil (at the duff-upper A-horizon interface), soil structure is highly dependent on the organic material (humus) to “glue” soil particles together to form aggregates. Thus, when the organic material in the upper soil is consumed by fire, the soil can become disaggregated and, as a result, more erodible. In addition, the collapse in soil structure decreases both total porosity and pore size, which reduces infiltration rates (DeBano and others 2005). Generally, soils with greater infiltration rates, higher levels of organic matter, and improved soil structure are less erodible.
- *Time since the fire*—Natural recovery of native vegetation reduces erosion over time. The greatest erosion usually is measured during the first post-fire year, and the second post-fire year and subsequent years can be an order of magnitude lower (Robichaud and Brown 1999; Pierson and others 2001; Robichaud and others 2008a). However, recovery rates vary by climate and vegetation type. For example, post-fire recovery in the Colorado Front Range is longer than those reported above; the typical intense summer convection storms can produce large sediment yields for several years after a fire due to the highly erodible granitic soils, sparse vegetative cover, and steep topography (Pietraszek 2006).

The factors discussed above are interrelated, and changes in one factor are often reflected in changes of others. For example, immediately following a wildfire, areas burned at high severity will have little ground cover (other than the ash layer), and the amount of exposed bare soil will be high. As time since the fire increases, the ground cover will increase and the amount of bare soil will decrease; thus, *time since the fire* is indirectly related to *amount of bare soil* exposed.

In a study of post-wildfire sediment yields in the western United States, Moody and Martin (2009b) determined that *soil availability* is a dominant factor in predicting post-fire sediment yields. Soil availability is dependent on soil erodibility, ground cover, and the amount of stored sediment on hillslopes and in channels. Wildfires increase soil erodibility and remove the vegetation and forest floor material that hold soil in place and protect the soil from forces of raindrop impact and overland flow. Thus, wildfires make more soil available for detachment and transport. Post-fire sediment yields reflect the amount of protective ground cover lost, the magnitude of the erosion drivers (rain, wind, and overland flow), the change in soil physical properties related to erodibility (for example, loss of organic material and disaggregation of soil particles), and the amount of accumulated sediment in hillslope and channel storage areas.

Post-Fire Erosion by Wind and Gravity

Wind-driven erosion is generally an issue in arid climates and in areas with prevailing drought conditions. Increased wind erosion following wildfires in grasslands and rangelands is well documented (see introduction in Sankey and others 2009). Although less pervasive than in arid landscapes, the occurrence and rate of wind erosion can temporarily increase after wildfires in humid, forested areas as well (Scott and others 2009; Whicker and others 2006). Ravi and others (2006, 2009) have shown the presence of fire-induced soil water repellency increases wind erosion rates. Although some post-fire treatments, such as wood mulches and hydromulches, are known to resist displacement by wind, little attention has been given to the use of post-fire treatments to mitigate wind erosion. Post-fire wind erosion is likely to become more of a concern, particularly in the southwestern and Great Basin areas of the United States where climate models predict continued drought and increased wildfire potential (Brown and others 2004; Flannigan and others 2000; Westerling and others 2006).

Dry ravel, or gravity-driven erosion, generally occurs in steep landscapes where surface soils are coarse or gravelly and soil particles are pulled downhill by gravity (Scott and others 2009). In the United States, dry ravel is commonly associated with chaparral landscapes in southern California where most of the known wildfire effects on dry ravel have been studied (for example, Krammes 1960; Wells and others 1979). Destabilized hillslopes are created when wildfires consume plant roots and ground cover that hold soil on hillslopes and can result in large increases in dry ravel the first post-fire year. The material that is transported as dry ravel generally is deposited in channels where it becomes a sediment source for water-driven erosion in subsequent wet season rains (Scott and others 2009). Many post-fire hillslope stabilization treatments applied in southern California are intended to mitigate dry ravel and, thereby, decrease the sediment availability for debris flows during the following winter wet seasons (Wohlgemuth and others 2009).

Comparing Results and Scale of Measurements

In recent years, direct measurements of watershed processes (for example, runoff, peak flows, and sediment yields) have been made to assess post-fire treatment effectiveness in many areas of the western United States. It can be challenging to compare the results of different field studies given the high variability in rainfall, soil type, topography, and other relevant variables. Site variability is often problematic within a single field study, and comparisons between studies compound that variability. In addition, the general practice of normalizing, or converting erosion rates and sediment yields to common units (for example, tons per acre [ton ac^{-1}] or megagrams per hectare [Mg ha^{-1}]), can be misleading as erosional processes do not scale-up in a simple way.

Erosion rates can be expressed as sediment flux rates—the mass of sediment transported across a unit hillslope contour (feet [meter]) per unit time (day) or per rain event (Moody and Martin 2009b). However, most post-fire treatment effectiveness studies have measured runoff and/or sediment yields at the base or outlet of a study area. The spatial extent of these study areas can range over several orders of magnitude. For example, we have used hillslope plots (200 to 350 ft^2 [20 to 30 m^2]) (fig. 5), swales (0.25 to 1.25 ac [0.1 to 0.5 ha]) (fig. 6), and small catchments (2.5 to 25 ac [1 to 10 ha]) (fig. 7) for post-fire treatment effectiveness studies (Robichaud 2005). Field measurements are generally normalized (converted) to mass of eroded sediment (tons [megagrams]) or depth of runoff (inch [millimeter]) per unit area (acre [hectare]) per unit time (year) or per rain event or rain amount (inch [millimeter]). Extrapolating runoff and sediment yields from the smaller scale measurement units (lb ft^{-2} [kg m^{-2}]) to larger scale normalized units (ton ac^{-1} [Mg ha^{-1}]) makes it easier to compare results from different studies that were done at various locations and scales of measurement. However, the various types of water erosion (interrill or sheet erosion, rill erosion, and channel and gully erosion) function differently across spatial scales. Erosion at the plot scale usually is limited to interrill and rill components, while erosion measured at the scale of swales and small catchments includes those two processes as well as channelized flow.

Figure 5. Hillslope plot with a contour-felled log and a silt fence at the base for sediment collection on the 2000 Valley Complex Fires in Montana.

Figure 6. Hillslope plot that incorporates a swale with a double silt fence at the base for sediment collection on the 2000 Bobcat Fire in Colorado.

Figure 7. Cleaned-out sediment basin at the outlet of a catchment study site on the 2002 Hayman Fire in Colorado.

Channelized flow—including deposition within the study area rather than at the outlet where the sediment yield is measured—becomes a more dominant process as the contributing area increases (Moody and Martin 2009b; Pietraszek 2006).

In general, runoff decreases as hillslope length increases, which is largely attributed to spatial variability in infiltration (for example, Gomi and others 2008; Joel and others 2002). However, after large wildfires, this trend may not always hold as lower infiltration rates (due to fire effects) may be fairly consistent over large areas burned at high severity. Similarly, sediment yields tend to decrease as area of measurement increases. The scale dependency of sediment yield has been attributed to the deposition of eroded sediment in hillslope sediment sinks before reaching the base of the research plot where it would be measured (for example, Wilcox and others 1997). However, this explanation is likely too simplistic; other explanations have been suggested by researchers (for example, Parsons and others 2004, 2006) but have not been universally accepted. Nonetheless, it is clear that erosion rates are influenced by the scale at which they are measured, and erosion rates measured at one scale should not simply be extrapolated to larger scales (Parsons and others 2006).

Little work has been done to examine the scale-dependency of post-fire runoff, peak flow, and sediment yield measurements. However, some scaling effects on sediment yields were documented in a two-month study that examined scale effects on post-fire treatment effectiveness (reduction in sediment yields due to treatment with LEBs) on an area burned at high severity (Gartner 2003). A set of paired catchments were established to measure treatment effectiveness at four spatial scales—plot (10 to 50 ft^2 [1 to 5 m^2]), hillslope (~4,300 ft^2 [~400 m^2]), sub-catchment (2.5 to 12 ac [1 to 5 ha]), and catchment (~40 ac [~16 ha]). The study areas were nested such that the largest areas (catchments) contained the smaller areas (sub-catchments, hillslopes, and plots). At the smallest scale (plots), where interrill processes dominated, no effect from the LEBs could be detected. At the hillslope and sub-catchment scale, LEBs generally were effective for the low intensity rain events observed during the study period. At the catchment scale, no treatment effect was observed, but the author suggested that these results were likely related to inexact pairing rather than scale or LEB treatment effects (Gartner 2003).

Erosion Barrier Treatments

Erosion barriers, made from natural and engineered materials, have been used for decades to mitigate post-wildfire runoff and erosion (Robichaud and others 2000). These structures are designed to slow runoff, cause localized ponding, and store eroded sediment. When the erosion barriers function as designed, they can decrease the erosive energy of runoff, increase infiltration, and reduce downstream sedimentation (Robichaud 2005). Common post-wildfire hillslope erosion barriers include contour-felled logs (LEBs) (fig. 8), straw wattles (10 inches [0.25 m] diameter, 13 to 20 ft [4 to 6 m] long nylon mesh tubes filled with straw) (fig. 9), contour trenches (hand or machine dug trenches), and straw bales (blocks of straw bound with twine) (fig. 10). To eliminate long uninterrupted flow paths, erosion barriers are generally installed in staggered tiers with the center of each erosion barrier directly downslope from the gap between the two erosion barriers above it.

Prior to 2000, LEBs were widely used for post-fire hillslope stabilization, as most forest fires leave dead trees that can be felled and limbed for this use. Managers assumed that hillslope installations of LEBs increased surface roughness and slowed runoff, allowing runoff to pond in the storage areas behind the LEBs. This increased infiltration, reduced the amount and flow velocity of the runoff, and resulted in reduced erosion (Robichaud and others 2000). Although there was little quantitative evidence for these assumptions at the time, Wagenbrenner

Figure 8. A contour-felled log erosion barrier with soil end berms to increase sediment storage capacity.

and others (2006) did measure greater infiltration rates in the disturbed areas immediately upslope of an LEB than in surrounding, less-disturbed burned areas.

Figure 9. A recently installed straw wattle erosion barrier.

Straw wattles have been used as a reasonable alternative to LEBs in burned areas where logs were scarce or poorly shaped (for example, in the chaparral areas of southern California, as seen in fig. 9). Straw wattles are permeable barriers that detain surface runoff long enough to reduce flow velocity and provide for some sediment storage. Like LEBs, straw wattles can be laid out in staggered tiers on a hillslope (fig. 11) but are flexible and conform to the soil surface so that gaps rarely occur. The disadvantages of straw wattles include the expense of manufacturing and shipping, and the potential for the straw fill to be a source of non-native seed and an attractive food source for animals.

When Robichaud and others (2000) surveyed land managers with post-fire treatment experience, 65 percent reported that LEB installations were "good" or "excellent" at reducing post-fire erosion. Most of these positive responses were based on observations of sediment stored behind the LEBs on treated hillslopes (McCammon and Hughes 1980; Miles and others 1989). Although the amount of sediment stored by LEBs on a hillslope could be used as a measure of treatment effectiveness, a more relevant measure is a quantitative comparison of post-fire runoff, peak flow, and/or sediment yield from equivalent treated and untreated areas, as in the studies presented in Appendix B.

Figure 10. A set of straw bale erosion barriers installed in a burned swale on the 2002 Hayman Fire in Colorado.

Figure 11. Straw wattles installed in a staggered layout on a burned hillslope.

Erosion Barrier Performance Characteristics

To differentiate and clarify the two types of sediment measurements—sediment held by the erosion barrier itself and sediment yields at the base of the hillslope—we use the concept of "erosion barrier performance" (Robichaud and others 2008a). Erosion barrier performance can be quantified by comparing the amount of sediment held by the erosion barrier(s) to the total amount of sediment that was mobilized. Thus, erosion barrier treatment performance, EB_{PERF} (%), would be

$$EB_{PERF} = \left(\frac{M_{EB}}{M_{EB} + M_{CS}} \right) 100$$

where M_{EB} *is* the dry weight (lbs [kg]) of sediment stored by the erosion barrier(s), and M_{CS} is the dry weight (lbs [kg]) of collected sediment or sediment flux below the erosion barrier treatment (Robichaud and others 2008a). Hillslope plots with one of three post-fire erosion barrier treatments (LEB, straw wattle, or hand-dug trench) or no treatment were installed with sediment fences at the base to determine erosion barrier performance as well as the treatment effectiveness (see Appendix B-Study III). Robichaud and others (2008a) measured EB_{PERF} over three sediment-producing rain events during the first post-fire year. After the first sediment-producing storm, mean EB_{PERF} was 87 percent for contour-felled logs, 83 percent for straw wattles, and 72 percent for contour trenches. However, the barriers captured little additional sediment after that first storm, and their performance declined as additional rain events occurred (fig. 12). In general, EB_{PERF} decreases over time as more hillslope erosion takes place and the proportion of M_{CS} compared to M_{EB} increases (Robichaud and others 2008a).

Another erosion barrier performance measurement compares the actual volume of sediment stored behind an erosion barrier to the total sediment storage capacity of that erosion barrier (fig. 13). The sediment-trapping ability of any erosion barrier installation is dependent on the site characteristics (for example, slope and soil type), the individual erosion barrier features (such as diameter, length, accuracy of contour placement, and seal between the barrier and the ground), and the density and pattern of erosion barriers over the landscape. When LEB installations have been examined to determine how much sediment-holding capacity is used, the mean sediment storage performance of the barriers is around 60 to 70 percent (Robichaud and others 2008a, b). Robichaud and others (2008a) qualitatively evaluated erosion barrier performance over three natural rain events. In 13 of 29 observations, runoff and sediment flowed over the top of the barrier, yet only 3 of the 13 barriers were filled to capacity and 5 barriers were at or below 50 percent full. Overland flow patterns and LEB shapes often result in uneven filling of the sediment storage area above the LEB that leaves a portion of sediment storage capacity unused (fig. 14).

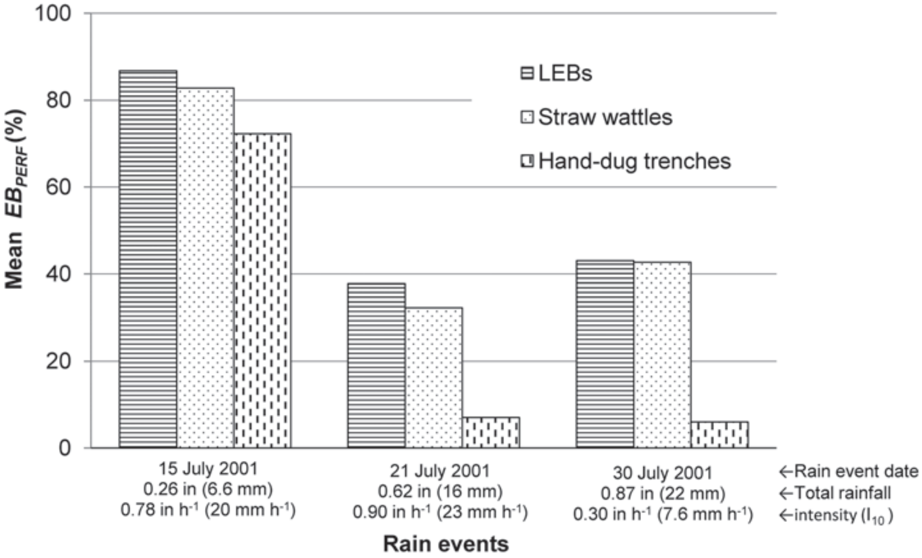


Figure 12. Mean erosion barrier performance (EB_{PERF} [%]) for three successive natural rainfall events in post-fire year one as measured on hillslope study plots established on the 2000 Valley Complex Fires in western Montana. The date, total rainfall amount, and maximum 10-min rainfall intensity are listed for each event (Robichaud and others 2008a).

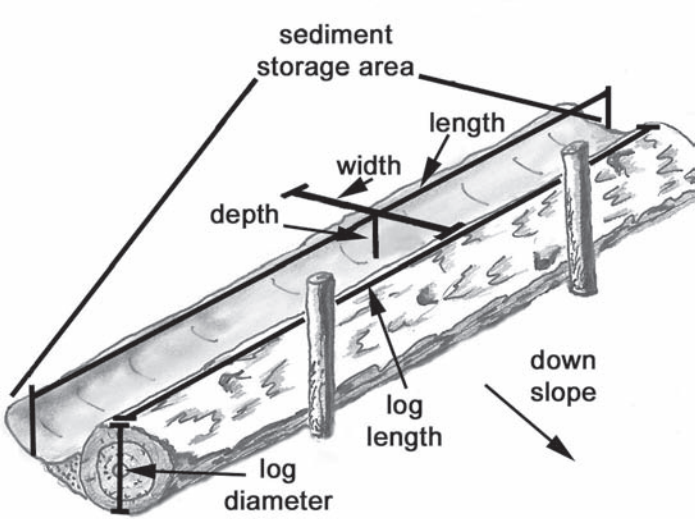


Figure 13. Schematic of measurements made on a contour-felled log to calculate the sediment storage capacity of the erosion barrier (from Robichaud and others 2008a).

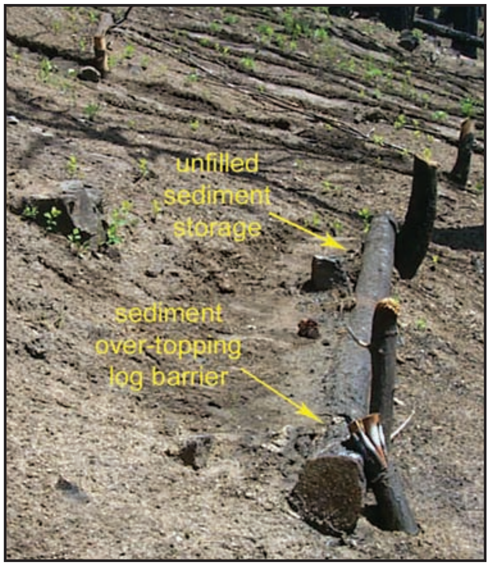


Figure 14. A partially filled LEB with unused sediment storage capacity indicated.

Consequently, even when an erosion barrier installation provides adequate capacity to hold predicted sediment yields, the actual volume held is usually less than full capacity, and observed runoff that goes over the tops and around the ends of the LEBs carries entrained sediment (Robichaud and others 2008a).

Erosion barrier treatment effectiveness (the reduction in sediment yield at the base of the hillslope) is impacted by the erosion barrier performance. Erosion barrier performance is highest when barriers are new and have little or no sediment stored behind them. Not surprisingly, post-fire LEB hillslope treatments are most effective for the first few sediment-producing events, with effectiveness declining over time. As a corollary, erosion barrier treatment effectiveness can be improved by increasing the performance of the installation. EB_{PERF} can be improved by adding soil berms to the ends of LEBs (or turning the ends of the straw wattle upslope) to create a "smile-shaped" barrier, which increases the sediment storage capacity of erosion barriers by 10 percent or more (Robichaud and others 2008a). Increasing the erosion barrier density on the hillslope also increases the sediment storage capacity of the installation. Sediment storage capacity is dependent on careful installation to ensure that erosion barriers are accurately placed along the hillslope contours and securely anchored, with gaps between the erosion barrier and the ground completely sealed. In post-fire field installations, with hundreds of barriers installed by crews of varying skill and supervision, it is likely that some of the barriers will be poorly installed. In a study of LEBs installed by field crews in Colorado, an average of 32 percent of the barriers from seven sites and as many as 70 percent of the barriers from a single site were off-contour and/or had incomplete contact with the ground (Wagenbrenner and others 2006). Improving the quality of an erosion barrier installation may improve performance, but it will also increase the time and labor costs for installation.

Erosion Barrier Treatment Effectiveness

Recent research efforts in which hillslope runoff and/or sediment have been measured have provided insight as to effectiveness and limitations of erosion barriers (see Appendix B). The consensus among these studies is that erosion barriers, and LEBs in particular, may reduce runoff and sediment yields for low intensity rain events, but they are unlikely to have a significant effect for high intensity rain events.

Robichaud and others (2008b) completed a multi-year, multi-site study of the effectiveness of LEBs for reducing post-fire runoff, peak flows, and sediment yields (see Appendix B-Study IV). The study involved six paired watershed sites in the western United States that were established immediately after wildfires on areas burned at high severity. At each site, two small, comparable watersheds had sheet metal head walls with overflow weirs installed at the outlet. One watershed was treated with LEBs and one was left untreated as the control. Event runoff and sediment yields were measured at the base outlet and correlated to rainfall characteristics over several post-fire years (Robichaud and others 2008b). These measurements are listed by site in tables AB-4 to AB-9 in Appendix B. High intensity rainfall (maximum rainfall intensity for a 10-minute period [I_{10}] ≥ two-year return period) produced most of the measured runoff and sediment yields, except in the southern California site where long-duration rain events produced most of the runoff and erosion (fig. 15). Runoff, peak flows, and sediment yields were significantly smaller in the treated watersheds for smaller rain events (I_{10} < two-year return period). However, and perhaps more importantly, no treatment effects were measured for rain events with larger return periods—the events that produced most of the measured runoff and sediment yields (Robichaud and others 2008b).

These results are similar to other studies in which LEBs were evaluated at smaller scales and/or shorter times. Wagenbrenner and others (2006) found LEBs were ineffective in large storms but could be effective for small events given sufficient sediment storage capacity (see Appendix B-Study I). Gartner (2003) found that LEBs generally were effective for low intensity rain events observed during the two-month study period (see Appendix B-Study II). Robichaud and others (2008a) compared three types of erosion barriers—LEBs, straw wattles, and hand-dug contour trenches—using a relatively low intensity (I_{10} < two-year return period) simulated rainfall (1 inch h^{-1} [26 mm h^{-1}]) with added overland flow (13 gal min^{-1} [48 L min^{-1}]). The LEBs and straw wattles reduced total runoff, and all three erosion barrier treatments reduced peak flow rates; however, only the straw wattles significantly reduced sediment yields compared to the controls (table AB-3 in Appendix B) (Robichaud and others 2008a). In the subsequent three years, sediment yields from natural rainfall were measured, and there were no treatment effects associated with 10 sediment-producing rain events. In addition, sediment yields increased with increasing total rainfall and rainfall intensity. The erosion barrier treatment effectiveness measured during low intensity simulated rainfall (even with added inflow) did not apply during higher intensity summer storms typical of western Montana (see Appendix B-Study III) (Robichaud and others 2008a). Given that high intensity rain events produce the largest post-fire event sediment yields, the

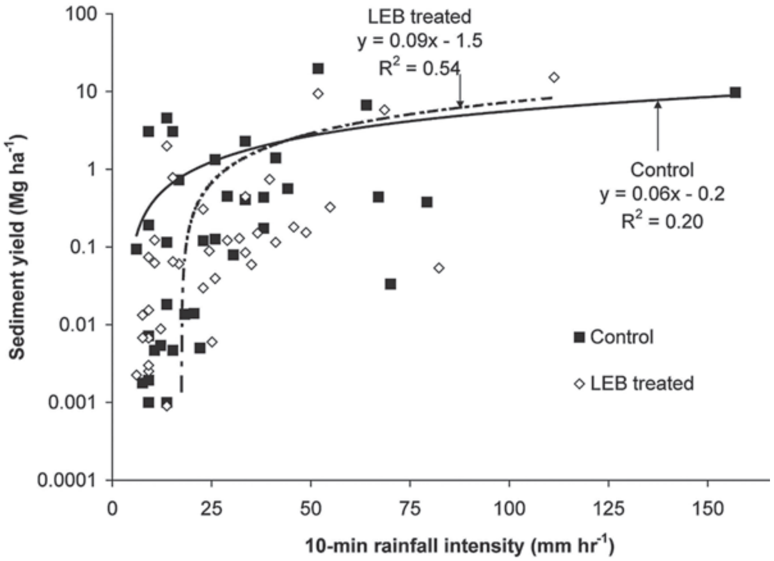


Figure 15. Rainfall intensity versus sediment yield (logarithm scale) from a paired watershed study that involved six sites and data from up to six post-fire years in the western United States (Robichaud and others 2008b).

lack of treatment effectiveness for these storms is a serious consideration in treatment choice.

There is some evidence that the installation of erosion barriers may cause enough soil disturbances to increase sediment yields in the first few rain events following installation (Robichaud and others 2008b). In one of six sites, first post-fire year sediment yields in the LEB-treated watershed were greater than in the control watershed, but the treated watershed had lower sediment yields in post-fire years two and three (see table AB-5 in Appendix B). In another two of the six sites, sediment was measured in the treated but not the control watersheds for the first two sediment-producing rain events (see tables AB-4 and AB-7 in Appendix B).

Post-fire rehabilitation treatment decisions involve balancing the need to reduce the post-fire risk of damage from increased runoff and erosion with the predicted effectiveness, availability, and installation costs of the treatments selected for use in the burned area. The labor-intensive installation, which involves the skilled, and relatively hazardous, felling of standing burned timber, and the need for quality control make most erosion barrier treatments expensive given their limited reduction of erosion risk. In areas where high intensity rainfall is common, treatment decisions do not favor the use of erosion barriers for hillslope erosion mitigation. However, erosion barriers can be combined with other treatments, such as mulches and/or seeding, and may contribute to the overall effectiveness of the treatment (Dean 2001; de Wolfe and others 2008). Another consideration for most erosion barrier treatments is their lack of longevity. Over time, performance decreases due to loss of sediment storage capacity and breakdown of barrier installation (such as loss of ground-barrier sealing and movement of the barrier) and the erosion barriers lose effectiveness. If burned hillslopes will be vulnerable to erosion for more than one or two years, an erosion barrier installation may not retain enough capacity to be effective for even small rain events.

Mulch Treatments

Mulch is material spread over the soil surface to protect it. In agricultural uses, mulches are applied to modulate soil moisture and temperature, control weeds, reduce soil sealing, and, in the case of organic mulches such as compost, improve soil structure and nutrient content. Mulch is increasingly applied as an emergency post-fire treatment to reduce rain drop impact, overland flow, and erosion (Bautista and others 2009). Because mulching can be effective ground cover immediately after application, it is an attractive choice for post-fire hillslope stabilization. It is often used in conjunction with seeding to provide ground cover in critical areas and to increase the success of seeding by improving moisture retention. Due to the cost and logistics of mulching, it is usually applied where there are downstream values at high risk for damage such as above municipal water intakes, heavily used roads, and stream reaches that are critical habitat for protected species.

Mulch has been shown to increase soil infiltration capacity, moisture content, and aggregate size while decreasing surface compaction and temperature (Bautista and others 1996, 2009). Changes in microclimatic conditions and water availability in the surface soil can improve natural vegetative recovery and benefit seeded species, which in turn can positively impact runoff and erosion (Bautista and others 1996; Dean 2001; Wagenbrenner and others 2006). The mulches used in post-fire treatments are generally divided into two groups based on how they are applied. Wet mulches, usually referred to as hydromulch, are prepared by mixing the components with water to form a slurry that is applied to the soil surface. Dry mulches, such as agricultural straws and wood materials, are applied without water.

Dry Mulches

Straw mulch was first used for post-fire treatments in the 1980s (for example, Gross and others 1989; Miles and others 1989), but it was not widely used until 2000 when the number of large, high soil burn severity fires began to increase. Miles and others (1989) gave mulching a "high" efficacy rating, but the installation rate was "slow." During the past decade, aerial application techniques for straw mulch have made it possible to apply mulches more efficiently and to treat inaccessible burned areas, making it a viable treatment alternative for the large fires that occur in the mountainous western United States. Straw mulching has been the primary hillslope treatment following some recent large fires, including:

- the 2002 Rodeo-Chedeski Fire in Arizona where more than 18,000 ac (7300 ha) were treated with straw mulch (Richardson 2002);
- the 2002 Hayman Fire in Colorado where 7700 ac (3100 ha) were straw mulched (and more than 3000 ac [1200 ha] were hydromulched) (Robichaud and others 2003); and
- the 2006 Tripod Fire in Washington where more than 14,000 ac (5700 ha) were treated with straw mulch (USDA Forest Service 2006).

Mulch Impacts Soil Temperature

Contributed by Greg Kuyumjian
Forest Hydrologist
Okanogan-Wenatchee National Forest, WA

Post-fire mulch treatments can provide benefits beyond erosion reduction. Soil temperatures measured after the 2000 Cerro Grande Fire in New Mexico showed that the dry straw mulch treatment had shaded the soil surface and reduced soil temperatures. Lower soil temperatures increase available moisture, which can be an advantage for revegetation after forest fires, especially in dry, arid environments like the Southwest. Temperature data were averaged for a four-day period (July 22 to 25) for each of the first three post-fire years (table SB2-1). On the untreated site, the average maximum daily temperature of the soil (taken at 1 inch [2.5 cm] depth) was always greater than the average maximum daily temperature of the ambient air for each of the three years. On the mulched site, it was the opposite—the average maximum daily temperature of the soil was less than the average maximum daily temperature of the air for each of the three years.

Table SB2-1. Maximum ambient air temperatures and maximum soil temperatures at 1 inch (2.5 mm) depth were measured on two sites—one with straw mulch treatment and one without mulch. Data for July 22 to 25 are shown for post-fire years one, two, and three (2001, 2002, and 2003). The average differences between maximum air temperature and maximum soil temperature by year are shown.

		No mulch Pueblo Canyon		**Mulch Pajarito Canyon**	
	Day	**Air temp. (°F) [°C]**	**Soil temp. (°F) [°C]**	**Air temp. (°F) [°C]**	**Soil temp. (°F) [°C]**
2001	**July 22**	77 [25]	77 [25]	79 [26]	70 [21]
	July 23	82 [28]	86 [30]	83 [28]	75 [24]
	July 24	81 [27]	86 [30]	80 [27]	75 [24]
	July 25	77 [25]	83 [28]	87 [31]	72 [22]
	Average difference	soil temp. was 4 [2] degrees ***greater*** than the air temp.		soil temp.was 9 [5] degrees ***less*** than the air temp.	
2002	**July 22**	73 [23]	83 [28]	74 [23]	73 [23]
	July 23	70 [21]	74 [23]	71 [22]	69 [21]
	July 24	79 [26]	84 [29]	81 [27]	73 [23]
	July 25	84 [29]	78 [26]	84 [29]	72 [22]
	Average difference	soil temp. was 3 [2] degrees ***greater*** than the air temp.		soil temp. was 6 [3] degrees ***less*** than the air temp.	
2003	**July 22**	87 [31]	90 [32]	89 [32]	78 [26]
	July 23	86 [26]	84 [29]	88 [31]	73 [23]
	July 24	89 [32]	91 [33]	90 [32]	79 [26]
	July 25	87 [31]	93 [34]	88 [31]	78 [26]
	Average difference	soil temp. is 2 [0.5] degrees ***greater*** than the air temp.		soil temp. was 12 [6] degrees ***less*** than the air temp.	

There are on-going post-fire treatment effectiveness studies within these burned areas. Although few studies have been published, preliminary data indicate that dry mulching can be a highly effective post-fire hillslope treatment. Data showing successful erosion mitigation using dry mulch have encouraged increased use of post-fire mulching and the development of new mulch materials and application techniques.

Mulch is frequently applied to improve the germination of seeded grasses, and a combination of mulching and seeding has been more effective than seeding alone at multiple locations (Badia and Marti 2000; Bautista and others 2005; Dean 2001). The mulch cover enhances seed germination and growth by increasing soil moisture and protecting the seeds from being washed downslope (fig. 16). However, some studies have shown that combined mulching and seeding does not increase vegetative cover over mulching alone (for example, Kruse and others 2004; Rough 2007).

Agricultural straw mulches often contain non-native seed species that can persist and compete with the re-establishment of native vegetation (Beyers 2004; Robichaud and others 2000). BAER teams and land managers prescribe certified "weed free" straw for post-fire mulching, but it is not always available in the locations and quantities needed. This problem occurred following the 2002 Hayman Fire in Colorado when the straw that was trucked into the burned area for post-fire application, despite being certified "weed free" in its state of origin, contained seeds of cheat grass (*Bromus tectorium*), an invasive grass in Colorado (Robichaud and others 2003). This has likely contributed to the establishment of cheat grass in portions of the recovering landscape of the Hayman Fire (P.R. Robichaud, field observations, July 2006). Rice straw is less likely to bring in noxious weeds since rice is grown in moist habitats, and successful weeds from rice fields are unlikely to germinate or spread in dry forest environments (Beyers 2004). However, when rice straw was applied with and without barley seed on burned forest land in northern California, the mulch-only quadrant had significantly higher non-native species, and all mulched quadrants had significantly reduced density and frequency of conifer seedlings (Kruse and others 2004).

Figure 16. Following the 2000 Cerro Grande Fire near Los Alamos, New Mexico, areas were treated with aerial seeding and mulching. After three growing seasons, the ground cover in the mulched and seeded area (background) is much greater than in the seeded only area (foreground).

Although wood mulching is less common than straw mulching, wood chips, wood shreds, and wood strands (thin wood strips manufactured from non-merchantable timber or production waste, such as WoodStraw™) are increasingly being developed and used for post-fire treatment. As we look at post-fire stabilization effects over a longer time frame, new approaches that fit into ecological restoration schemes are gaining interest. The use of wood mulches developed from local, site-specific forest materials (wood chips or wood shreds manufactured on site from burned trees, shredded debris from forest-clearing or post-fire logging, etc.) for post-fire erosion control is an emergency stabilization treatment that fits into a broader ecological restoration context (Bautista and others 2009) (fig. 17). Forestry equipment manufacturers are adapting wood chippers and shredders to handle burned timber and are developing application technologies for the output from these devices. Using materials from the local environment reduces the cost and time for transporting mulch materials to the treatment areas.

Hydromulches

Hydromulches are combinations of various short, bonded, organic fibers (wood shreds, paper, cotton, flax, etc.), tackifiers, suspension agents, seeds, etc., that are mixed with water and applied to the soil surface. Hydromulch is a useful rehabilitation treatment for erosion control on road cut-and-fill slopes and areas of bare soil at construction sites, and it is increasingly being used for post-fire hillslope stabilization (Napper 2006). The matrix formed by the hydromulch holds moisture and seeds on steep slopes, which fosters seeded plant germination while holding the soil in place. Since hydromulch binds to the soil surface, it is very wind-resistant; however, the smooth, dense mat has little resistance against the shear force of concentrated flow. Consequently, hydromulch mitigates water erosion more effectively on short slope lengths where concentrated flow and rill erosion are not as likely as on longer slopes (Napper 2006).

Figure 17. Woody mulch made from forest debris. Photo by S. Bautista.

There are numerous tackifiers, bonded fiber, seeds, etc., that can be included in hydromulch mixes. Generally, the tackifier ("glue" that bonds the fiber to the soil), mulch material, and seeds are selected separately and mixed with water just prior to application. The selection of the tackifier is particularly important as the environmental impacts, performance characteristics, availability, and cost vary widely. Selection is complicated by the large number of choices and difficulty in knowing the chemical composition of the tackifier when formulations are covered by proprietary rights and are not disclosed. Both organic (polysaccharides derived from plants such as guar, plantago, and corn) and synthetic (polyacrylamide [PAM], polyacrylates, and co-polymers of these two base chemicals) materials are sources for the long-chained molecules used in tackifiers (Etra 2007). The specific types and proportion of hydromulch components as well as the application rates have varied in post-fire hillslope stabilization projects; thus, hydromulch performance measured to date may not be indicative of the potential performance of new components, combinations, or application rates.

Performance Characteristics of Mulches

The amount of bare soil exposed, or, stated conversely, the amount of ground cover is related to watershed response and to the treatment effectiveness of post-fire hillslope mulching treatments whose basic functional feature is coverage of bare soil (Burroughs and King 1989; MacDonald and Robichaud 2007; Robichaud and others 2000; Wagenbrenner and others 2006). According to Foltz and Copeland (2009: 785), "… the percentage of cover is more important than the type of erosion control material [applied]. Cost effectiveness, long-term durability, and impacts on revegetation become controlling factors in erosion control material selection." Generally, post-fire mulch treatments need to provide 60 to 80 percent ground cover to reduce hillslope erosion (Napper 2006; Pannkuk and Robichaud 2003). However, Foltz and Wagenbrenner (2010) reported that a 50 percent cover of wood shreds significantly reduced sediment yields nearly as well as 70 percent cover. The percent ground cover of any mulch installation is dependent on application rates and techniques. Aerial application of mulch is constantly being refined to accommodate various types of mulch and to improve the consistency of mulch thickness and bare soil coverage across a burned landscape. In addition, the length of time that mulch can effectively mitigate erosion is dependent on the length of time the ground stays covered. Thus, longevity of the mulch material and its propensity to stay in place are also directly related to mulch treatment effectiveness. The length(s) of the mulch fibers and its impact on post-fire revegetation are also important performance characteristics.

Ground Cover Amounts and Application Techniques—Straw mulch can be applied by hand, with blowers, or from aircraft. Ground application is preferred for relatively small areas where 100 percent of the ground can be covered by a thin, even mulch layer. However, hand application requires large crews to get the mulch cover in place in a timely manner (fig. 18). Trailer- or truck-mounted blowers, although faster than hand distribution, are limited to areas above and below roads or other drivable areas such as fire lines (fig. 19). Helicopters were first used to apply

Figure 18. Hand application of post-fire straw mulch treatment (photo from Napper 2006: 28)

Figure 19. Post-fire straw mulch treatment being applied downslope from a road using a trailer-mounted blower pulled by a tractor on the 2007 Cascade Complex Fires in Idaho.

straw mulch in 2001, and this method has become more common as it allows large areas to be treated quickly and efficiently at a lower cost than hand application. The straw bales break apart as they fall from a suspended cargo net and spread further upon impact (fig. 20) (Bautista and others 2009; Napper 2006). Under ideal conditions, aerial application can provide an even distribution of straw mulch over the ground; however, depending on wind conditions, steepness of the hillslopes, number of standing trees, experience of the helicopter pilot, and the moisture content of the mulch, application can be uneven and can require ground-based workers to break up clumps and smooth out the mulch (Santi and others 2006).

Like straw mulch, wood-based mulches can be spread by hand, ground-based machinery, and aircraft. Wood chippers and shredders may be fitted with blowers that spread the mulch as it is produced. Aerial application techniques are being developed to distribute chipped, shredded, and manufactured wood mulch materials at a rate that provides 50 to 60 percent ground cover. After the 2005 School Fire in southeastern Washington, manufactured wood strands were applied by helicopters with suspended cargo nets that delivered the mulch over the treatment area (heli-mulching), resulting in 54 percent average wood strand cover. In 2007, following the Cascade Complex Fires in Idaho, a study was initiated on a 5-ac (2-ha) area burned at high severity that was heli-mulched with wood shreds. The wood shreds spread into an even, but thin mulch cover (37 percent) in the treated watershed (fig. 21), leaving about 50 percent bare soil exposed compared to the 77 percent bare soil exposed in the control watershed.

Figure 20. Aerial application of post-fire straw mulch treatment using a cargo net suspended below a helicopter; the cargo net is released over the target area (photo from Napper 2006: 25).

Figure 21. Wood shred coverage after aerial application on an experimental watershed site established on an area burned at high severity on the 2007 Cascade Complex Fires in Idaho. The PVC pipe frame (39 inches [1 m] on a side) is strung with twine to form 100 intersection points and is used to sample ground cover.

Hydromulch components are transported as dry materials and mixed with water in large truck-mounted tanks to form a slurry that is sprayed or dropped on the soil (fig. 22). Some hillslope applications have been completed using truck-mounted sprayers; however, the effective range of truck-mounted hydromulch sprayers is about 120 ft (40 m) on either side of roads. These ground-based hydromulch treatments are mostly used for small areas and to stabilize and seed burned-over forest road cut-and-fill slopes. Aerial application methods have made it possible to apply hydromulch over large burned areas (fig. 23). The hydromulch slurry is transferred from the mixing tank into aircraft-mounted tanks at a staging area. While flying over a target treatment area, the slurry tanks are opened to apply the mulch. Given the limited capacity of the tanks, many trips to and from the staging area are needed, which makes aerial hydromulching expensive even when compared to other mulching treatments (Napper 2006).

In areas where the application rate is large enough, the hydromulch slurry dries to form a continuous mat that

Figure 22. Trailer-mounted sprayer used to apply hydromulch from the road as a post-fire hillslope treatment on the 2002 Hayman Fire in Colorado.

Figure 23. Large-capacity helicopters fitted with slurry tanks are used to apply hydromulch as a post-fire hillslope treatment on the 2002 Hayman Fire in Colorado.

covers and adheres to the soil (fig. 24). An application rate of ~1 ton ac^{-1} (~2 Mg ha^{-1}) of dry mulch material (prior to being mixed with water) is needed to obtain at least 70 percent hydromulch ground cover (Bautista and others 2009). However, the calculated application rates have not always attained the target cover amounts—especially when aerial application is used. For example, after the 2003 Cedar Fire, the hillslope application of hydromulch was targeted for 70 percent coverage but only 56 percent coverage was achieved (Hubbert, unpublished paper 2005). Residual canopy and standing trees on burned hillslopes may intercept some of hydromulch during the application process, reducing the actual ground cover and potential treatment effectiveness. For example, in one of the first post-fire aerial applications of hydromulch, 1450 ac (590 ha) were treated with hydromulch after the 2000 Cerro Grande Fire in Los Alamos, New Mexico. It was estimated that in burned areas that were heavily timbered, as much as 40 percent of the application was intercepted by standing trees (G. Kuyumjian, personal communication as reported in Napper 2006: 15).

Mulch Impacts on Post-Fire Revegetation—Optimizing the thickness of post-fire mulch is a balance between soil protection and the potential suppression of revegetation and establishment of seeded species (Bautista and others 2009). Thick layers of mulch can prevent sunlight from reaching the soil surface and can physically obstruct seedling emergence (Beyers 2004). Robichaud and others (2000) reported that shrub seedlings were more abundant at the edge of mulch piles where the straw mulch material was less than 1 inch (2.5 cm) deep. The suppression of post-fire vegetation is seen as an advantage when mulches reduce encroachment of undesirable plants into the burned area. However, vegetation suppression is a significant disadvantage when mulches inhibit natural recovery. Beyers and others (2006) reported that none of the studied post-fire treatment mulches (wood chips, hydromulch, and rice straw mulch) increased vegetation cover; and wood chip mulching inhibited vegetation recovery more than other treatments while providing the most total ground cover and greatest reduction in erosion for several years. It is widely assumed that mulch thickness impacts post-fire revegetation, but the optimum thickness for post-fire mulch treatments has not been established. Debats and others (unpublished report 2008) found that 100 percent hydromulch coverage reduced initial plant density on post-fire hillslopes in southern California chaparral. They compared their findings with Hubbert and others (unpublished report 2005) who reported no apparent vegetation suppression due to the 51 percent coverage of hydromulch on similarly burned landscapes following the 2003 Cedar Fire in southern California.

Longevity or Durability—The amount of time mulch remains in place on a hillslope may impact treatment effectiveness. Residence time of mulches varies depending on

Figure 24. A small piece of the aerially-applied hydromulch mat (exposed surface is brown) has been lifted off the burned soil (black) and flipped over to expose the underside of the mat (black and green). The pocket-sized field notebook is included for scale.

Mulch Effects on Post-Fire Revegetation

Contributed by
Jan Beyers, Research Ecologist, USDA Forest Service, Pacific Southwest Research Station

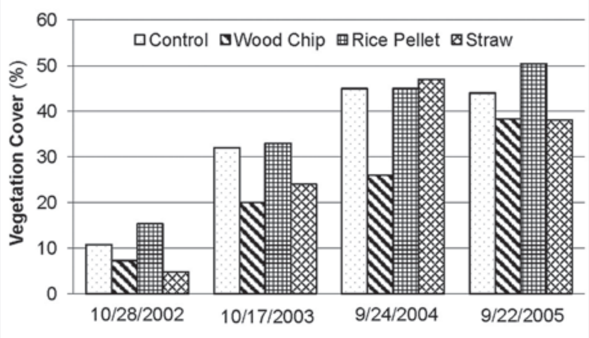
A study was conducted on the 2002 Indian Fire on Prescott National Forest in Arizona to determine the effectiveness of three mulch treatments—wood chips (SB3-fig. 1), rice straw (SB3-fig. 2), and pulverized rice-straw and PAM pellets (SB3-fig. 3). In addition to the sediment yield data (see Appendix Y-Study VI), ground cover and vegetation data were taken on the mulched research plots immediately after installation (June 2002) and twice each year through post-fire year three. Rice straw pellets disintegrated as designed and did not appear to inhibit vegetation establishment. Post-fire vegetation recovered more slowly on straw and wood chip treated slopes (SB3-fig. 4). Wood chip mulch retained the greatest ground cover over time (SB3-fig. 5) and had the lowest sediment production compared to the control.

By 2007, five years after the fire, no difference in vegetation recovery was observed among treatments (SB3-fig. 6) (Beyers, personal communication).

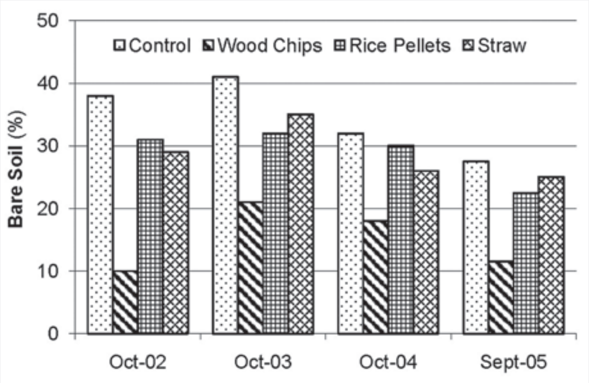
SB3-fig. 1. Wood chips used for post-fire hillslope treatment. Note that wood chips that were entrained in the overland flow are piled at the outlet of the swale.

SB3-fig. 2. Rice straw applied as post-fire hillslope treatment.

SB3-fig. 3. Pellets of pulverized rice straw and granular PAM were applied dry and compressed and are shown here after a rain expanded the pellets. The insert in the upper right corner shows the small rice straw fibers more closely (felt tip pen inserted for scale).



SB3-fig. 4. The mean percent cover that is live vegetation is shown by treatment and by post-fire year.



SB3-fig. 5. The mean percent bare soil is shown by treatment and by post-fire year.

SB3-fig. 6. The same swale (treated with wood chips) shown in SB3-fig. 1 is pictured here in 2007—post-fire year five.

the type, size, and amount of the mulch material applied. Rice straw is stouter and, thus, more durable than wheat or barley straw, which can increase its residence time on the ground but makes the application more time-consuming and costly than other agricultural straws. Woody mulches are decay resistant—wood strands were clearly visible seven years after application on the 2002 Hayman Fire in Colorado (P.R. Robichaud 2009 field observation). In contrast, hydromulch generally decays within a few months to a year (Bautista and others 2009). The rapid decay of hydromulch may result in much less ground cover than deemed necessary for hillslope stabilization in the first and second post-fire years. Hubbert (unpublished report 2005) reported that the hydromulch that had been applied on the Cedar Fire in southern California was greatly reduced following the first winter rains and was completely gone from the site following the heavy winter rains of the second year.

Wind Redistribution—The light weight of agricultural straw mulch makes it susceptible to strong winds that can blow it off-site, leaving unprotected bare soil and deep mulch piles that inhibit seed germination. After the 2003 Grand Prix/Old Fire on the San Bernardino National Forest, strong Santa Anna winds blew the straw mulch into thick piles, leaving large areas of exposed soil (Hubbert, unpublished report 2005). The flooding events that occurred in conjunction with the Christmas Day Storm (25 Dec 2003) were partly attributed to the loss of effective straw cover in some treated watersheds. Wind displacement can be minimized by increasing the mulching rate (>1.5 ton ac^{-1} [3 Mg ha^{-1}]), pushing the straw mulch into the soil (crimping), adding a tackifier to "glue" the mulch strands to one another and to the soil, or felling trees on top of the mulch at a right angle to the prevailing winds to hold it in place (Bautista and others 2009; Napper 2006).

Wood mulches have greater resistance to wind displacement and provide greater wind erosion reduction than straw mulch. In wind tunnel testing, wood strand mulch resisted wind velocities of up to 40 mi h^{-1} (18 m s^{-1}), while wheat straw mulch moved at wind speeds of 15 mi h^{-1} (6.5 m s^{-1}) (Copeland and others 2009).

Hydromulch can resist wind displacement during the first 6 to 12 months after application but likely loses this capacity as the tackifier degrades (Etra 2007). In an area of burned-over sand dunes, hydromulch was applied to mitigate potential "brownouts," situations in which sands are blown over a highway, causing severely reduced visibility. Tice (2006) reported that soon after the hydromulch had been installed, wind speeds of over 50 mi h^{-1} (80 km h^{-1}) occurred with little or no wind erosion from the dunes treated with hydromulch; however, the article did not say how effective the treatment was over time.

Strand Length—Faucette and others (2007) compared the hydrological function of mulch materials to the litter and humus components of the natural forest floor; the larger mulch particles (analogous to forest floor litter) function primarily to reduce sediment yield, while the smaller mulch particles (analogous to forest floor humus) primarily absorb rainfall to reduce runoff. In studies, long-stranded mulches (for example, agricultural straws, wood shreds, ponderosa pine needles, etc.) have been observed forming "mini-debris dams" as mulch fibers become interlocked along flow paths on the slope. These mulch clumps contort overland flow paths, slow the flow velocity, and hold sediment on the hillslope (Foltz and Copeland 2009; Groenier and Showers 2004; Pannkuk and Robichaud 2003; Yanosek and others 2006). In addition, long fiber mulches require greater shear force to displace them compared to shorter-fiber mulches (Groenier and Showers 2004). Hydromulches tend to have thin, short fibers and depend on the formation of a smooth mat and/or soil adherence for effectiveness (Bautista and others 2009).

Mulch Treatment Effectiveness

There are few completed studies that measured the effectiveness of mulch in reducing post-fire runoff and/or erosion, and most of the available studies are of short duration. Of the field- and lab-based studies described in Appendix C, only one has data through three post-fire years (see Appendix C-Study II). Longer-term studies at different scales of measurement are on-going, but data have not been analyzed or published.

Agricultural Straw—Robichaud and others (2000) summarized results from four quantitative studies of post-fire straw mulching treatment effectiveness that had been completed prior to 2000. All four studies reported a significant reduction in sediment yield due to straw mulching. Since 2000, the data consistently show that straw mulch (ground cover of over 60 percent) is highly effective in reducing post-fire hillslope erosion on steep (up to 65 percent) slopes (Napper 2006). Examples of measured effectiveness include:

- After the Cerro Grande Fire in New Mexico, the application of straw mulch with seed reduced mean annual sediment yields by 70 percent in the first post-fire year and 95 percent in the second post-fire year; however, precipitation was below normal during the two study years (Dean 2001) (see Appendix C-Study I).

- Wagenbrenner and others (2006) reported that straw mulch immediately increased the mean ground cover to nearly 80 percent and facilitated vegetative regrowth after the 2000 Bobcat Fire in Colorado. Mulching did not reduce sediment yields in the year of the fire when a large amount of sediment was produced from a single 5- to 10-year return interval storm. Yet, in post-fire years one, two, and three, there was over 95 percent reduction in mean sediment yield on the straw mulch treated plots as compared to the untreated control plots (Wagenbrenner and others 2006) (see Appendix C-Study II).
- Using paired swale plots installed on the 2002 Hayman Fire, Rough (2007) measured reductions in sediment yields of 94 percent in post-fire year one and 90 percent in post-fire year two on the straw mulch swale compared to the untreated control swale (see Appendix C-Study III).
- After a 1991 wildfire in northeastern Spain, hillslope plots were established on steep hillslopes of two different soils (gypsiferous and calcareous) to study the effectiveness of dry barley straw mulch combined with seeding and seeding alone for reducing sediment yields. Both treatments significantly reduced sediment yields as compared to the untreated controls on both soils and in both post-fire years one and two. Except for post-fire year one on gypsiferous soil, there were no significant differences between the mean sediment yields for mulch and seed combination and seeding alone within each soil type and post-fire year (Badia and Marti 2000) (see Appendix C-Study IV).
- Immediately after the 2002 Indian Fire, one set of paired swales was used to compare sediment yields from a straw mulch treated plot and an untreated control plot after a high intensity ($I_{10} = 4.6$ inch h^{-1} [117 mm h^{-1}]) rain event. The straw mulch reduced the sediment yield by 81 percent compared to the control (Riechers and others 2008) (see Appendix C-Study VI).
- Rainfall simulations ($I = 3.3$ inch h^{-1} [83 mm h^{-1}]) were done on small (5.3 ft^2 [0.5 m^2]) hillslope plots after the 2002 Fox Creek Fire. In post-fire year 1, the 10 wheat straw mulched plots had 86 percent less sediment compared to the 10 control plots. (Groen and Woods 2008) (see Appendix C-Study VII).
- In the area burned by the 2002 Hayman Fire, aerial straw mulch treatment (1 ton ac^{-1} [2.5 Mg ha^{-1}]) is being evaluated using a paired watershed study. Preliminary results show that the watershed treated with straw mulch reduced erosion by 63 percent in the first post-fire year and 68 percent in the second post-fire year as compared to the untreated control watershed (Robichaud and Wagenbrenner, unpublished report 2006).

Given the measured effectiveness of straw mulch in reducing post-fire erosion, it is considered one of the more cost-effective emergency stabilization treatments currently available.

Wood-Based Mulches—Wood mulches are a promising new material for use in post-fire hillslope stabilization. Preliminary and laboratory-based studies indicate that manufactured wood mulch products as well as shredded trees can be equal to or more effective than straw mulch in reducing post-fire hillslope erosion. Examples include:

- Immediately after the 2002 Indian Fire, one set of paired swales was used to compare sediment yields from a wood chip mulched plot and an untreated control plot after three erosion-causing summer rain events. The wood chip mulch reduced the sediment yield by about 95 percent compared to the control for the first two smaller rain events; the effectiveness decreased for the third, high intensity ($I_{10} = 4.6$ inch h^{-1} [117 mm h^{-1}]) rain event when the wood chip mulch reduced sediment yields by less than 68 percent. After the third rain event, wood chips were observed at the bottom of the slope where they had been deposited after being washed downslope by overland flows (Riechers and others 2008) (see Appendix C-Study VI).
- Wood strands, a manufactured wood mulch product, have been tested in two laboratory rainfall/overland flow simulation studies using screened forest soils in a rectangular plot placed at a 30 percent slope. In the first study, several sizes of wood strands were compared to equal cover amounts of agricultural straw, and it was shown that wheat straw and two sizes of wood strands were equally effective at reducing erosion by over 98 percent (Foltz and Dooley 2003). Building on these results, two wood strand blends were tested on two soil types, two slopes, and three coverage amounts with simulated rainfall and added inflow. Compared to the untreated controls, wood strand materials reduced sediment yield by at least 70 percent for all treatment combinations. In addition, when compared to sediment yield reductions due to agricultural straw (as reported by Burroughs and King 1989), wood strand materials were equally effective on coarse-grained soils and superior to straw on fine-grained soils (Yanosek and others 2006) (see Appendix C-Study VIII, Lab Study 2).

- Wood shreds, a mulch material of variable-sized pieces produced on site from small-diameter trees and woody debris (Groenier and Showers 2004), were tested using rainfall and overland flow simulation. Sediment yield reductions ranged from 60 to nearly 100 percent, depending on the soil type (gravelly sand had greater sediment yields as compared to sandy loam), amount of concentrated flow, and mulch cover amount (Foltz and Copeland 2009) (see Appendix C-Study VIII, Lab Study 3).
- Wood shreds were further tested using the same laboratory rainfall and overland flow simulations on the burned surface soil and ash collected following the 2006 Tripod Fire in north-central Washington. This study was done to determine the optimum strand length(s) of wood shreds to use for post-fire hillslope stabilization. By controlling the proportion of "fine" shreds (shreds less than 1 inch [2.5 cm]) in the mulch blend, three shred blends were evaluated for runoff and sediment concentration reduction. All the blends reduced runoff amounts, but the blend with all fine shreds removed was most effective for both runoff and sediment yield reduction during rainfall and rainfall plus concentrated flow. In addition, there was no significant difference between 50 and 70 percent shred ground cover (Foltz and Wagenbrenner 2010) (see Appendix C-Study VIII, Lab Study 4).
- After the 2002 Hayman Fire, manufactured wood strands were one of three treatments (wood strands, wheat straw, and contour raking) evaluated using hillslope plots. Of the three treatments, only wood strands had significantly lower sediment yields as compared to the control plots in postfire years one and two. Also, in post-fire year two the remaining wood strand component of the ground cover was seven times greater than the remaining wheat straw component of the ground cover, suggesting that wood strands have greater longevity as compared to wheat straw (Robichaud and Wagenbrenner, unpublished report 2006).
- In Spain, Bautista and others (2009) found that a natural mulch (shredded forest debris), with and without seeds, was highly effective at reducing erosion. During the first post-fire year, average sediment yield from untreated plots was about 9 ton ac^{-1} (20 Mg ha^{-1}), but mulched sites had negligible sediment yields (Bautista and others 2009).

Given the potential effectiveness indicated by these studies, the manufacture, transportation, and broadcast application of wood-based mulches are evolving to accommodate its use in post-fire hillslope stabilization. Several wood mulch post-fire treatment effectiveness studies are in progress on burned areas of the 2002 Hayman Fire (Front Range, Colorado), 2005 School Fire (southeastern Washington), 2007 Cascade Complex Fire (central Idaho), and 2008 Jesusita Fire (southwest California).

Natural Burned Needle Cast Mulch—

- Conifer forests burned at low and moderate severity often have trees that are charred and partially consumed by fire, leaving dead needles in the canopy. These needles fall to the ground or are blown from the charred canopy by the wind to provide a natural mulch ground cover. In a rainfall and overland flow simulation laboratory study, Pannkuk and Robichaud (2003) tested the effectiveness of 50 percent ground cover of Douglas-fir and ponderosa pine needle cast. The short, flat Douglas-fir needles laid directly on the ground for their full length and reduced interrill erosion by 80 percent compared to a 60 percent reduction with ponderosa pine needles. The long, bundled, and curved ponderosa pine needles tended to form mini-debris dams on the soil surface and reduced rill erosion by 40 percent compared to a 20 percent reduction with Douglas-fir needles. Although the natural needle cast mulch is effective, it generally is unavailable in high burn severity areas where the needles are consumed by the fire (Pannkuk and Robichaud 2003) (see Appendix C-Study VIII, Lab Study 1).

Hydromulch—Hydromulching is relatively new in post-fire hillslope stabilization, and effectiveness data are scarce. However, effectiveness monitoring indicates that hydromulch may reduce sediment yields during the first few storms, but it shows little resistance to concentrated flow, degrades quickly, and its long-term effectiveness is not known.

- After the 2002 Hayman Fire, 1560 ac (630 ha) of steep, inaccessible hillslopes were treated with hydromulch to protect Denver's municipal water reservoir system, and another 1500 ac (610 ha) adjacent to forest roads were treated using truck-mounted sprayers (Robichaud and others 2003). In post-fire year one, the aerial hydromulch reduced sediment yield by 95 percent as compared to the control; in post-fire year two, the sediment yield reduction was 50 percent. However, the ground-based application of hydromulch did not significantly reduce sediment yields as compared to the control plots in either year (Rough 2007) (see Appendix C-Study III).

- The aerial hydromulch treatment at the 2002 Hayman Fire is also being evaluated using a paired watershed study, and the preliminary data show that the hydromulch was less effective in reducing erosion during the first and second post-fire years than was reported by Rough (2007). The sediment yield from the hydromulch treated watershed was only 18 percent less in the first post-fire year and 27 percent less in the second post-fire year as compared to the sediment yields from the control watershed (Robichaud and Wagenbrenner, unpublished report 2006).
- After the 2003 Cedar Fire in southern California, hillslopes burned at high soil burn severity were treated with aerial hydromulch using two configurations—application over 100 percent of the treatment area (H100) and application of 100 ft (30 m) wide contour strips of hydromulch such that 50 percent of the area was treated (H50). A paired watershed study is being used to measure treatment effectiveness, but differences in rainfall between the watersheds have confounded the preliminary results. The H50 watershed, which is approximately 1 mi (1.6 km) from the H100 and control watersheds, received greater rainfall amounts at higher intensities in comparison to the other two. In 2003, the year of the fire, the H100 watershed reduced the sediment yield by 53 percent compared to the control, and the H50 watershed had a larger sediment yield than either of the other two. In post-fire year one, the control and the H100 watersheds had over three times more rainfall at greater intensities than the previous year, but the H50 watershed again had greater rainfall amount and intensity than either of these. These greater rain amounts resulted in greater sediment yields in all the watersheds. The H100 watershed had 43 percent less sediment compared to the control; and the H50 watershed, despite its larger, more intense rainfall, had 37 percent less sediment compared to the control (Wohlgemuth and others, unpublished report 2006).
- The effectiveness of the hydromulch treatment on the Cedar Fire was also monitored using hillslope plots with silt fence sediment traps (Robichaud and Brown 2002). In post-fire year one, the H50 hydromulch reduced sediment yields by more than 50 percent, and the H100 hydromulch cover reduced sediment yields by about 75 percent (Hubbert, unpublished report 2007) (see Appendix C-Study V).

The use of hydromulch treatments for post-fire hillslope stabilization are of particular interest in the steep chaparral areas of southern California where wildfires are common and the Santa Anna winds are known to dislocate and deeply pile lighter dry mulches, leaving bare soil exposed to winter rains. Besides the ongoing studies discussed above, post-fire hydromulch treatments for hillslope stabilization are being studied on three recent southern California fires—the 2007 Santiago Fire, the 2008 Gap Fire, and the 2009 Jesusita Fire.

Chemical Soil Surface Treatments

Tackifiers, or soil binding agents, are mixed with fiber, seeds, and/or fertilizer for use in hydromulching and hydro-seeding; however, tackifiers may be used alone as a surface soil treatment. Soil binders are applied by putting them into solution and spraying them on the soil or by spreading solid granulated particles on the soil where they can dissolve in rain and/or overland flow. When the soil binder solution dries, it forms a thin web of polymer that coats the soil particle surfaces at the water-soil interface, which increases the shear force needed to detach those particles (Sojka and others 2007). In addition, some soil binders such as polyacrylamide (PAM) are flocculants that can connect small particles, thus increasing their size and mass, which allows them to settle out of solution and be deposited (Sojka and others 2007). Some research has shown that chemical surface treatments reduce soil sealing and erosion more effectively when combined with physical treatments such as mulch or erosion barriers (McLaughlin 2007; McLaughlin and others 2009; Zhang and others 1998).

Chemical soil binders are often classified by their source. Natural or organic binders such as guar and starches are derived from plant materials, and synthetic binders such as polyacrylamide (PAM) formulations are derived from petroleum products. Though natural guar tackifiers have been used in post-fire hydromulch treatments (Moore, personal communication), PAM is the only soil binder that has been used as a post-fire hillslope stabilization treatment.

PAM is a class of synthetic polymers with hundreds of specific formulations that can be categorized by molecular structure (linear or cross-linked), charge (anionic—negatively charged; cationic—positively charged; or nonionic—no charge), solubility, molecular weight, and other characteristics (Sojka and others 2007). Various types of PAM have been used for over 50 years to improve soil structure and permeability (Ajwa and Trout 2006). In agriculture, PAM is mainly used to reduce erosion and increase infiltration in sprinkler irrigated agricultural soils and low-flow irrigation trenches (Lentz and Sojka

2000; Sojka and others 2007). Natural and synthetic polymers, including PAM, are used on disturbed areas such as construction sites, mining operations, landfills, and unpaved roads for dust abatement, erosion control, soil stabilization, and turbidity reduction in storm water runoff (Faucette and others 2007; Hayes and others 2005; Tice 2006). Though tackifiers have been applied over dry mulches such as straw, pine needles, and wood materials to bind the material and hold it on the soil surface (Etra 2007; McLaughlin and Brown 2006), this combination of tackifier on mulch has only recently been tried experimentally as a post-fire hillslope treatment.

Cationic and non-ionic PAMs are known to be toxic for fish and other aquatic life. However, the class of anionic PAMs used for soil erosion and infiltration management shows no measurable toxicity at concentrations of 100 ppm, an order of magnitude safety margin for the highest concentration of PAM present (10 ppm) in agricultural applications (Sojka and others 2007). Although negative environmental impacts have not been documented when the anionic PAMs are applied at recommended concentration rates, contractors for post-fire hillslope PAM treatment applications have recommended application rates that exceed manufacturer recommendations to improve performance (Moore, personal communication). In addition, there is some concern surrounding the use of PAM due to the presence of residual, unreacted acrylamide monomers (AMD), a known neurotoxin and suspected carcinogen in humans and animals, as a product contaminant. However, PAM does not revert to AMD on degradation, and the small residual amounts of AMD contained in PAM are rapidly metabolized in soil or natural waters by microorganisms (Sojka and others 2007). Though anionic PAMs are considered safe if used as directed, prolonged skin exposure and exposure to PAM dust can result in skin irritation and inflammation of mucous membranes (Sojka and others 2007).

Performance Characteristics of PAM and Other Polymers

Longevity—Longevity of soil binders is generally expressed in months, not years. The California Department of Transportation (2007) developed a management guide for erosion control on all road construction projects. This guide includes a comparison matrix of three types of plant-based materials (including guar and starches) and five synthetic polymeric chemicals (including PAM) that are rated on several criteria, including longevity. Guar and starches, which degrade through biological decomposition, have short (1- to 3-month) longevity ratings, while PAM, which photo-degrades, has a moderate (3- to 12-month) longevity rating. Given that post-fire hillslope stabilization treatment effectiveness is needed for at least two to three years while revegetation occurs, the rapid degradation of PAM and other soil binders is a drawback to their use in post-fire treatment.

Soil Type and Cation Ion Availability—Adsorption of PAM on soil and clay mineral surfaces differs based on soil texture, organic matter content, and dissolved salts (Lu and others 2002). PAM has a high affinity for clay mineral surfaces and, once adsorbed, is not easily removed. Generally, PAM is less easily adsorbed onto coarse-textured soils, and organic matter tends to interfere with the adsorption process (Sojka and others 2007). Rough (2007) reported that PAM preferentially bound to ash over mineral soil when used after the 2002 Schoonover Fire in Colorado.

Adsorption of anionic PAMs to mineral surfaces, which carry predominately negative charges, is aided by an abundance of divalent cations such as Ca^{2+} (calcium ions) in the solution. Consequently, PAM is often applied with gypsum ($CaSO_4$-$2H_2O$) as a source for the Ca^{2+} ions. Flanagan and others (2002) compared three treatments (liquid PAM, liquid PAM plus dry gypsum, and untreated control) using rainfall simulation on tilled silt loam soil placed in 32 percent hillslope plots (10 ft [3.0 m] wide and 30 ft [9.1 m] long). Although the PAM and PAM plus gypsum results were not significantly different, total runoff on the treated plots was 40 to 52 percent less than on the control plots, and sediment yield on the treated plots was 83 to 91 percent less than on the control plots (Flanagan and others 2002). Although this study showed that PAM and PAM plus gypsum provided effective runoff and sediment yield reductions on steep slopes, it did not look at the effectiveness of PAM over time.

Viscosity and Infiltration Rate—Much of the research on PAM use in agricultural irrigation has reported increases in infiltration rates, which generally have been attributed to PAM stabilizing soil surface structure and preventing the formation of surface seals (Sojka and others 2007). However, if the soil structure has already deteriorated (as is often the case in areas of high soil burn severity) or if the soil is sandy (larger particles and less structured soil), PAM's tendency to increase viscosity of the infiltrating water may reduce rather than increase infiltration (Sojka and others 2007). Ajwa and Trout (2006) used packed soil column experiments to measure infiltration rates of an unburned sandy loam soil with a range of PAM concentration (5 to 20 mg PAM L^{-1}) in the infiltration water. Final infiltration rates of 5 mg PAM L^{-1} were 35 percent less with emulsified PAM and 64 percent less with granular PAM as compared to deionized water, and these reductions in infiltration rates increased with increasing PAM concentrations (Ajwa and Trout 2006). Obviously, any reduction in infiltration would be detrimental in post-fire stabilization treatments and is a significant disadvantage to using PAM in burned areas.

Effectiveness of PAM and Other Polymers

The effectiveness of PAM has been documented for use in agricultural irrigation and in disturbed but not burned areas; however, only a few of these studies involve the types of soil and water control needed in post-fire hillslope stabilization. Very few studies measure the effectiveness of PAM or other polymers in post-fire applications. PAM and guar products have been used in hydromulch mixes applied for post-fire hillslope stabilization, but there have been few attempts to evaluate the effectiveness of the polymer component of the hydromulch treatment. For example, one of the three mulch treatments Riechers and others (2008) compared was a manufactured rice straw pellet that contained PAM (Appendix C-Study VI). However, PAM effectiveness could not be evaluated as the treatments did not include rice straw pellets without PAM or PAM applied directly on the soil.

Post-fire treatment effectiveness studies that include PAM have generally been inconclusive or have shown no treatment effect. After the 2000 Bobcat Fire in Colorado, a test using simulated rainfall on small (11 ft^2 [1 m^2]), high burn severity hillslope plots in the northern Colorado Front Range found some initial erosion reduction that disappeared after the first 30 min of the 1-hour rain simulation (Benavides-Solorio and MacDonald, unpublished report 2000). Following the 2002 Williams Fire in southern California, sediment yields from a pair of watersheds (2 and 6 ac [0.75 and 2.4 ha])—one treated with aerially applied PAM and one untreated—were compared for one year and no significant difference was found (Wohlgemuth 2003).

After the 2002 Schoonover Fire in Colorado, PAM was tested over three years on paired hillslope swales. PAM was reapplied each year to half of the treated swales, and the other half received only the initial application. Although the PAM treatments reduced sediment yield during lower, less intense rainfall periods, it was not effective when rainfall amounts and intensities increased. These results were inconclusive, and storm erosivity explained 58 percent of the variability in sediment yields (Rough 2007) (see Appendix D-Study I).

After the 2004 Red Bull Fire in central Utah, PAM was one of four treatments (PAM, straw mulch, PAM plus straw mulch, and untreated control) evaluated on aerially seeded sites. Erosion bridges (three per treatment) were used to measure soil movement over three years. No rainfall data were reported and the small differences in net soil movement were not significant (Davidson and others 2009) (see Appendix D-Study II).

Treatment Combinations

Combining seeding with other treatments, especially mulching, is relatively common on burned hillslopes. Often, large areas burned at high and moderate severity have been treated with broadcast seeding, and areas that are particularly vulnerable to erosion are dry mulched over the seeding to provide immediate ground cover and hold seeds and moisture to enhance potential seed germination. Seeds are often included in hydromulch mixes and applied with the mulch slurry. Post-fire treatments applied to establish seeded plants (main objective) are reviewed in separate syntheses by Jan Beyers and several others (as described in the Preface). The combination treatment studies discussed here include those studies in which seeding and other erosion control measures were applied and erosion control was the primary objective.

If treatment effectiveness studies were done on erosion barriers, mulching, or PAM in combination with seeding, they have been presented in the previous section related to the non-seeding portion of the treatment. There is one additional study of a treatment—hand scarification (using McLeod rakes to disturb the surface soil)—that was combined with seeding that does not fit into any of the previous sections. In this study, Rough (2007) found no difference in sediment yields among paired swales that were hand scarified and seeded and the untreated controls (see Appendix E-Study I).

Treatment combinations that include two or more hillslope treatments other than seeding are not common. Given the expense of hillslope treatments, it is difficult to justify applying more than a single treatment in one area. After the 2000 Cerro Grande Fire in New Mexico, Dean (2001) found that a combination of contour-felled log erosion barriers (LEBs), straw mulch, and seeding significantly ($p<0.05$) reduced sediment yields from hillslope plots by 77 percent in the year of the fire and by 96 percent in post-fire year one. However, these results were not significantly different than the reduction in sediment yields from plots treated with straw mulch and seeding; Dean (2001) concluded that the LEBs added no additional erosion mitigation over the straw mulch plus seeding treatment (see Appendix E-Study II).

When resources that are at risk for damage due to erosion are of very high value and/or difficult to repair, erosion mitigation treatments may be combined to provide more protection for the values-at-risk. For example, after the

2002 Missionary Ridge Fire in Colorado, several hillslope erosion control measures and some channel treatments were installed at higher than normal density above Lemon Dam to protect the intake structures of the dam from being filled with sediment. Since the dam is a critical component of the water supply system for the city of Durango, Colorado, the Water Conservation District was anxious to ensure continuous facility operation (deWolfe and others 2008). The hillslope treatments included: LEBs at 90 to 250 LEBs ac^{-1} (220 to 620 LEBs ha^{-1}), 200 to 600 percent of typical; hand-spread and crimped straw mulch at 2.5 ton ac^{-1} (5.6 Mg ha^{-1}), 125 percent of typical; and hand-spread seeding at 60 to 75 lbs ac^{-1} (67 to 84 kg ha^{-1}), 150 percent of typical. In addition, 13 check dams and 3 debris racks were installed in the main drainage channel of the basin. The erosion barriers, check dams, and debris racks were cleaned out and rehabilitated after each sediment-producing storm to ensure maximum performance for the next event. This combination of treatments virtually eliminated sedimentation into the reservoir. The authors attribute the success of this treatment combination to 1) the high density of application for each treatment, 2) the enhancement of treatments working in concert, 3) the quality of treatment installation, and 4) sediment and debris removal from barrier treatments and repair of treatments to extend their useful life (deWolfe and others 2008).

Management Implications

Post-fire emergency hillslope stabilization treatments cannot prevent erosion, but they can reduce overland flow, erosion, and sedimentation for some rainfall events, thereby reducing the risk to public safety and risk of damage to structures, roads, water quality, and critical habitat. However, the effectiveness of any hillslope stabilization treatment depends on actual rainfall amounts and intensities, especially in the first post-fire years (Robichaud and others 2000; Robichaud 2005). Wagenbrenner and others (2006) found that none of the treatments, including straw mulch, were effective in reducing sediment yields from large, high-intensity storm events after the 2000 Bobcat Fire in Colorado. The need to protect the valued resources in and around burned areas has motivated efforts to refine post-fire erosion prediction models, improve the effectiveness of post-fire rehabilitation treatments, and evaluate new treatment technologies.

Longer-Term Treatment Effectiveness

BAER treatments are, by definition, emergency protection of public safety and short-term stabilization of burned landscapes. When the BAER program was established, it was generally assumed that most burned sites were well stabilized within three years of burning. Subsequent research has shown that this is not always the case (Robichaud and others 2008b). Some sites, especially in arid or semi-arid regions where naturally sparse ground vegetation leaves exposed soil, may need erosion protection for more than three years after a fire. Thus, the length of time a treatment remains effective has become more important as we better understand the recovery process for various ecosystems.

Choosing Treatments

Since 2000, post-fire treatment spending and fire suppression costs have increased, and like fire suppression spending, BAER costs have come under scrutiny, and cost containment protocols are being explored. Treatment justification has been reframed from “reducing a threat” to “protecting values-at-risk” so that the values-at-risk for damage or loss are clearly identified before an area is designated for treatment (Calkins and others 2007). The cost of repairing or replacing those identified values-at-risk is weighed against the cost of treatment and the potential treatment success. In some burned areas, the “no treatment” option may be the most appropriate response. This is particularly true for areas burned at low or moderate severity where adequate ground cover is provided by remaining forest floor material and natural mulch, such as scorched conifer needles, and for areas where rapid natural recovery is expected.

The no treatment option may also be appropriate in areas burned at high severity that do not pose a high risk to identified values. Calkins and others (2007) have developed a Value-at-Risk assessment tool (the VAR tool) to assist BAER teams with the cost-risk analysis needed to justify post-fire treatment decisions. This procedure can be helpful as it provides a framework to identify downstream values, provides monetary values when available, and uses the *implied minimum value* (Calkins and others 2007) for non-monetary values-at-risk (water quality, habitat for threatened species, recreational value, etc.). In addition, the VAR tool incorporates the probability of treatment success, an essential part of this valuation process that may be determined through modeling (such as the Erosion Risk Management Tool [ERMiT]) and/or professional judgment (Calkins and others 2007). This approach emphasizes the need to select treatments that are known to be effective and to apply those treatments in areas where stability is needed to protect public safety and/or valued resources. Once it is established that there are values-at-risk and that BAER treatments are necessary to stabilize hillslopes above and upstream of those values, there is still the question of which treatment(s) to use.

Protecting a Municipal Water Supply

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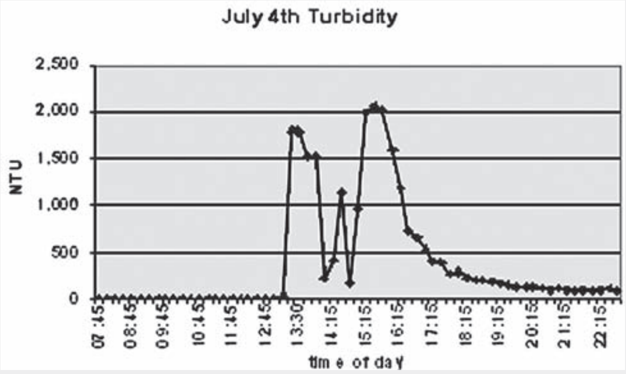
The 2003 Myrtle Fire burned 3600 ac (1460 ha) within the municipal watershed of Bonners Ferry, Idaho. The steep, burned area was aerially straw mulched and seeded, and areas along all roads were hydromulched and seeded. Light rains followed the fire, and both seeded and natural vegetation was very robust, providing an effective ground cover over much of the burned area (uncommon in post-fire year one). On 4 July 2004, one year after the fire, a high intensity storm of 1.6 inch (41 mm) of rain in two hours occurred over the burned area. Nearly all ephemeral draws within the burned area had surface flow, but erosion was relatively minor because the draws were well vegetated (SB4-fig.1). Despite the protection from dense vegetation, the State of Idaho municipal water supply turbidity standard (50 NTU) was greatly exceeded (SB4-fig. 2). This spike in turbidity was short-lived; about nine hours after the surge in turbidity had begun, the readings were nearing pre-storm levels (SB4-fig. 2). The city of Bonners Ferry maintained continuous water service to its customers by using back-up sources while allowing substandard surface water to bypass its system.

SB4-fig. 1. Photo taken after the 4 July 2004 storm showing overland flow in a swale near the top of the ridge above Myrtle Creek.



SB4-fig. 2. Graph of the hourly turbidity monitoring measurements for Myrtle Creek, Bonners Ferry primary municipal water source, on 4 July 2004, 10 months after the Myrtle Creek Fire. The graph shows a pulse of sediment that passed through the system due to storm runoff. (Water Quality monitoring data from the City of Bonners Ferry Water and Sewer Department.)

Post-Fire Recovery

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The potential for dramatic increases in hillslope erosion after fires is well documented (see Moody and Martin 2009 for a synthesis of post-fire sediment yields in the western United States). The time needed for burned hillslopes to recover, or return to the pre-fire erosion potential, is not as well known. Based on limited data, this recovery time is estimated to be about three years for most western forests, and the effectiveness of post-fire hillslope stabilization treatments are generally evaluated using this time frame. During the past few years, some longer-term monitoring projects have provided evidence suggesting that the recovery time needed for post-fire hillslope stability may be longer than three years (SB5-fig. 1).

The magnitude of the potential post-fire erosion response is dependent on burn severity, topography, soil type, soil moisture, and ground cover (live vegetation and litter). The actual erosion response is dependent on rainfall characteristics—especially intensity and amount. In the first two years after a fire, rainfall intensities with less than two-year return intervals have resulted in large sediment yields in many locations (Moody and Martin 2009). Although it generally takes a larger rain event to trigger a large erosion response after three or four post-fire recovery years, such responses have been documented (see Appendix B, table AB-5 for PFy5 [high intensity storm] and PFy6 [long-duration storm]; see also table AB-9 for PFy4 [high intensity storm]). These observations confirm that the potential erosion response remains above pre-fire levels for more than three years in some burned areas.

SB5-fig. 1. In post-fire year four, a paired watershed study site on the 2002 Cannon Fire in California had a rainfall event with maximum 10-min intensity (I_{10}) of 6.22 inch h^{-1} (158 mm h^{-1}). The sediment basin filled and then over-topped, depositing large rocks and tree debris both inside and outside the sheet metal wall that forms the sediment basin. The sediment yield from the contour-felled log treated catchment was estimated at over 3.9 ton ac^{-1} (8.7 Mg ha^{-1}) (see table AB-9 in Appendix B).

There is no single best approach to post-fire hillslope stabilization. Appendix A contains a chart that summarizes the known effectiveness and specific performance issues related to the post-fire treatments currently in use. However, each BAER team will have to match their treatment recommendations to the specific environmental and climatic factors, burn conditions, and probable hydrological responses of the area.

Monitoring Post-Fire Treatment Effectiveness

When BAER teams recommend hillslope treatments, they often adapt application rates, mulch formulations, and/or treatment combinations to improve treatment effectiveness or to accommodate the climate or topography of the area being treated. The adaptations in treatment protocols combined with the distinctive characteristics of each burned area make each post-fire treatment installation unique. Monitoring the effectiveness of the specific treatment type and application rate for the climate (specifically the rainfall characteristics), topography, and burn severity of the area can provide valuable information to improve treatment selection. Measurements of treatment effectiveness are most useful when they are directly related to the objective(s) of the treatment. For example, if a hillslope treatment is applied to reduce runoff and erosion, then the monitoring should measure rainfall characteristics, hillslope runoff, and erosion rates over several years. With these data we can evaluate treatment effectiveness in terms of the characteristics that are known to limit effectiveness.

Using the "Best Available" Treatments

The selection of "best available" can be challenging for BAER teams. This synthesis is a direct response to the need for reporting and comparing hillslope treatment effectiveness information. However, a printed document is static—a description of our current knowledge. As post-fire treatments improve and new options become available, they too will need to be evaluated. The information on treatment performance characteristics and environmental factors that impact treatment effectiveness can be applied to these future choices even if the specific treatment is not included in this synthesis. A hillslope treatment effectiveness web page (http://forest.moscowfsl.wsu.edu/BAERTOOLS/HillslopeTrt) has been added to our suite of BAERTOOLS web pages. Information from this synthesis is posted on the web page, and new information will be posted as it becomes available.

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Appendix A. Hillslope Treatment Effectiveness and Performance Characteristics Summary Table

Table AA-1. Ratings of post-fire hillslope stabilization treatment effectiveness for three rainfall regimes (high intensity, low intensity, and high total amount; see fig. 4 and table 1 in main text) are presented in the table below. Treatment effectiveness codes: 1 = more effective; 2 = somewhat effective; and 3 = not effective. Treatments are also rated as more likely (more) or less likely (less) to exhibit performance characteristics that impact treatment effectiveness, post-fire recovery, and/or the environment. Other phrases are used to describe the performance characteristics of treatments that are dependent on circumstances or are not effectively rated as more or less likely. Details of treatment performance characteristics can be found in the individual treatment sections of the main text.

		Straw mulches	**Wood mulches**	**Hydro-mulches**	**Soil binders (PAM)**	**Contour-felled logs (LEBs)**	**Straw wattles**
Overall effectiveness (rating: 1, 2, or 3)	High intensity rainfall (>2-yr return interval)	**1**	**1**	**3**	**3**	**3**	**3**
	Low intensity rainfall	**1**	**1**	**1**	**2**	**1**	**1**
	High rainfall amount (>2 inch [50 mm] in 6 hr)	**1**	**1**	**2**	**3**	**2**	**2**
Performance characteristics that impact effectiveness	Resistant to wind displacement	less[a]	more[a]	more	more	more	more
	Remains functional for more than 1 year	more	more	less	less	more	more
	Provides ground cover	more	more	more	less	less	less
	Increases infiltration	more	more	not known	depends on conditions	less	less
	Increases soil moisture retention	more	more	more	less	less	less
	Shortens flow paths	more	more	less	less	more	more
	Traps sediment	more	more	less	less	more	more
	Slows development of concentrated flow	more	more	more	more	less	less
Other considerations	Contains noxious weed seeds	possible	less	less	less	less	possible
	Delays revegetation	depends on mulch thickness	depends on mulch thickness	less	less	less	less
	Harmful to the environment	less	less	depends on components	depends on type and concentration	less	less

[a] In wind tunnel tests, agricultural straw resisted movement in wind speeds of 15 mi h^{-1} (6.5 m s^{-1}), and wood straw resisted movement in wind speeds of 40 mi h^{-1} (18 m s^{-1}) (Copeland and others 2006).

Appendix B. Erosion Barrier Treatment Effectiveness Studies (2000 to the present)

Study I. Effectiveness of contour-felled logs (LEBs) in reducing sediment following the 2000 Bobcat Fire in central Colorado (Wagenbrenner and others 2006)

Study design: Contour-felled logs (LEBs) were hand-installed at a mean rate of 900 ft ac^{-1} (680 m ha^{-1}) on 20 to 35 percent slopes that were burned at high severity. Silt fence sediment traps were established at the base of paired swales to compare the sediment yields from treated and untreated areas.

Plot size(s): Paired swales ranged from 0.25 to 1.25 ac (0.1 to 0.5 ha), and each swale included a zero-order channel formed by convergent hillslopes.

Factors that impacted study design and/or results:

- In the year of the fire (FY), a large storm compromised storage capacity of the LEBs that had been installed. The old LEB plots remained in the study; however, new treated swales were established with sediment traps and compared to their paired control. In table AB-1, the sediment yields from the swale plots installed before the storm are labeled "old," and the sediment yields from the swale plots installed after the storm are labeled "new."
- In post-fire year three (PFy3), the two general study areas had different rainfall. Both rainfall amounts are reported (table AB-1).

Table AB-1. Results from LEB study following the 2000 Bobcat Fire. Rainfall amount, maximum 30-min intensity (I_{30}), and mean annual sediment yields are reported for each of the four years of the study. Mean percent difference in sediment yield between the control and the treated swales are reported for each year. Time since fire codes: FY = year of the fire; PFy1 = 1 year after the fire; PFy2 = 2 years after the fire; and PFy3 = 3 years after the fire (Wagenbrenner and others 2006).

	------------Rainfall-----------		------------------------Sediment yields------------------------		
Time since fire	**Amount** (inch [mm])	**I_{30}** (inch h^{-1} [mm h^{-1}])	**Control** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Treated** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Difference** (%)
FY	2.4 [60]	1.9 [48]	2.8 [6.2]	old[a]-2.6 [5.8] new[b]-NA	old-7.1 new-NA
PFy1	3.0 [75]	1.1 [29]	4.2 [9.5]	old-2.5 [5.7] new-1.2 [2.8]	old-40 new-71
PFy2	1.4 [36]	0.67 [17]	0.54 [1.2]	old-0.01 [0.03] new-0.09 [0.2]	old-98 new-83
PFy3	0.67 [17] 4.3 [110]	0.71 [18] 1.4 [35]	0.3 [0.7]	old-0.009 [0.02] new-0.03 [0.07]	old-97 new-10

[a] old = sediment yields from plots installed before the large storm that occurred the same year as the fire.

[b] new = sediment yields from plots installed after the large storm that occurred the same year as the fire.

Generalized results:

LEBs were ineffective in large storms but could be effective for small events given sufficient sediment storage capacity (Wagenbrenner and others 2006).

Study II. Measured effectiveness of LEBs in reducing sediment, and the effect of study plot size on these measurements; the 2000 Hi Meadows Fire in central Colorado (Gartner 2003)

Study design: In post-fire year one, a two-month study (1 Jul 01 to 31 Aug 01) examined the effect of study plot size on LEB treatment effectiveness in reducing sediment yield. LEBs were installed at a rate of 71 LEBs ac^{-1} (175 LEBs ha^{-1}) or 320 LEB ft ac^{-1} (240 LEB m ha^{-1}) on steep slopes that had been burned at high severity. **Plot size(s):** Two paired catchments of ~40 ac (~16 ha) were selected and one was treated with LEBs. Nested within these two catchments were plots (10 to 50 ft^2 [1 to 5 m^2]), hillslopes (~4,300 ft^2 [~400 m^2]), and sub-catchments (2.5 to 12 ac [1 to 5 ha]). Cumulative (two-month) sediment yields were determined for the hillslopes, sub-catchments, and catchments, while sediment flux (lb ft^{-1} [kg m^{-1}]) was measured on the smallest plots.

Table AB-2. Results from LEB study following the 2000 Hi Meadows Fire. Rainfall amount and maximum 10-min intensity (I_{10}) are reported for the study area. Mean sediment flux (lb ft^{-1} [kg m^{-1}]) is reported for plots. Mean cumulative sediment yields (ton ac^{-1} 2-mo^{-1} [Mg ha^{-1}2-mo^{-1}]) for the hillslopes, sub-catchments, and catchments are reported for the study period of 2 months. Mean percent difference in sediment yield between the paired control and the treated study areas are reported. Time since fire code: PFy1 = 1 year after the fire (Gartner 2003).

	-------------Rainfall--------------			-------------------------Sediment yields-----------------------		
Time since fire	**Amount** (inch 2-mo^{-1} [mm 2-mo^{-1}])	**I_{10}** (inch h^{-1} [mm h^{-1}])		**Control** (lb ft^{-1} [kg m^{-1}])	**Treated** (lb ft^{-1} [kg m^{-1}])	**Difference** (%)
PFy1	4.2 [107]	1.3 [34]	**Plots**	511 [762]	107 [161]	79
				Control (ton ac^{-1} 2-mo^{-1} [Mg ha^{-1} 2-mo^{-1}])	**Treated** (ton ac^{-1} 2-mo^{-1} [Mg ha^{-1} 2-mo^{-1}])	
			Hillslopes	1.3 [2.8]	0.21 [0.46]	84
			Sub-catchment	0.29 [0.64]	0.27 [0.61]	7
			Catchment	0.38 [0.86]	0.05 [0.11]	87

Generalized results:

LEBs generally were effective for low intensity rain events observed during the two-month study period (Gartner 2003).

Study III. Comparing the effectiveness of three erosion barrier treatments in reducing sediment following the 2000 Valley Complex Fire in western Montana (Robichaud and others 2008a)

Study design: Sixteen hillslope plots with a single erosion barrier installed across the lower width of each treated plot were established immediately after the fire on steep planar slopes burned at high severity. Four repetitions of four treatments (LEBs, straw wattles, hand dug contour trenches, and untreated controls) were randomly applied. Low intensity rainfall plus overland flow simulations were used immediately after the fire (2000) to measure treatment effectiveness. After the simulation study, silt fences were installed at the base of each plot below the erosion barrier. Sediment yields from natural rainfall were measured for post-fire years one, two, and three.

Plot size(s): Hillslope plots were 200 to 350 ft^2 (20 to 30 m^2) with a single erosion barrier at the base of each treated plot.

Table AB-3. Results from erosion barrier study following the 2000 Valley Complex Fires. Mean rainfall amount, maximum 10-min intensity (I_{10}), and event sediment yields are reported for both the simulation study and the natural rainfall study. Mean percent difference in sediment yield between the control and the treated plots are reported for each year. Time since fire codes: FY = year of the fire; PFy1 = 1 year after the fire; PFy2 = 2 years after the fire; and PFy3 = 3 years after the fire (Robichaud and others 2008a).

Time since fire	Rainfall amount (inch [mm])			Sediment yields			
				Control (ton ac^{-1} [Mg ha^{-1}])	Treated (ton ac^{-1} [Mg ha^{-1}])		Difference (%)
	Rain + inflow simulation			0.98 [2.2]	LEB	0.26 [0.58]	74
FY	**Rain:** 1.1 [26] for 60 min				Straw wattle	0.09 [0.21][a]	90
	Inflow: 13 gal min^{-1} [48 L min^{-1}] for last 15 min				Trench	1.1 [2.5]	–14[b]
	Event amount (inch [mm])	**I_{10}** (inch h^{-1} [mm h^{-1}])	**Amount** (inch [mm])	**Control** (ton ac^{-1} [Mg ha^{-1}])	**Treated** (ton ac^{-1} [Mg ha^{-1}])		**Difference** (%)
			Cumulative for 5 events	**Cumulative for 5 events**	**Cumulative for 5 events**		
PFy1	1.1 [29]	0.54 [14]					
	0.26 [6.6]	0.78 [20]			LEB	6.7 [15]	48
	0.62 [16]	1.6 [40][c]	3.0 [77]	13 [29]	Straw wattle	12 [27]	7.7
	0.87 [22]	0.30 [7.6]			Trench	14 [32]	–7.7[b]
	0.15 [3.8]	0.54 [14]					
			Cumulative for 3 events	**Cumulative for 3 events**	**Cumulative for 3 events**		
	0.11 [2.8]	0.54 [14]			LEB	0.36 [0.8]	0
PFy2	0.30 [7.6]	1.7 [43][c]	0.71 [18]	0.36 [0.8]	Straw wattle	0.49 [1.1]	–38[b]
	0.29 [7.4]	0.84 [21]			Trench	0.31 [0.7]	13
			Cumulative for 2 events	**Cumulative for 2 events**	**Cumulative for 2 events**		
					LEB	0.08 [0.19]	–170[b]
PFy3	0.16 [4.1]	0.30 [7.6]	0.39 [10]	0.03 [0.07]	Straw wattle	0.14 [0.31]	–340[b]
	0.22 [5.6]	1.2 [31]			Trench	0.06 [0.14]	–100[b]

[a] Significant ($p = 0.005$) reduction in sediment yield compared with the control.

[b] Negative values in the percent difference column indicate that sediment yields were larger for the treated plots than for the control plots.

[c] 2- to 5-yr return period for 10-min duration (Miller and others 1973).

Generalized results:

The LEBs and straw wattles lower values for total runoff, and all three erosion barrier treatments had lower values for peak flow rates; however, only the straw wattles significantly reduced sediment yields compared to the controls. In the subsequent three years, sediment yields from natural rainfall were measured, and there was no treatment effect associated with 10 sediment-producing rain events. In addition, sediment yields increased with increasing total rainfall and rainfall intensity. The erosion barrier treatment effectiveness measured during low intensity simulated rainfall (even with added inflow) was not evident during higher intensity summer storms typical of western Montana (Robichaud and others 2008a).

Study IV. A multi-year, multi-site study of the effectiveness of LEBs for reducing post-fire runoff and sediment yields (Robichaud and others 2008b)

Overall study design: Between 1998 and 2002, six paired watershed sites were established following six wildfires to measure the effectiveness of LEBs in reducing post-fire runoff and erosion. In each location, two small, matched watersheds were selected, and each had a sheet metal headwall with an overflow weir installed at the base outlet. One watershed was treated with LEBs and one was left untreated as the control. Event runoff and sediment yields were measured at the base outlet over several post-fire years (Robichaud and others 2008b).

Plot size(s): Paired watersheds ranged from 2.5 to 25 ac (1 to 10 ha).

Factors that impacted study design and/or results: Results from each of the six sites are reported separately below.

Study IV—Site 1

Fire: 1998 North 25 Mile Fire

Location: North-central Washington

Site specific design: Mean slopes for the watersheds were 39 percent on the treated and 50 percent on the control. LEBs were installed at a rate of 19 ac^{-1} (46 ha^{-1}) and had an estimated 2.2 ton ac^{-1} (5.0 Mg ha^{-1}) total sediment storage capacity.

Table AB-4. Results from LEB effectiveness study following the 1998 North 25 Mile Fire. Event rainfall amount, maximum 10-min intensity (I_{10}), runoff, peak flow, and sediment yields are reported for rainfall events that resulted in runoff and/or sediment. Data for large events ($I_{10} \geq$ 2-year return period) are in bold type and the return period is shown as a subscript. Mean percent difference in sediment yield between the control (C) and the treated (T) plots are reported for each event. **---** indicates that no rainfall events resulted in measurable runoff or sediment in that year. Time since fire codes: PFy1 = 1 year after the fire; PFy2 = 2 years after the fire; PFy3 = 3 years after the fire; and PFy4 = 4 years after the fire (Robichaud and others 2008b).

	-----------**Rainfall**----------		--------**Runoff**---------		--------**Peak flow**-------		-------------------**Sediment yield**---------------		
	Event amount	**I_{10}**	(inch [mm])		(X 10^{-2} ft^{3}s^{-1}ac^{-1} [m^{3}s^{-1}km^{-2}])		(ton ac^{-1} [Mg ha^{-1}])		**Difference**
Time since fire	(inch [mm])	(inch h^{-1} [mm h^{-1}])	**C**	**T**	**C**	**T**	**C**	**T**	(%)
PFy1	0.23 [5.8]	0.63 [16]	0 [0]	Not measured	0 [0]	Not measured	0 [0]	0.14 [0.31]	–100[a]
	0.14 [3.6]	0.75 [19]	0 [0]		0 [0]		0 [0]	0.33 [0.74]	–100[a]
	0.43 [11]	1.2 [31]	0.01 [0.3]		0 [0]		0.20 [0.45]	0.06 [0.13]	71
	0.52 [13]	0.31 [8.0]	0.05 [1.2]		0.3[0.02]		0.08 [0.19]	0 [0]	100
PFy2	---	---	---	---	---	---	---	---	---
PFy3	---	---	---	---	---	---	---	---	---
PFy4	**0.99 [25]**	**1.6 [40]$_{10\text{-}25}$**	**0 [0]**	**Not measured**	**0 [0]**	**Not measured**	**0.08 [0.17]**	**0 [0]**	**100**

[a] Negative values in the percent difference column indicate that sediment yields were larger for the treated plots than for the control plots.

Study IV—Site 2

Fire: 1999 Mixing Fire

Location: Southern California

Site specific design: Mean slopes for the watersheds were 24 percent on the treated and 19 percent on the control. LEBs were installed at a rate of 53 ac^{-1} (131 ha^{-1}) and had an estimated 31 ton ac^{-1} (70 Mg ha^{-1}) total sediment storage capacity.

Table AB-5. Results from LEB effectiveness study following the 1999 Mixing Fire. Event rainfall amount, maximum 10-min intensity (I_{10}), runoff, peakflow, and sediment yields are reported for rainfall events that resulted in runoff and/or sediment. Data for large events (I_{10} ≥ 2-year return period) are in bold type and the return periods shown as a subscript. Mean percent difference in sediment yield between the control (C) and the treated (T) plots are reported for each event. n.d. means that no data was obtained. **---** indicates that no rainfall events resulted in measurable runoff or sediment in that year. + indicates that the event sediment yield was added to next event sediment yield. Time since fire codes: PFy1 = 1 year after the fire; PFy2 = 2 years after the fire; ...; and PFy6 = 6 years after the fire (Robichaud and others 2008b).

	-----------Rainfall----------		---------Runoff------------ (inch [mm])		----------Peak flow--------- (X 10^{-2} ft^{3}s^{-1}ac^{-1} [m^{3}s^{-1}km^{-2}])		----------------------Sediment yield---------------------- (ton ac^{-1} [Mg ha^{-1}])		
Time since fire	**Event amount** (inch [mm])	**I_{10}** (inch h^{-1} [mm h^{-1}])	**C**	**T**	**C**	**T**	**C**	**T**	**Difference** (%)
PFy1	0.67 [17]	0.35 [9]	0 [0]	0.02 [0.4]	0 [0]	4.3 [0.3]	0 [0]	0.009 [0.02]	–100[a]
	0.55 [14]	0.35 [9]	0 [0]	0.004 [0.1]	0 [0]	1.4 [0.1]	**+**	+	
	0.66 [17]	0.12 [3]	0 [0]	0.01 [0.2]	0 [0]	1.4 [0.1]	0 [0]	0 [0]	0
	0.59 [15]	0.43 [11]	0 [0]	0.004 [0.1]	0 [0]	2.9 [0.2]	0 [0]	0.054 [0.12]	–100[a]
	0.56 [14]	0.31 [8]	0.004 [0.1]	0.004 [0.1]	0 [0]	1.4 [0.1]	0 [0]	0.004 [0.01]	–100[a]
	0.87 [22]	0.43 [11]	n.d.	0.004 [0.1]	n.d.	0 [0]	0.004 [0.01]	0.025 [0.06]	–500[a]
	0.48 [12]	0.94 [24]	n.d.	n.d.	n.d.	n.d.	0 [0]	0.040 [0.09]	–100[a]
	0.56 [14]	0.71 [18]	n.d.	0.004 [0.1]	n.d.	1.4 [0.1]	0 [0]	0.025 [0.06]	–100[a]
	0.57 [14]	0.67 [17]	n.d.	0.004 [0.1]	n.d.	1.4 [0.1]	0.004 [0.01]	0.031 [0.07]	–600[a]
	0.73 [19]	0.35 [9]	n.d.	0.004 [0.1]	n.d.	1.4 [0.1]	0 [0]	0.004 [0.01]	–100[a]
PFy2	0.54 [14]	0.43 [11]	n.d.	0.004 [0.1]	n.d.	1.4 [0.1]	+	+	
	0.61 [16]	0.43 [11]	n.d.	0.004 [0.1]	n.d.	0 [0]	0.004 [0.01]	0.004 [0.01]	0
	0.48 [12]	0.24 [6]	n.d.	0.004 [0.1]	n.d.	0 [0]	+	+	
	0.50 [13]	0.31 [8]	0.02 [0.6]	0 [0]	0 [0]	0 [0]	0 [0]	0.005 [0.01]	–100[a]
	0.61 [16]	1.5 [38]	0.01 [0.3]	n.d.	1.4 [0.1]	n.d.	0.60 [1.3]	0.025 [0.06]	95
PFy3	0.87 [22]	0.83 [21]	0.01 [0.3]	n.d.	5.7 [0.4]	n.d.	0 [0]	0 [0]	0
PFy4	2.85 [72]	0.63 [16]	0.02 [0.6]	n.d.	1.4 [0.1]	n.d.	0 [0]	0 [0]	0
PFy5	1.43 [36]	0.43 [11]	0.004 [0.1]	n.d.	0 [0]	n.d.	0 [0]	0 [0]	0
	0.71 [18]	0.43 [11]	0 [0]	n.d.	0 [0]	n.d.	0 [0]	0 [0]	0
	2.62 [66]	**2.95 [75]**$_{5-10}$	**0.04 [1.0]**	**0.06 [1.6]**	**16 [1.1]**	**13 [0.9]**	**+**	**+**	
	4.01 [102]	0.83 [21]	0.02 [0.6]	0.02 [0.5]	1.4 [0.1]	0 [0]	0.20 [0.44]	0.022 [0.05]	89
	1.67 [43]	0.47 [12]	0.004 [0.1]	0.01 [0.3]	0 [0]	0 [0]	0 [0]	0 [0]	0
PFy6	0.28 [7.1]	0.31 [8]	0.004 [0.1]	0.004 [0.1]	0 [0]	0 [0]	0 [0]	0 [0]	0
	3.9 [100]	0.67 [17]	0.03 [0.7]	0.03 [0.8]	1.4 [0.1]	0 [0]	0.33 [0.73]	0 [0]	100

[a] Negative values in the percent difference column indicate that sediment yields were larger for the treated plots than for the control plots.

Study IV—Site 3

Fire: 2000 Valley Complex Fires

Location: Western Montana

Site specific design: Mean slopes for the watersheds were 39 percent on the treated and 46 percent on the control. LEBs were installed at a rate of 48 ac^{-1} (119 ha^{-1}) and had an estimated 33 ton ac^{-1} (73 Mg ha^{-1}) total sediment storage capacity.

Table AB-6. Results from LEB effectiveness study following the 2000 Valley Complex Fires. Event rainfall amount, maximum 10-min intensity (I_{10}), runoff, peakflow, and sediment yields are reported for rainfall events that resulted in runoff and/or sediment. Data for large events ($I_{10} \geq$ 2-year return period) are in bold type and the return periods shown as a subscript. Mean percent difference in sediment yield between the control (C) and the treated (T) plots are reported for each event. n.d. means that no data was obtained. **---** indicates that no rainfall events resulted in measurable runoff or sediment in that year. + indicates that the event sediment yield was added to next event sediment yield. Time since fire codes: PFy1 = 1 year after the fire; PFy2 = 2 years after the fire; ...; and PFy6 = 6 years after the fire (Robichaud and others 2008b).

	-----------Rainfall----------				**--------Peak flow-------**		**------------------------Sediment yield----------------------**		
Time since fire	**Event amount** (inch [mm])	**I_{10}** (inch h^{-1} [mm h^{-1}])	**-----------Runoff-------------** (inch [mm]) **C**	**T**	(X 10^{-2} ft^{3}s^{-1}ac^{-1} [m^{3}s^{-1}km^{-2}]) **C**	**T**	(ton ac^{-1} [Mg ha^{-1}]) **C**	**T**	**Difference** (%)
PFy1	0.29 [7]	1.2 [30]	0 [0]	0 [0]	0 [0]	0 [0]	0.36 [0.08]	0 [0]	100
	0.35 [9]	**1.7 [42]$_5$**	**0 [0]**	**0.004 [0.1]**	**2.9 [0.2]**	**1.4 [0.1]**	+	+	
	0.39 [10]	**1.3 [32]$_2$**	**0 [0]**	**0.004 [0.1]**	**1.4 [0.1]**	**1.4 [0.1]**	**0.25 [0.56]**	**0.067 [0.15]**	**73**
PFy2	0.53 [14]	0.51 [13]	0.06 [1.5]	0 [0]	0 [0]	0 [0]	0.05 [0.11]	0.0 [0.0]	100
	0.93 [24]	**2.3 [59]$_{25}$**	**0.01 [0.3]**	**0.004 [0.1]**	**2.9 [0.2]**	**2.9 [0.2]**	**0.17 [0.38]**	**0.15 [0.33]**	**11**
	0.50 [13]	**1.3 [32]$_2$**	**0.01 [0.2]**	**0.01 [0.2]**	**4.3 [0.3]**	**2.9 [0.2]**	**0.20 [0.44]**	**0.067 [0.15]**	**65**
PFy3	0.04 [1.1][a]	0.20 [5][a]	0.22 [5.7][a]	0 [0][a]	0 [0][a]	0 [0][a]	0.040 [0.09][a]	0 [0][a]	100
PFy4	---	---	---	---	---	---	---	---	---
PFy5	---	---	---	---	---	---	---	---	---
PFy6	0.74 [19][a]	0.47 [12][a]	0.10 [2.5][a]	0.004 [0.1][a]	0 [0][a]	0 [0][a]	0.054 [0.12][a]	0 [0][a]	100

[a] The runoff and sediment produced by this event were caused by snowmelt.

Study IV—Site 4

Fire: 2001 Fridley Fire

Location: Southern Montana

Site specific design: Mean slopes for the watersheds were 37 percent on the treated and 43 percent on the control. LEBs were installed at a rate of 28 ac^{-1} (70 ha^{-1}) and had an estimated 21 ton ac^{-1} (48 Mg ha^{-1}) total sediment storage capacity.

Table AB-7. Results from LEB effectiveness study following the 2001 Fridley Fire. Event rainfall amount, maximum 10-min intensity (I_{10}), runoff, peak flow, and sediment yields are reported for rainfall events that resulted in runoff and/or sediment. Data for large events ($I_{10} \geq$ 2-year return period) are in bold type and the return periods shown as a subscript. Mean percent difference in sediment yield between the control (C) and the treated (T) plots are reported for each event. n.d. means that no data was obtained. **---** indicates that no rainfall events resulted in measurable runoff or sediment in that year. + indicates that the event sediment yield was added to next event sediment yield. Time since fire codes: PFy1 = 1 year after the fire; PFy2 = 2 years after the fire; PFy3 = 3 years after the fire; and PFy4 = 4 years after the fire (Robichaud and others 2008b).

Time since fire	**---------Rainfall--------** **Event amount** (inch [mm])	**I_{10}** (inch h^{-1} [mm h^{-1}])	**--------Runoff---------** (inch [mm])		**--------Peak flow-------** (X 10^{-2} ft^{3}s^{-1}ac^{-1} [m^{3}s^{-1}km^{-2}])		**---------------------Sediment yield------------------** (ton ac^{-1} [Mg ha^{-1}])		**Difference** (%)
			C	**T**	**C**	**T**	**C**	**T**	
PFy1	0.73 [19]	0.91 [23]	0 [0]	0.004 [0.1]	0 [0]	1.4 [0.1]	0 [0]	0.054 [0.12]	–100[a]
	0.42 [11]	1.3 [34]	0 [0]	0.004 [0.1]	0 [0]	1.4 [0.1]	0 [0]	0.080 [0.18]	–100[a]
	0.57 [15]	**2.2 [55]**$_{5}$	**0.01 [0.3]**	**0.01 [0.2]**	**7.1 [0.5]**	**5.7 [0.4]**	**+**	**+**	
	0.56 [14]	**1.9 [47]**$_{2\text{-}5}$	**n.d.**	**n.d.**	**2.9 [0.2]**	**n.d.**	**+**	**+**	
	0.81 [21]	**1.8 [45]**$_{5}$	**n.d.**	**n.d.**	**0 [0]**	**n.d.**	**3.0 [6.7]**	**2.6 [5.8]**	**13**
PFy2	0.19 [4.8][b]	0.12 [3.0][b]	0.19 [4.7][b]	0.01 [0.3][b]	4.3 [0.3][b]	5.7 [0.4][b]	0.13 [0.29][b]	0.071 [0.16][b]	45
PFy3	---	---	---	---	---	---	---	---	---
PFy4	0.28 [7.1]	0.28 [7.1]	0.004 [0.1]	0 [0]	n.d.	0 [0]	0.004 [0.01]	0.004 [0.01]	0
	1.10 [27]	1.10 [27]	0.004 [0.1]	0 [0]	n.d.	0 [0]	0.004 [0.01]	0 [0]	100

[a] Negative values in the percent difference column indicate that sediment yields were larger for the treated plots than for the control plots.

[b] The runoff and sediment produced by this event were caused by snowmelt.

Study IV—Site 5

Fire: 2002 Hayman Fire

Location: Central Colorado

Site specific design: Mean slopes for the watersheds were 27 percent on the treated and 33 percent on the control. LEBs were installed at a rate of 45 ac^{-1} (110 ha^{-1}) and had an estimated 31 ton ac^{-1} (69 Mg ha^{-1}) total sediment storage capacity.

Table AB-8. Results from LEB effectiveness study following the 2002 Hayman Fire. Event rainfall amount, maximum 10-min intensity (I_{10}), runoff, peak flow, and sediment yields are reported for rainfall events that resulted in runoff and/or sediment. Mean percent difference in sediment yield between the control (C) and the treated (T) plots are reported for each event. n.d. means that no data was obtained. **---** indicates that no rainfall events resulted in measurable runoff or sediment in that year. + indicates that the event sediment yield was added to next event sediment yield. Time since fire codes: FY = year of the fire; PFy1 = 1 year after the fire; and PFy2 = 2 years after the fire (Robichaud and others 2008b).

	----------Rainfall---------		--------Runoff---------		--------Peak flow-------		--------------------Sediment yield----------------		
Time since fire	**Event amount** (inch [mm])	**I_{10}** (inch h^{-1} [mm h^{-1}])	(inch [mm]) **C**	**T**	(X 10^{-2} $ft^3s^{-1}ac^{-1}$ [$m^3s^{-1}km^{-2}$]) **C**	**T**	(ton ac^{-1} [Mg ha^{-1}]) **C**	**T**	**Difference** (%)
FY	1.2 [31]	0.35 [9.0]	0.08 [2.1]	0 [0]	34 [2.4]	0 [0]	0.33 [0.74]	0.031 [0.07]	91
PFy1	0.18 [4.6]	0.51 [13]	0 [0]	0 [0]	0 [0]	0 [0]	0.004 [0.01]	0 [0]	100
	0.17 [4.3]	0.91 [23]	0 [0]	0 [0]	0 [0]	0 [0]	0 [0]	0.13 [0.03]	–100[a]
	0.71 [18]	2.0 [52]	0.34 [8.6]	0.21 [5.3]	71 [5.0]	71 [5.0]	8.8 [20]	4.2 [9.4]	52
	1.1 [29]	0.91 [23]	0.21 [5.4]	0.07 [1.7]	53 [3.7]	37 [2.6]	2.0 [4.6]	0.89 [2.0]	38
PFy2	0.16[4.1]	0.59 [15]	0 [0]	0 [0]	0 [0]	0 [0]	+	+	
	0.46 [12]	0.35[9.0]	0 [0]	0 [0]	0 [0]	0 [0]	+	+	
	0.41 [10]	0.67 [17]	0.03 [0.8]	0.02 [0.5]	37 [2.6]	31 [2.2]	1.4 [3.1]	0.35 [0.78]	74
	0.35 [9.0]	0.39 [10]	0 [0]	0 [0]	0 [0]	0 [0]	0.009 [0.02]	0 [0]	100
	0.27[6.9]	0.63 [16]	0.02 [0.4]	0.004 [0.1]	36 [2.5]	2.9 [0.2]	+	+	
	0.31 [8.0]	0.51 [13]	0.004 [0.1]	0 [0]	5.7 [0.4]	0 [0]	0.59 [1.3]	0.02 [0.04]	3.3
	0.46 [12]	1.1 [27]	0.03 [0.8]	0.03 [0.8]	34 [2.4]	27 [1.9]	1.0 [2.3]	0.20 [0.45]	78
	0.35 [9.0]	0.83 [21]	0.01 [0.2]	0.004 [0.1]	5.7 [0.4]	1.4 [0.1]	0.18 [0.41]	0.04 [0.09]	78
	0.46 [12]]	0.47 [12]	0 [0]	0 [0]	0 [0]	0 [0]	0.13 [0.03]	0 [0]	100

[a] Negative values in the percent difference column indicate that sediment yields were larger for the treated plots than for the control plots.

Study IV—Site 6

Fire: 2002 Cannon Fire

Location: East-central California

Site specific design: Mean slopes for the watersheds were 44 percent on the treated and 38 percent on the control. LEBs were installed at a rate of 36 ac^{-1} (90 ha^{-1}) and had an estimated 7.1 ton ac^{-1} (16 Mg ha^{-1}) total sediment storage capacity.

Table AB-9. Results from LEB effectiveness study following the 2002 Cannon Fire. Event rainfall amount, maximum 10-min intensity (I_{10}), runoff, peak flow, and sediment yields are reported for rainfall events that resulted in runoff and/or sediment. Data for large events (I_{10} ≥ 2-year return period) are in bold type and the return periods shown as a subscript. Mean percent difference in sediment yield between the control (C) and the treated (T) plots are reported for each event. **---** indicates that no rainfall events resulted in measurable runoff or sediment in that year. Time since fire codes: FY = year of the fire; PFy1 = 1 year after the fire; PFy2 = 2 years after the fire; PFy3 = 3 years after the fire; and PFy4 = 4 years after the fire (Robichaud and others 2008b).

	---------Rainfall--------		--------Runoff---------		--------Peak flow------- (X 10^{-2} ft^{3}s^{-1}ac^{-1} [m^{3}s^{-1}km^{-2}])		------------------Sediment yield---------------- (ton ac^{-1} [Mg ha^{-1}])		
Time since fire	**Event amount** (inch [mm])	**I_{10}** (inch h^{-1} [mm h^{-1}])	(inch [mm]) **C**	**T**	**C**	**T**	**C**	**T**	**Difference** (%)
FY	3.9 [100]	1.1 [29]	0.004 [0.1]	0.004 [0.1]	0 [0]	0 [0]	0.058 [0.13]	0.054 [0.12]	7.7
PFy1	0.77 [20]	0.39 [10]	0 [0]	0 [0]	0 [0]	0 [0]	0.004 [0.01]	0 [0]	100
PFy2	---	---	---	---	---	---	---	---	---
PFy3	---	---	---	---	---	---	---	---	---
PFy4	**1.2 [30]**	**5.3 [134]**$_{100}$	**0.02 [0.6]**	**0.04 [0.9]**	**14 [1.0]**	**23 [1.6]**	**4.3 [9.7]**	**6.8 [15]**	**–158**[a]

[a] Negative values in the percent difference column indicate that sediment yields were larger for the treated plots than for the control plots.

Generalized results:

High intensity rainfall (maximum 10-min rainfall intensity [I_{10}] ≥ two-year return period), produced most of the measured runoff and sediment yields, except in the southern California site where long-duration rain events produced most of the runoff and erosion. Runoff, peak flows, and sediment yields showed a significant treatment effect for smaller rain events (I_{10} < two-year return period) where all three response variables were lower in the treated watersheds than in the control watersheds. However, and perhaps more importantly, there were no treatment effects for rain events with larger return periods (Robichaud and others 2008b).

Appendix C. Mulch Treatment Effectiveness Studies (2000 to the present)

Study I. Effectiveness of straw mulch + seeding treatment to reduce sediment yields following the 2000 Cerro Grande Fire in central New Mexico (Dean 2001)

Study design: Six repetitions of three treatments (straw mulch + seeding; straw mulch + seeding + contour-felled LEBs; and untreated control) were installed on 23 to 24 percent slopes that had been burned at high severity. These sites were monitored for two years.

Plot size(s): The hillslope plots were 200 to 350 ft^2 (20 to 30 m^2) with silt fence sediment traps installed at the base.

Factors that impacted the study design and/or results:

Results comparing the straw mulch + seeding to the untreated controls are reported here; results comparing straw mulch + seeding + contour-felled LEBs treatment to the untreated controls are reported in Appendix E-Study II (combination studies). The differences in sediment yield between the straw mulch + seeding treatment and the straw mulch + seeding + LEBs treatment were not significant.

Table AC-1. Results from straw mulch plus seeding hillslope treatment following the 2000 Cerro Grande Fire. Annual rainfall amount, maximum 10-min intensity (I_{10}), and mean annual sediment yields are reported for the year of the fire (FY) and the post-fire year one (PFy1). Difference (%) in mean sediment yields between the control and treated plots are reported for both years and were significant at the p<0.05 level (Dean 2001).

	---------Rainfall----------		------------------------Sediment yields------------------------		
Time since fire	**Amount** (inch [mm])	**I_{10}** (inch h^{-1} [mm h^{-1}])	**Control** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Straw mulch + seeding** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Difference** (%)
FY	2.1 [52]	0.94 [24]	3.7 [8.3]	1.1 [2.5]	70
PFy1	6.1 [156]	3.9 [99]	5.6 [12.6]	0.30 [0.67]	95

Generalized results:

Agricultural straw mulch with seed significantly reduced mean annual sediment yields by 70 percent in the first post-fire year and 95 percent in the second post-fire year; however, precipitation was below normal during the two study years (Dean 2001).

Study II. Effectiveness of straw mulch in reducing erosion following the 2000 Bobcat Fire in central Colorado (Wagenbrenner and others 2006)

Study design: Dry straw mulch treatment was hand-placed on hillslopes of stony or gravelly sandy loam with 23 to 54 percent slopes burned at high severity. Silt fence sediment traps were established at the base of paired swales to compare the sediment yields from treated and untreated areas.

Plot size(s): Paired swales ranged from 0.25 to 1.25 ac (0.1 to 0.5 ha), and each swale included a zero-order channel formed by convergent hillslopes.

Factors that impacted study design and/or results: In the year of the fire (FY), a large storm compromised the placement and decomposition of the straw mulch that had been applied. These straw mulch plots remained in the study; however, new straw mulch plots were established with a paired control. The sediment yields from the plots installed before the storm are labeled "old," and the sediment yields from the plots installed after the storm are labeled "new" (table AC-2). Also, in post-fire year three (PFy3), the two general study areas had different rainfall. Both rainfall amounts are reported (table AC-2).

Table AC-2. Results from straw mulch study following the 2000 Bobcat Fire. Rainfall amount, maximum 30-min intensity (I_{30}), and mean annual sediment yields are reported for each of the four years of the study. Mean percent difference in sediment yield between the control and the treated plots are reported for each year. Time since fire codes: FY = year of the fire; PFy1 = 1 year after the fire; PFy2 = 2 years after the fire; and PFy3 = 3 years after the fire (Wagenbrenner and others 2006).

	-----------Rainfall-----------		--------------------Sediment yields--------------------		
Time since fire	**Amount** (inch [mm])	**I_{30}** (inch h^{-1} [mm h^{-1}])	**Control** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Straw mulch** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Difference** (%)
FY	2.4 [60]	1.9 [48]	2.8 [6.2]	old[a]-1.4 [3.2] new[b]-NA	old-48.4 new-NA
PFy1	3.0 [75]	1.1 [29]	4.2 [9.5]	old-0.2 [0.5] new-0.009 [0.02]	old-95.2 new-99.8
PFy2	1.4 [36]	0.67 [17]	0.54 [1.2]	old-0.009 [0.02] new-0.003[0.006]	old-98.3 new-99.5
PFy3	0.67 [17] 4.3 [110]	0.71 [18] 1.4 [35]	0.3 [0.7]	old-0.00 [0.001] new-0.00 [0.000]	old-99.9 new-99.9

[a] old = sediment yields from plots installed before the large storm that occurred the same year as the fire.
[b] new = sediment yields from plots installed after the large storm that occurred the same year as the fire.

Generalized results:

Although straw mulch immediately increased the mean ground cover to nearly 80 percent, it did not reduce sediment yields in the year of the fire when a large amount of sediment was produced from a single large (5- to 10-year return interval) storm. In post-fire years one, two, and three, there was over 95 percent reduction in mean sediment yield on the straw mulch plots as compared to the untreated control plots (Wagenbrenner and others 2006).

Study III. Mulch treatment effectiveness in reducing erosion following the 2002 Hayman Fire in central Colorado (Rough 2007)

Study design: Four repetitions of three mulch treatments—dry straw mulch (StrM), ground-based hydromulch (GHM), and aerial hydromulch (AHM)—were applied to swales that were paired with an untreated control on the gravelly sandy loam hillslopes that had burned at high severity. Silt fence sediment traps to hold eroded sediment from the swales were established at the base of each of the 24 swales.

Plot size(s): Paired swales ranged from 0.25 to 1.25 ac (0.1 to 0.5 ha), and each swale included a zero-order channel formed by convergent hillslopes.

Factors that impacted study design and/or results: All mulch treatments were placed on burned areas that had been aerially seeded. Although the treatments were applied the same year as the fire, sediment-producing rain events had occurred prior to site installation. No data from 2002, the year of the fire, are included in this study.

Table AC-3. Results from straw mulch and hydromulch study following the 2002 Hayman Fire. Rainfall amount, maximum 30-min intensity (I_{30}), and mean annual sediment yields are reported for post-fire years one (PFy1) and two (PFy2). Mean percent difference in sediment yield between the control and treated plots are reported for both years. Treatment codes: StrM = dry straw mulch; GHM = hydromulch-ground application (sprayed on); and AHM = hydromulch-aerial application (applied with aircraft) (Rough 2007).

	----------Rainfall----------			------------------Sediment yield------------------		
Time since fire	**Amount** (inch [mm])	**I_{30}** (inch h^{-1} [mm h^{-1}])	**Treatment**	**Control** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Treated** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Difference** (%)
PFy1	6.0 [153]	1.6 [40.4]	StrM	5.9 [13.2]	0.33 [0.74]	94
			GHM	4.5 [10.2]	3.8 [8.5]	17
			AHM	3.2 [7.2]	0.17 [0.39]	95
PFy2	11.9[303]	0.87 [23.2]	StrM	4.9 [11.0]	1.1 [2.5]	90
			GHM	3.8 [8.5]	3.1 [6.9]	19
			AHM	2.0 [4.5]	1.0 [2.3]	50

Generalized results:

The straw mulch reduced sediment yields by 94 percent in post-fire year one and 90 percent in post-fire year two as compared to the untreated control swale. In comparison, the aerial hydromulch reduced the sediment yield by 95 percent in post-fire year one but only 50 percent in post-fire year two as compared to the control. The hydromulch that was applied from the ground did not significantly reduce sediment yields as compared to the control plots in either year (Rough 2007).

Study IV. Effectiveness of dry barley straw mulch and seeding treatments in reducing erosion following a 1991 wildfire in northeastern Spain (Badia and Marti 2000)

Study design: Four repetitions of three treatments (12 plots)—combination of seed plus dry barley straw mulch (Mulch + Sd), seed only, and untreated control—were established on two soils (calcareous and gypsiferous) on steep hillslopes (40 to 49 percent) burned at moderate severity.

Plot size(s): PVC troughs were embedded at the base of each bounded, rectangular hillslope plot (86 ft^2 [8 m^2]) to measure sediment yields.

Factors that impacted study design and/or results:

- Rainfall was not directly reported in this article but was estimated from a bar graph showing monthly totals.
- This study included straw mulch combined with seed and seed only treatments. Although seeding as a hillslope stabilization treatment is not covered in this report, table AC-4 does include the reported sediment yields for the seed only treatment.

Table AC-4. Results from barley straw mulch plus seeding study following a 1991 wildfire in Spain. Annual rainfall amounts have been estimated from a bar graph of monthly amounts. Maximum intensity was not reported. Mean annual sediment yields are reported for post-fire years one (PFy1) and two (PFy2) by soil type (gypsiferous; calcareous) and treatment (Mulch + Sd = straw mulch plus seed; and Seed only). Difference (%) in mean sediment yields between the control and treated plots are reported for both years and were significant at the p<0.05 level; differences (%) between treatments were significant only for post-fire year one on gypsiferous soils (Badia and Marti 2000).

	-----------Rainfall----------		-------------------------------Sediment yields--------------------------		
Time since fire	**Amount** (inch [mm])	**Intensity** (inch h^{-1} [mm h^{-1}])	**Control** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Treated** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Difference** (%)
PFy1	~12 [295]	Not reported	Gypsiferous soil	Mulch + Sd 0.19 [0.43]	83
			1.14 [2.56]	Seed only 0.36 [0.80]	69
			Calcareous soil	Mulch + Sd 0.18 [0.41]	59
			0.45 [1.01]	Seed only 0.28 [0.63]	38
PFy2	~10 [247]	Not reported	Gypsiferous soil	Mulch + Sd 0.63 [1.42]	59
			1.6 [3.49]	Seed only 0.56 [1.25]	64
			Calcareous soil	Mulch + Sd 0.32 [0.71]	64
			0.87 [1.96]	Seed only 0.44 [0.98]	50

Generalized results:

Straw mulch with seeding and seeding alone significantly reduced sediment yields as compared to the untreated controls on both gypsiferous and calcareous soils in post-fire years one and two. Except for post-fire year one on gypsiferous soil, there were no significant differences between mean sediment yields for seeding with mulch and seeding alone within each soil type and post-fire year.

Study V. Effectiveness of hydromulch treatment in reducing erosion following the 2003 Cedar Fire in southern California (Hubbert, unpublished report 2007)

Study design: A total of 54 silt fence plots were installed to monitor treatment effectiveness of hydromulch applied over 100 percent of the treatment area and hydromulch applied in 100 ft (30 m) wide contour strips over 50 percent of the hillslope. The treatments were applied on two different parent materials—granite bedrock and gabbro bedrock. The distribution of the silt fence plots was: 13 gabbro control; 11 gabbro strip hydromulch; 10 granitic control; 10 granitic strip hydromulch; and 10 granitic full hydromulch. (Note: no gabbro full hydromulch plots were included.)

Plot size(s): Planar hillslope plots approximately 100 ft (30 m) long and 16 ft (5 m) wide.

Factors that impacted study design and/or results:

- The hydromulch was applied in December 2003, but the silt fence plots were not installed until late January 2004. Thus, the plots were not monitoring sediment yields for the first winter rain events.
- Rock cover differed by parent material—23 percent for the gabbro and 3 percent for the granitic.
- The actual hydromulch coverage was less than desired. The actual level of soil cover observed for the full hydromulch treatment was 56 percent and 27 percent for the strip hydromulch treatment.
- Sediment yields were not directly reported but were estimated from bar graphs.

Table AC-5. Results from an aerial hydromulch study following the 2003 Cedar Fire. Rainfall amount and sediment yields are reported by treatment and parent material for three series of rainfall events in post-fire year one. Treatment codes: Strip HM-gabbro or Strip HM-granitic = hydromulch applied in 100 ft [30 m] wide contour strips over 50 percent of a burned area with gabbro or granitic parent material; Full HM-granitic = hydromulch applied over 100 percent of a burned area with granitic parent material; and Control-gabbro or Control-granitic = untreated control area with gabbro or granitic parent material. The sediment yields are estimated from bar graphs in the monitoring report. Mean percent difference in sediment yield between the control and treated plots are reported for all three periods. (Hubbert, unpublished report 2007).

Time since fire (mo)	Rainfall (inch [mm]) (period)	Treatment	Sediment yields		
			Control (ton ac^{-1} [Mg ha^{-1}])	Treated (ton ac^{-1} [Mg ha^{-1}])	Difference (%)
4	5.7 [145] 2 Feb-2 Mar	Strip HM-gabbro		0.6 [1.3]	63
		Control-gabbro	1.6 [3.6]		
		Full HM-granitic		0.4 [0.9]	87
		Strip HM-granitic		0.8 [1.8]	74
		Control-granitic	3.1 [7.0]		
5	0.85 [21.6] 3 Mar-13 Apr	Strip HM-gabbro		1.6 [3.6]	52
		Control-gabbro	3.3 [7.4]		
		Full HM-granitic		0.5 [1.1]	62
		Strip HM-granitic		1.0 [2.2]	23
		Control-granitic	1.3 [2.9]		
6	0.41 [10.4] 14 Apr-16 May	Strip HM-gabbro		0.1 [0.2]	50
		Control-gabbro	0.2 [0.4]		
		Full HM-granitic		0.01 [0.02]	90
		Strip HM-granitic		0.05 [0.1]	50
		Control-granitic	0.1 [0.2]		

Generalized results:

In post-fire year one, the strip hydromulch treatment reduced sediment yields by more than 50 percent, and the full hydromulch treatment reduced sediment yields by about 75 percent (Hubbert, unpublished report 2007).

Study VI. Effectiveness of mulch treatment in sediment reduction following the 2002 Indian Fire in central Arizona (Riechers and others 2008)

Study design: A single repetition of four treatments (three different mulches and one control) were applied on matched and adjacent swales that contained zero-order channels with slopes of 30 to 40 percent at the top and less than 10 percent at the toe. The treatments were 1) wood chips made on-site from fire-killed trees and spread by the wood chipper for 100 percent cover; 2) manufactured pellets consisting of compressed, pulverized rice straw and a polyacrylamide (PAM) soil flocculant/tackifier, which was hand-dispersed at 50 percent coverage, resulting in 80 to 90 percent coverage after becoming wet and expanding; 3) rice straw hand-applied at 2 ton ac^{-1} (4.5 Mg ha^{-1}); and 4) untreated control. These treatments were compared during three summer rain events.

Plot size(s): Double silt fence sediment traps were installed at the channel outlets of the large matched swales (0.8 to 1.2 ac [0.3 to 0.5 ha]); each swale included a zero-order channel formed by convergent hillslopes.

Factors that impacted study design and/or results:

- Not all silt fences were installed on catchments prior to the first post-fire rain events: the control and wood chip swales were installed prior to the July event; the pellet swale was added prior to the August event; and all four treatments were installed prior to the September event.
- The wood chip mulch floated off the slope in heavy overland flows, which decreased the cover by 58 percent three months after application. The pellets degraded rapidly, causing the cover to decrease by 27 percent in three months.

Table AC-6. Results from a study of three mulches following the 2002 Indian Fire. Rainfall amount, maximum 10-min intensity (I_{10}), and mean sediment yields are reported for three post-fire erosion-causing summer rain events that occurred in the year of the fire (FY). Treatments were wood chips, compressed pellets (PAM plus pulverized rice straw), and rice straw. Mean percent difference in sediment yield between the control and treated plots are reported for all three events by treatment. "na" indicates that no data were available because plots had not yet been established (Riechers and others 2008).

	---------Rainfall---------		------------------------------Sediment yields-------------------------------			
Post-fire period of 2002	Amount (inch [mm])	I_{10} (inch h^{-1} [mm h^{-1}])	Control (ton ac^{-1} per^{-1} [Mg ha^{-1} per^{-1}])	Treated (ton ac^{-1} per^{-1} [Mg ha^{-1} per^{-1}])		Difference (%)
13 Jul to 30 Jul	0.36 [9.2]	0.9 [22.9]	2.8 [6.4]	Wood chips	0.18 [0.42]	93
				Pellets	na	na
				Straw	na	na
31 Jul to 14 Aug	0.36 [9.1]	1.5 [38.1]	4.8 [10.8]	Wood chips	0 [0]	99.9
				Pellets	0.92 [2.2]	80
				Straw	na	na
15 Aug to 14 Sep	2.4 [61]	4.6 [117]	21.6 [48.4]	Wood chips	> 6.9 [> 15.5][a]	< 68
				Pellets	12.6 [28.2]	42
				Straw	4.1 [9.1]	81

[a] Silt fences over-topped, resulting in unmeasured sediment; the amount reported is less than the actual total sediment yield.

Generalized results:

The wood chip mulch reduced the sediment yield by about 95 percent compared to the control for the first two smaller rain events; the effectiveness decreased for the third, high intensity (I_{10} = 4.6 inch h^{-1} [117 mm h^{-1}]) rain event when the wood chip mulch reduced sediment yields by less than 68 percent. After the third rain event, wood chips were observed at the bottom of the slope where they had been deposited after being washed downslope by overland flows. The compressed pellets were in place for the second, smaller rain event and the third, high intensity rain event where they reduced sediment yield by 80 percent and 42 percent, respectively, as compared to the control. The straw mulch plots were in place for the third, high intensity rain event only and reduced sediment yield by 81 percent compared to the control (Riechers and others 2008).

Study VII. Effectiveness of straw mulch treatment in sediment reduction following the 2002 Fox Creek Fire in northwest Montana (Groen and Woods 2008)

Study design: This field-based rainfall simulation study was done on 9 to 17 percent hillslopes of sandy loam soil that burned at high severity. Three treatments (10 replicates) were tested: 1) seed only, applied at 8 lb ac^{-1} (9 kg ha^{-1}); 2) wheat straw mulch, applied at 1 ton ac^{-1} (2.24 Mg ha^{-1}); and 3) untreated control.

Plot size(s): Each plot was a small frame of 5.3 ft^2 (0.5 m^2).

Factors that impacted study design and/or results:

- Some plot frames were damaged between years of the study so that in post-fire year two (PFy2), the rain simulations were repeated on two seeded plots, three mulched plots, and four control plots only.
- The short flow path within the framed plots used in this study precluded rill erosion processes, and, as a result, measured sediment yields predominantly are from interrill (sheet wash) erosion only.

Table AC-7. Results from field-based, small plot, straw mulch study using rainfall simulation following the 2002 Fox Creek Fire. The mean value for the simulated rainfall amount and intensity are the same because the intensity was held constant over each hour-long simulation. Mean sediment yields and mean percent difference between control and treated plots are reported for each year. Treatments were wheat straw mulch (Mulch); seeding (Seed); and untreated (Control). Time since fire codes: PFy1 = 1 year after the fire and PFy2 = 2 years after the fire (Groen and Woods 2008).

				Sediment yield		
Time since fire	**n** (#)	**Treatment**	**Rainfall amount** (inch [mm]) **Intensity** (inch h^{-1} [mm h^{-1}])	**Control** (ton ac^{-1} [Mg ha^{-1}])	**Treated** (ton ac^{-1} [Mg ha^{-1}])	**Difference** (%)
PFy1	10	Mulch	3.3 [84]		0.5 [1.0]	86
	10	Seed	3.2 [82]		2.6 [5.8]	19
	10	Control	3.3 [83]	3.2 [7.2]		
PFy2	3	Mulch	2.5 [64]		1.0 [2.2]	48
	2	Seed	2.7 [68]		0.8 [1.8]	57
	4	Control	2.6 [66]	1.9 [4.2]		

Generalized results:

In post-fire year one, the 10 wheat straw mulched plots had 86 percent less sediment compared to the 10 control plots. The small number of usable plots available in post-fire year two did not provide enough data for drawing conclusions (Groen and Woods 2008).

Study VIII. Laboratory studies of mulch effectiveness in reducing runoff and/or erosion on forest soils with post-fire treatment applications

Lab Study 1. Effectiveness of needle cast in reducing post-fire runoff and erosion (Pannkuk and Robichaud 2003)

Study design: Following wildfires, burned ponderosa pine (PP) and Douglas-fir (DF) needles that had fallen to the ground (needle cast) were collected, and burned surface soils (0 to 4 inch [0 to 10 cm])—volcanic silty loam from central Washington and granitic sandy loam from Idaho—were excavated for use in laboratory studies. The needles were placed over the soils in a rectangular plot to create four ground cover amounts (0, 15, 40, and 70 percent). Both rainfall and rainfall with additional surface flow added at the top of the plot were included in the simulation. One rainfall intensity (1.3 inch h^{-1} [34 mm h^{-1}]) was combined with one of four concentrated flow rates (0, 1.5, 2.4, and 3.9 L min^{-1}) over a 25-min simulation: 0 to 10 min = rain only; 10 to 15 min = 1.5 L min^{-1}; 15 to 20 min = 2.4 L min^{-1}; and 20 to 25 min = 3.9 L min^{-1}. Six replications of the rainfall-inflow simulation were run with each combination of soil, needles, and cover amounts.

Plot size(s): The plot was a 13- by 3.3-ft (4- by 1-m) rectangular tray placed at a 40 percent slope under the rainfall simulators. Two inflow regulators allowed two trials to be run simultaneously by dividing the plot in half.

Factors that impacted study design and/or results: During some runs on the granitic soil, water leaked out from under the soil (soil depth = 8 inch [0.2 m]) during the final five-minute inflow period. Therefore, data from these portions of the runs were not used in the results.

Table AC-8. Results from a laboratory study of post-fire needle cast mulch treatment effectiveness. Mean runoff and sediment yields are reported for granitic and volcanic soil for the by needle type (PP = ponderosa pine; DF = Douglas-fir), cover amounts (%), and inflow rates (L min^{-1}). The symbol "nd" signifies no data. Different letters within a column group indicate a significant difference at $\alpha = 0.05$ (Pannkuk and Robichaud 2003).

		----------Runoff--------- (L min^{-1})		---------Sediment yield------- (g min^{-1})	
	Soil type→	**Granitic**	**Volcanic**	**Granitic**	**Volcanic**
Needle type	**PP**	1.83a	2.32a	440a	506a
	DF	1.75b	2.17b	441a	392b
Mulch cover (%)	**0**	1.83a	2.32a	623a	509a
	15	1.85a	2.21ab	565b	514a
	40	1.82a	2.28ab	425c	464a
	70	1.66b	2.1b	146d	309b
Inflow rate (L min^{-1})	**0**	0.56c	0.28d	62c	18d
	1.5	2.05b	1.93c	551b	398c
	2.4	2.75a	2.75a	707a	512b
	3.9	nd	4.09a	nd	868a

Generalized results:

The short, flat Douglas-fir needles laid directly on the soil for their full lengths and reduced interrill erosion by 80 percent compared to a 60 percent reduction with ponderosa pine needles. The long, bundled, and curved ponderosa pine needles tended to form mini-debris dams on the soil surface and reduced rill erosion by 40 percent compared to a 20 percent reduction with Douglas-fir needles (Pannkuk and Robichaud 2003).

Lab Study 2. Effectiveness of manufactured wood strands on reducing runoff and erosion on forest soils (Yanosek and others 2006)

Study design: Three lengths of wood strands (6.3, 3.1, and 1.6 inch [160, 80, and 40 mm]) were manufactured from wood waste veneer and combined in two blends (160-40 blend and 160-80 blend) to be tested for effectiveness in reducing erosion. The 160-40 blend contained an equal weight (1:4 piece ratio) of long and short strands. The 160-80 blend contained an equal weight (1:2 piece ratio) of long and medium strands. The strands were tested using rainfall and inflow simulations on two soils (coarse-grained gravelly sand and a fine-grained sandy loam), two slopes (15 and 30 percent), and at four coverage amounts (0, 30, 50, and 70 percent). Four replications of each combination were run.

Rainfall of 2.0 inch h^{-1} [50 mm h^{-1}] was applied throughout each run (25 minutes total). The simulation periods were: R = rain only; R+1 = rain plus 1 L min^{-1} concentrated flow rate; and R+4 = rain plus 4 L min^{-1} concentrated flow rate. The rainfall-inflow simulation periods were applied over the 25 minutes in the following intervals: R = 0 to 15 min; R+1 = 15 to 20 min; and R+4 = 20 to 25 min.

Plot size(s): The rectangular, steel plot was 13 ft long by 4.1 ft wide by 0.7 ft deep (4.0 m long by 1.2 m wide by 0.2 m deep).

Factors that impacted study design and/or results: Percent decreases in runoff and sediment yield were not directly reported in this article but were estimated from line graphs (Yanosek and others 2006: figs. 5 and 6).

Table AC-9. Results from a laboratory rainfall and inflow simulation study on the effectiveness of manufactured wood strands for mitigating runoff and erosion. Reduction in runoff (%) and sediment yield (%) as compared to bare plots at 30 percent slope are reported by soil type (sandy loam and gravelly sand), percent cover (%), and simulation period (R = rain only [0 to 15 min]; R+1 = rain plus 1 L min^{-1} inflow [15 to 20 min]; and R+4 = rain plus 4 L min^{-1} inflow [20 to 25 min]). The percent reductions are estimated from line graphs as reported in Yanosek and others (2006: figs. 5 and 6).

Mulch cover (%)	**Runoff reduction compared to bare plots** (%)					
	Sandy loam soil			**Gravelly sand soil**		
	R	**R+1**	**R+4**	**R**	**R+1**	**R+4**
0	0	0	0	0	0	0
30	86	56	36	80	50	25
50	99	83	59	95	75	40
70	<100	95	72	99	83	48
Mulch cover (%)	**Sediment reduction compared to bare plots** (%)					
	Sandy loam soil			**Gravelly sand soil**		
	R	**R+1**	**R+4**	**R**	**R+1**	**R+4**
0	0	0	0	0	0	0
30	93	79	73	91	81	75
50	<100	92	86	99	94	91
70	<100	99	90	<100	95	94

Generalized results:

Compared to the untreated controls, wood strand materials reduced sediment yield by at least 70 percent for all treatment combinations. In addition, when compared to sediment yield reductions due to agricultural straw (as reported by Burroughs and King 1989), wood strand materials were equally effective on coarse-grained soils and superior to straw on fine-grained soils (Yanosek and others 2006).

Lab Study 3. Efficacy of using wood shreds for reducing runoff and erosion on forest soils (Foltz and Copeland 2009)

Study design: Laboratory rainfall plus inflow simulations were run on two soils to test the effectiveness of wood shreds produced by a prototype wood shredding device. The tested wood shred mulch, which in actual use would be produced on-site from locally available materials, was produced from lodgepole pine logging slash and had a range of lengths from < 1 inch (25 mm) to > 8 inch (200 mm) with similarly variable widths and thicknesses. The strands were tested using rainfall and inflow simulations on two soils (coarse-grained gravelly sand and a fine-grained sandy loam) and at four coverage amounts (0, 30, 50, and 70 percent). Three replications of each combination were run.

Rainfall of 2.0 inch h^{-1} (50 mm h^{-1}) was applied throughout the entire run (25 minutes total). The simulation periods were: R = rain only; R+1 = rain plus 1 L min^{-1} concentrated flow rate; and R+4 = rain plus 4 L min^{-1} concentrated flow rate. The rainfall-inflow simulation periods were applied over the 25 minutes in the following intervals: R = 0 to 15 min; R+1 = 15 to 20 min; and R+4 = 20 to 25 min.

Plot size(s): The rectangular, steel plot was 13 ft long by 4.1 ft wide by 0.7 ft deep (4.0 m long by 1.2 m wide by 0.2 m deep) and set at a 30 percent slope.

Table AC-10. Results from a laboratory rainfall and inflow simulation study on the efficacy of wood shreds for mitigating erosion. Mean runoff depths (mm) and sediment yields (g) are reported by soil type (sandy loam and gravelly sand), percent cover (%), and simulation period (R = rain only [0 to 15 min]; R+1 = rain plus 1 L min^{-1} inflow [15 to 20 min]; and R+4 = rain plus 4 L min^{-1} inflow [20 to 25 min]). nr = no runoff (Foltz and Copeland 2009).

Mulch cover (%)			**Runoff depth** (mm)			
	Sandy loam soil			**Gravelly sand soil**		
	R	**R+1**	**R+4**	**R**	**R+1**	**R+4**
0	3.1	6.3	11	<0.01	1.3	4.2
30	0.2	1.8	5.7	<0.01	0.9	3.7
50	nr	0.4	3.4	nr	0.4	2.7
70	nr	<0.01	1.3	nr	0.2	2.6
Mulch cover (%)			**Sediment yield** (g)			
	Sandy loam soil			**Gravelly sand soil**		
	R	**R+1**	**R+4**	**R**	**R+1**	**R+4**
0	780	1310	2330	4	790	3670
30	20	170	480	0.1	160	1470
50	nr	20	190	nr	50	460
70	nr	<0.01	50	nr	20	210

Generalized results:

Sediment yield reductions ranged from 60 to nearly 100 percent, depending on the soil type (gravelly sand had greater sediment yields as compared to sandy loam), amount of concentrated flow, and mulch cover amount (Foltz and Copeland 2009).

Lab Study 4. Effectiveness of wood shreds for reducing runoff and erosion on burned forest soils (Foltz and Wagenbrenner 2010)

Study design: Laboratory rainfall plus inflow simulations were run on a burned, sandy loam forest soil to determine the most effective blend of wood shred sizes for use in post-fire hillslope treatments to reduce runoff and sediment yield. The soil used for the simulations was collected from an area of high soil burn severity six months after the 2006 Tripod Fire in north-central Washington. The soil was obtained from the top 8 inches (20 cm) and included an ash layer approximately 1.6 inch (4 cm) thick. The wood shreds, produced by a horizontal grinder from lodgepole pine logging slash, were combined into three size blends containing different amounts of "fines" (shreds less than 1 inch [2.5 cm] in length). These blends were designated: 1) AS IS—the standard blend produced by the grinder; 2) MIX—50 percent fewer fines than the AS IS blend; and 3) REDUCE—all fines removed. The wood strand blends were tested at two coverage amounts (50 and 70 percent). Six replications of each combination were run.

Rainfall of 2.0 inch h^{-1} [50 mm h^{-1}] was applied throughout the entire run (25 minutes total). The simulation periods were: R = rain only; R+1 = rain plus 1 L min^{-1} concentrated flow rate; and R+4 = rain plus 4 L min^{-1} concentrated flow rate. The rainfall-inflow simulation periods were applied over the 25 minutes in the following intervals: R = 0 to 15 min; R+1 = 15 to 20 min; and R+4 = 20 to 25 min.

Plot size(s): The rectangular, steel plot was 13 ft long by 4.1 ft wide by 0.7 ft deep (4.0 m long by 1.2 m wide by 0.2 m deep) and set at a 40 percent slope.

Table AC-11. Results from a laboratory rainfall simulation study to evaluate three size blends of wood shreds for mitigating post-fire erosion. Mean runoff depths (mm) and sediment concentrations (g L^{-1}) are reported for statistically significant treatment effects ($\alpha = 0.05$). Results are presented by mulch blend (NONE; AS IS; MIX; and REDUCE), cover amount (0, 50, and 70 percent), and simulation period (R = rain only [0 to 15 min]; R+1 = rain plus 1 L min^{-1} inflow [15 to 20 min]; and R+4 = rain plus 4 L min^{-1} inflow [20 to 25 min]). Each combination of mulch blend and cover amount are shown for the rain only (R) period as cover amount was a significant factor only during that period. The results of 50 and 70 percent cover are combined for the simulation periods that included inflow. Superscript letters denote statistical groupings from pairwise comparisons within a simulation period (across a row) for either runoff depth or sediment concentrations (Foltz and Wagenbrenner 2010).

		-------------Runoff depth------------ (mm)				**--------Sediment concentrations---------** (g L^{-1})			
	Mulch blend→	**NONE**	**AS IS**	**MIX**	**REDUCE**	**NONE**	**AS IS**	**MIX**	**REDUCE**
	Cover (%)								
R	0	1.5^{a}				130^{a}			
	50		0.34^{ab}	0.52^{ab}	0.18^{b}		24^{bc}	36^{b}	32^{b}
	70		0.29^{b}	0.23^{b}	0.27^{b}		6.9^{c}	$21b^{c}$	17^{bc}
R+1		3.3^{a}	0.81^{b}	0.95^{b}	0.81^{b}	240^{a}	40^{b}	61^{b}	96^{b}
R+4		8.7^{a}	5.2^{b}	5.5^{b}	4.7^{b}	450^{a}	420^{a}	320^{ab}	270^{b}

Generalized results:

All wood shred blends reduced runoff amounts, but the blend with all fines removed was most effective for both runoff and sediment yield reduction under conditions of rainfall and rainfall plus concentrated flow. No significant difference between 50 and 70 percent ground cover was observed (Foltz and Wagenbrenner 2010).

Appendix D. Polyacrylamide (PAM) Treatment Effectiveness Studies (2000 to the present)

Study I. Effectiveness of anionic polyacrylamide (PAM) treatment in reducing sediment yields following the 2002 Schoonover Fire in central Colorado (Rough 2007)

Study design: Six paired swales were installed per treatment on steep slopes (mean 37 percent) of coarse-textured soil burned at high severity. The anionic, water-soluble PAM was applied in two forms—dry PAM that consisted of small particles that were scattered over the soil (5.0 lb ac^{-1} [5.6 kg ha^{-1}]), and wet PAM, which was a slurry of PAM, water, and aluminum sulfate (10 lb ac^{-1} [11 kg ha^{-1}]) that was sprayed on the soil. The study extended over three years, but dry PAM was used only in the first year (year of the fire [FY]). In subsequent years, wet PAM was applied on the swales that previously had been treated with dry PAM. Each treated swale was paired with an untreated control. Thus, the study design was:

- Fire year (FY): three swales treated with dry PAM, three swales treated with wet PAM, and each treated swale paired with one of six untreated control swales
- Post-fire year one (PFy1): three dry PAM swales retreated with wet PAM; no further treatment on the other nine swales
- Post-fire year two (PFy2): three retreated swales from PFy1 were treated with wet PAM for the second time; no further treatment on the other nine swales

Plot size(s): Swales had a mean contributing area of 0.46 ac (0.19 ha) and included zero-order channels formed by convergent slopes.

Factors that impacted study design and/or results:

- A separate laboratory test found that PAM preferentially binds to ash over soil.
- The rain erosivity explained 58 percent of the variability in sediment yields.

Table AD-1. Results from PAM treatment effectiveness study following the 2002 Schoonover Fire. Rainfall amount, maximum 30-min intensity (I_{30}), and mean annual sediment yields are reported for three post-fire years. Difference (%) in sediment yield between the control and treated plots are reported, and significant differences ($p \le 0.05$) are in bold type. Time since fire codes: FY = year of the fire; PFy1 = 1 year after the fire; and PFy2 = 2 years after the fire (Rough 2007).

	--------Rainfall--------		----------Sediment yields----------			
Time since fire	Amount (inch [mm])	I_{30} (inch h^{-1} [mm h^{-1}])	Control (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	Treatment	Treated (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	Difference (%)
FY	4.2 [106]	0.64 [16]	1.2 [2.8]	Dry PAM	1.0 [2.3]	18
			1.6 [3.6]	Wet PAM	0.25 [0.55]	**85**
PFy1	4.8 [122]	0.72 [18]	0.89 [2.0]	Wet PAM—applied on dry PAM swales	1.2 [2.7]	–35[a]
			7.4 [17]	Wet PAM—no new application	4.5 [10.2]	40
PFy2	9.6 [245]	1.3 [33]	3.7 [8.3]	Wet PAM—reapplied to dry PAM swales	3.6 [8.1]	2
			6.0 [14]	Wet PAM—no new application	2.6 [5.8]	59

[a] Negative values in the percent difference column indicate that sediment yields were larger for the treated plots than for the control plots.

General results:

The results did not provide a clear indication of PAM effectiveness. PAM treatments reduced sediment yields during lower, less intense rainfall periods but were not effective when rainfall amounts and intensities increased. Storm erosivity explained 58 percent of the variability in sediment yields (Rough 2007).

Study II. Effectiveness of anionic polyacrylamide (PAM) treatment alone and in combination with straw mulch in reducing soil erosion following the 2004 Red Bull Fire in Utah (Davidson and others 2009)

Study design: Soil movement was measured using an erosion bridge at three locations within four different treatment blocks (PAM, straw, PAM + straw, and untreated control) that were created by dividing 21 ac (8 ha) of the treated area burned at high severity. The four treatment blocks were in gravelly clay loam colluvial soil, which contains calcareous lime (pH 8.2) and meets the recommended percent clay and divalent cation requirements for successful treatment with PAM. The PAM used in this study was granular anionic PAM pelletized with paper, which is water-activated to provide a time-release of various polyacrylamide polymers of different molecular weights. Application rate of PAM was 7 lb ac^{-1} (8 kg ha^{-1}). The agricultural wheat straw was applied at 1.5 ton ac^{-1} (3.4 Mg ha^{-1}). The study was done over three years.

Plot size(s): Erosion bridge measurements of soil movement were done midslope at three distinct locations within each treatment block.

Factors that impacted study design and/or results:

- No rainfall data were reported in this study.
- The treatments were established on an area that had been seeded.
- The aerial straw application provided, by the authors' description, uneven coverage.
- Net soil loss was presented as a single mean value for all three years so that changes over time could not be evaluated.
- In post-fire year one (PFy1), there was significantly less bare soil on the PAM plus straw (< 45 percent) and the PAM (< 35 percent) treatment areas than on the straw or the control (both > 65 percent); however, the impact of the ground cover on soil movement was not evaluated.

Table AD-2. Results from PAM and straw treatment effectiveness study following the 2004 Red Bull Fire. Mean value for net soil loss (inch [cm]) over a three-year post-fire period as estimated from a scatter plot. Estimated percent difference in soil loss between the control and treated plots are reported; however, none of these differences are significant at the $p < 0.05$ level. No rainfall data were reported (Davidson and others 2009).

Treatment	Soil loss (inch [cm])	Difference (%)
Control	–0.28 [-0.7]	
Straw	–0.31 [-0.8]	14
PAM	–0.12 [-0.3]	57
PAM plus straw	–0.16 [-0.4]	43

General results:

No rainfall data were reported. Soil movement results were reported as a single cumulative figure for all three years, and the small differences in net soil movement were not significant (Davidson 2009).

Appendix E. Combination Treatments Effectiveness Studies (2000 to present)

Study I. Combination treatment effectiveness in reducing erosion following the 2002 Hayman Fire in central Colorado (Rough 2007)

Study design: The study involved four repetitions of paired swales on steep slopes with treatments of hand scarification plus seeding and an untreated control.

Plot size(s): Silt fence sediment traps are located on paired swales that measure approximately 0.25 to 1.25 ac (0.1 to 0.5 ha), and include zero-order channels formed by convergent slopes.

Factors that impacted the study design: In the year of the fire, sediment producing rain events occurred prior to site treatment. Data from the year of the fire are not included.

Table AE-1. Results from the combination study following the 2002 Hayman Fire. Annual rainfall amount, maximum 30-min intensity (I_{30}), and mean annual sediment yields are reported for two treatments (hand scarification plus seeding and untreated controls) in post-fire year one (PFy1) and post-fire year two (PFy2). Difference (%) in sediment yield between the control and treated plots are reported (Rough 2007).

	------------Rainfall-------------		--------------------------Sediment yields------------------------		
Time since fire	**Amount** (inch [mm])	**I_{30}** (inch h^{-1} [mm h^{-1}])	**Control** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Scarification and seeding** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Difference** (%)
PFy1	6.0 [153]	1.6 [40.4]	4.3 [9.7]	4.0 [8.9]	7
PFy2	11.9 [303]	0.87 [23.2]	3.2 [7.1]	2.7 [6.0]	15

Generalized results:

There was no difference in sediment yields from paired swales that were hand scarified and seeded or the untreated controls (Rough 2007).

Study II. Effectiveness of treatment combinations to reduce sediment yields following the 2000 Cerro Grande Fire in central New Mexico (Dean 2001)

Study design: Six repetitions of three treatments (straw mulch + seeding; straw mulch + seeding + contour-felled LEBs; and untreated control) were installed on 23 to 24 percent slopes that had been burned at high severity. These sites were monitored for two years.

Plot size(s): The hillslope plots were 200 to 350 ft^2 [20 to 30 m^2] with silt fence sediment traps installed at the base.

Factors that impacted the study design and results:

- Precipitation was below normal during the two study years.
- Results comparing the straw mulch + seeding treatment to the controls are reported in Appendix C-Study I.
- The differences in sediment yield between the straw mulch + seeding treatment and the straw mulch + seeding + LEB treatment were not significant.

Table AE-2. Results from combined hillslope treatments following the 2000 Cerro Grande Fire. Annual rainfall amount, maximum 10-min intensity (I_{10}), and mean annual sediment yields are reported by treatment (straw mulch + seeding + LEBs and untreated controls) for the year of the fire (FY) and the post-fire year one (PFy1). Difference (%) in mean sediment yields between the control and treated plots are reported for both years and are significant at the $p < 0.05$ level (Dean 2001).

	----Rainfall----		----Sediment yields----		
Time since fire	**Amount** (inch [mm])	**I_{10}** (inch h^{-1} [mm h^{-1}])	**Control** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Straw mulch + seeding + LEBs** (ton ac^{-1} yr^{-1} [Mg ha^{-1} yr^{-1}])	**Difference** (%)
FY	2.1 [52]	0.94 [24]	3.7 [8.3]	0.84 [1.9]	77
PFy1	6.1 [156]	3.9 [99]	5.6 [12.6]	0.21 [0.47]	96

Generalized results:

A combination of contour-felled LEBs, straw mulch, and seeding significantly ($p < 0.05$) reduced sediment yields from hillslope plots by 77 percent in the year of the fire and by 96 percent in post-fire year one. The LEBs added no additional erosion mitigation over the straw mulch and seeding treatment, which reduced mean annual sediment yields by 70 percent in the first post-fire year and 95 percent in the second post-fire year (Dean 2001).

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