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Mitigating Postfire Runoff and Erosion in the Southwest using Hillslope and Channel Treatments

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Intermountain West Frequent-Fire Forest Restoration

Ecological restoration is a practice that seeks to heal degraded ecosystems by reestablishing native species, structural characteristics, and ecological processes. The international Society for Ecological Restoration defines ecological restoration as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed," and that "the goal of ecological restoration is to return a degraded ecosystem to its historic trajectory."[1]

Most frequent-fire forests throughout the Intermountain West have been degraded during the last 150 years. Many of these forests are now dominated by unnaturally dense thickets of small trees, and lack their once diverse understory of grasses, sedges, and forbs. Forests in this condition are highly susceptible to damaging, stand-replacing fires and increased insect and disease epidemics. Restoration of these forests centers on reintroducing frequent, low-severity surface fires—often after thinning dense stands—and reestablishing productive understory plant communities.

The Ecological Restoration Institute at Northern Arizona University is a pioneer in researching, implementing, and monitoring ecological restoration of frequent-fire forests of the Intermountain West. By allowing natural processes, such as low-severity fire, to resume self-sustaining patterns, we hope to reestablish healthy forests that provide ecosystem services, wildlife habitat, and recreational opportunities.

The Southwest Fire Science Consortium (SWFSC) is a way for managers, scientists, and policy makers to interact and share science. SWFSC's goal is to see the best available science used to make management decisions and scientists working on the questions managers need answered. The SWFSC tries to bring together localized efforts to develop scientific information and to disseminate that to practitioners on the ground through an inclusive and open process.

ERI working papers are intended to deliver applicable science to land managers and practitioners in a concise, clear, non-technical format. These papers provide guidance on management decisions surrounding ecological restoration topics. This publication would not have been possible without funding from the USDA Forest Service and the Southwest Fire Science Consortium. The views and conclusions contained in this document are those of the author(s) and should not be interpreted as representing the opinions or policies of the United States Government. Mention of trade names or commercial products does not constitute their endorsement by the United States Government or the ERI.

[1] Society for Ecological Restoration. "What is Ecological Restoration?" https://www.ser-rrc.org/what-is-ecological-restoration/

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Cover photo: An incised channel created by the erosion of a drainage after the Cerro Grande Fire in 2000 near Los Alamos, NM. The view is upstream and the blue backpack is about 3 feet tall. The incision seen in this photo was after the wildfire and subsequent rain storm; this drainage had no definite banks prior to the storm. *Photo by John A. Moody, US Geological Survey*

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Introduction

Wildfires in the southwestern US are getting larger, more frequent, and more severe due to changing climatic conditions like rising temperatures and prolonged drought (Singleton et al. 2018, Mueller et al. 2020). Catastrophic wildfire events directly impact communities, ecosystems, and cultural resources—and can pose continuing hazards long after the fire is extinguished. Flooding and erosion from heavy rainstorms are postfire emergencies caused by the severe loss of vegetation cover and the alteration of soil conditions. Because these postfire impacts can pose safety concerns and threaten property and infrastructure, there is a need to understand postfire treatments and their effectiveness toward ecosystem resilience and community protection.

The Burned Area Emergency Response (BAER) program is the primary response used by all federal land management agencies to address emergency postfire soil and slope stabilization issues. This federally funded program coordinates its postfire assessment and implementation efforts with state and tribal governments, local agencies, and emergency management departments (National Interagency Fire Center 2020). Both the US Department of Agriculture and US Department of Interior provide a guidebook to identify post-wildfire threats to values at risk on federal lands and steps to take immediate actions to manage those risks before the first damaging storm (Rowley 2020). Selecting the right treatment is a complex decision, but understanding the treatment costs, implementation methods, and ecological impacts can help inform that decision. The purpose of this working paper is to compare the effectiveness of treatments to mitigate the two most common forms of erosion, hillslope and channel erosion. With a focus on severely burned ponderosa pine (*Pinus ponderosa*) and mixed-conifer forest soils of the Southwest, this paper includes land management recommendations and treatment implications as well as examples of lessons learned and trade-offs among methods.

Hillslope and Channel Erosion

Hillslope and channel erosion are the two main types of erosion that land managers and BAER teams work to prevent. **Hillslope erosion** (Fig. 1A) is often broken down into three categories of increasing magnitude 1) rain splash, 2) sheet, and 3) concentrated flow or rill and gully erosion. Rain splash erosion occurs when raindrops hit bare soil and detach particles. Water flowing over weakened soils and entraining soil particles within it drives sheet erosion. Natural recovery of rain splash and sheet erosion usually occurs within three years of a fire when soil surface cover and water infiltration increase. Rills form when sheet flow becomes concentrated into small incisions on hillslopes. Rills can develop into larger more efficient flow paths known as gullies which can continue to grow until they reach bedrock or larger substrate materials that can no longer be eroded (Neary et al. 2012). **Channel erosion** (Fig. 1B) occurs when preexisting channels become overwhelmed by high peak flows and enlarge rapidly. Rills, gullies, and channels create much higher rates of runoff and erosion and can continue long after rain splash and sheet erosion subside (Neary et al. 2012). Because of this, treatments are often focused on preventing these types of erosion from beginning. Water-saturated debris flows are single large erosion events often triggered by longer duration, high intensity storms on steep hillslopes or in channels (Cannon et al. 2001, Neary et al. 2012). Although rare, these events are the largest and most destructive, making them both difficult to predict and prevent.

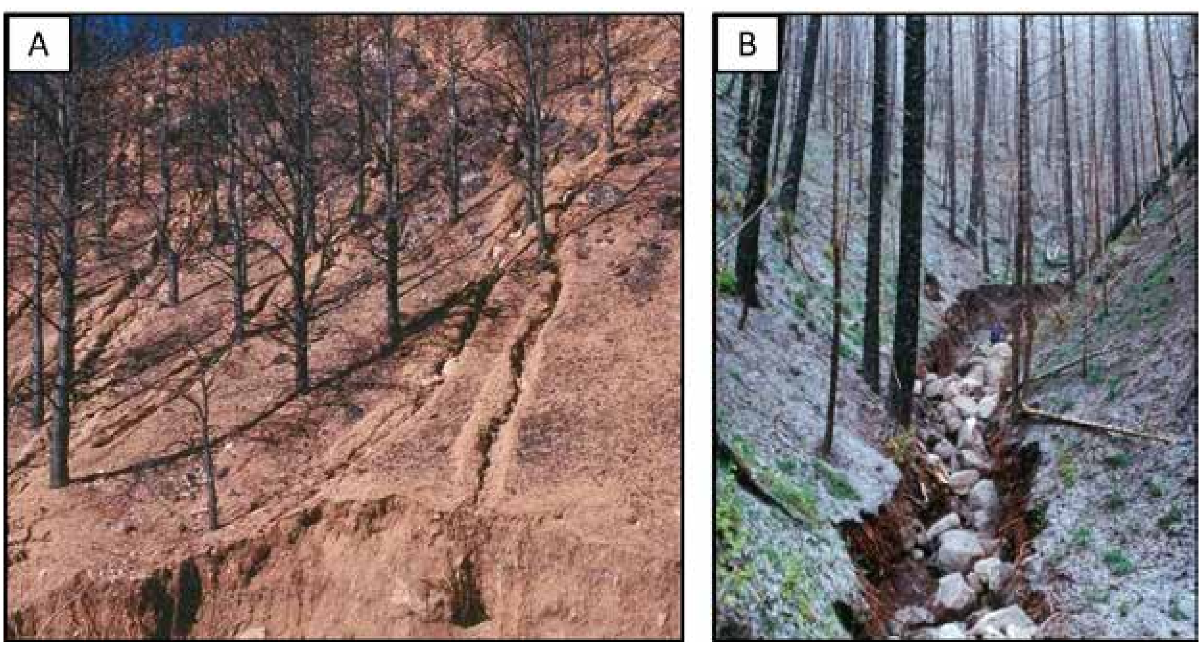

Figure 1. Postfire sheet and rill erosion on the 1994 Buffalo Creek Fire (A) and channel erosion on the 2000 Cerro Grande Fire (B). Courtesy of the USDA "After Fire: Toolkit for the Southwest" website photo library.

Postfire Assessments Inform Treatment Recommendations

A wildfire that triggers a BAER assessment varies among agencies but is largely driven by fire size. Burn severity, topography, and proximity to values at risk are also factors. USDA Forest Service BAER guidelines recommend assessments on fires greater than 500 acres, but there is no minimum size on DOI lands. Teams consist of a leader who requests specialists depending on anticipated values at risk that need protection, the complexity of the fire and potential for postfire damage. BAER teams arrive at roughly 40–60 percent fire containment and submit their assessment report to line officers within seven days of 100 percent containment of the wildfire on USDA lands and no more than 21 days from fire discovery on DOI lands.

The Runoff/Erosion Response and Soil Burn Severity

In the Southwest, a monsoon season typically brings an end to fire season. When these high rainfall intensity storms occur after wildfires, the likelihood of large runoff and erosion events increases with rates up to three orders of magnitude higher than pre-fire conditions (Adams and Comrie 1997, Moody and Martin 2009, Wagenbrenner and Robichaud 2014). Moderate and especially high soil burn severity can dramatically reduce water infiltration and soil resistance to erosion. Therefore, an important step in assessing postfire risks is creating a soil burn severity (SBS) map. SBS maps are a combination of satellite-derived Burned Area Reflectance Classification (BARC) maps (Key and Benson 2006) and field-based data including postfire ground cover, soil structure, soil water repellency, ash color and depth, and fine root scorch (Parsons et al. 2010).

Determining Values at Risk and Justifying Treatments

BAER teams must also determine the values at risk, such as human life and safety, property, and critical natural or cultural resources, from potential erosion and flooding. Wildfire incident management teams often have a list of values generated by the Wildfire Decision Support System (WFDSS) and agency administrators, which provide the BAER team a good starting point. Wildfire values at risk are usually not consistent with watershed response values because flooding and erosion can be transported outside burned areas. Local knowledge is essential in this process, especially when BAER teams are not familiar with resources; thus, an up-to-date GIS database of potential values at risk for each management unit can be a large asset.

To justify treatments for mitigating risks to values, the DOI and USDA mandate that teams complete a cost-risk analysis. The cost-risk analysis consists of weighing the potential damage to values when no treatments have been applied compared to the costs of applying treatments. To provide a better understanding of how BAER funding is justified, we examined values at risk from the 30 southwestern fires with the most expensive BAER treatment requests. Life and safety was the highest-ranking value on 26 fires, and public property was the second highest (Robichaud et al. 2014, Fig. 2). Federal land management agencies do not have the legislative authority to spend money outside of their jurisdictions. Because of this, agencies usually can only justify treatments based on values on federal property, but protecting private property is sometimes cited in funding requests (Fig. 2). When teams identify values at risk that are not on federal property, they collaborate with the Natural Resources Conservation Service (NRCS), and state, county, and local land management agencies to ensure that partner needs are met.

While it is relatively straightforward to assign a value to roads, campgrounds, and buildings, it is more difficult to assign dollar amounts to non-market values. As a rule, BAER teams do not assign dollar values to human life and safety. Other non-market values include water quality, endangered species, soil productivity, and other ecosystem services. Efforts are currently underway to better estimate non-market resource values in the Southwest; however, currently many BAER teams rely on experience to make these judgments. Tools and spreadsheets, such as the values at risk or VAR lite tool, have been developed to make these comparisons more consistent, but standardization is difficult from fire to fire as treatment cost, effectiveness, and values can vary widely (Calkin et al. 2007). Models are used to quantify the cost risks by quantifying the likelihood and extent of damage. For example, using the Forest Service Erosion Risk Management Tool (ERMiT) assessment, teams can predict soil loss from hillslopes that are untreated, seeded, or straw mulched at different rates (Robichaud 2008). Teams can then compare these estimates with the value of the soil and the cost of mulching to justify a treatment. On many wildfires in the Southwest, moderate and high soil burn severity is patchy, on low slopes, or does not pose great risks to values. In this scenario, natural recovery of the burned areas is usually the best course of action and BAER teams often recommend closing the fire perimeter to facilitate recovery and reduce risks to life and safety.

Understanding Erosion Mitigation Results: Context is Key

One must consider many factors when trying to interpret results from postfire erosion and runoff mitigation monitoring studies. For example, soils derived from a rhyolitic parent material are more susceptible to erosion than ones derived from limestone (Moosdorf et al. 2018). Coarse textured soils are more likely to be water repellent than fine soils (DeBano et al. 1970). Topographic features such as slope, slope length, concavity, and hillslope to channel connectivity are major drivers of downslope impacts (Moody et al. 2013). Aspect and biotic community can have large effects on vegetative recovery postfire (Robichaud et al. 2013b). These factors make it difficult to find comparable experimental units for study in postfire research, especially at relevant scales such as watersheds (Moody et al. 2013). Thus, extrapolating research results from one fire or one geographic region to another requires careful consideration of the context of those studies, which this working paper tries to accomplish.

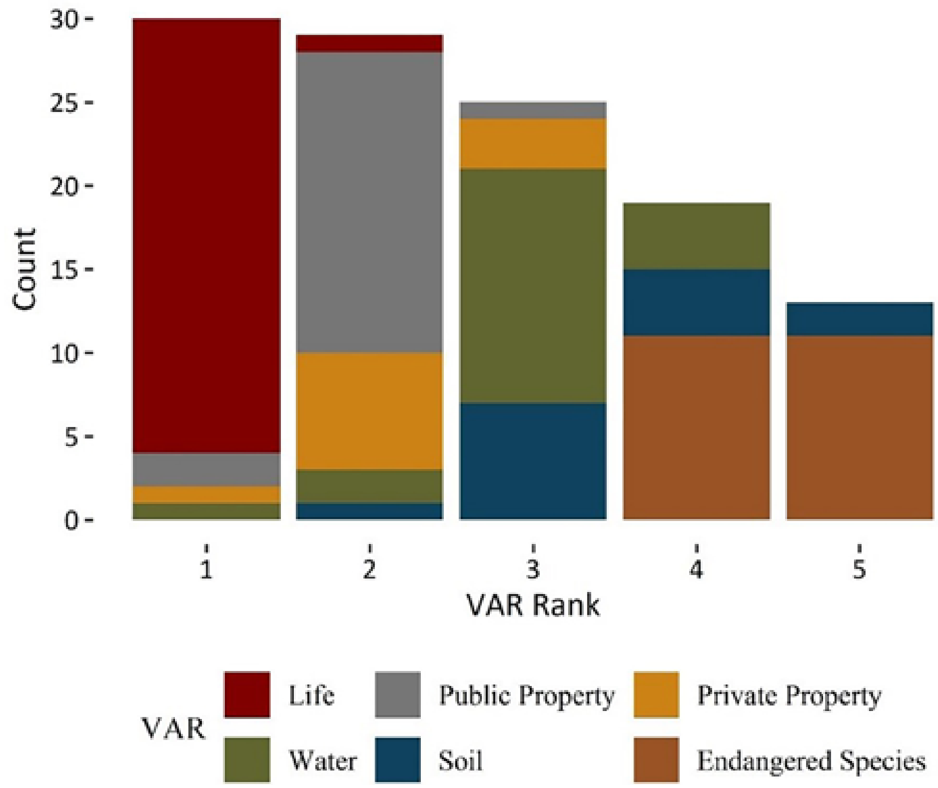

Figure 2. Values at risk (VAR) for the 30 largest BAER funding requests in the Forest Service Southwestern Region, 2000–2019. VAR rank refers to the order in which each value appeared. Adapted from Robichaud et al. (2014).

Hillslope Erosion Treatments

Hillslope erosion treatments are designed to reduce postfire hillslope erosion and runoff from fire-affected hillslopes and to protect downstream resources by reducing flooding and sediment deposition (Robichaud et al. 2010). Hillslope erosion treatments include three major categories: 1) erosion barriers, 2) mulching, and 3) seeding (Napper 2006). The majority of recent hillslope treatments include straw mulch, wood shred mulch, and less often seeding (Fig. 3).

Erosion Barriers

Erosion barriers are linear treatments installed on the hillslope contour with the intent of restricting sheet flow and trapping soil behind them. Straw wattles and contour felled logs were once widely used hillslope treatments, but their use declined from 2000–2010 as more effective mulching treatments were developed (Robichaud et al. 2010; Fig. 3). Erosion barriers are expensive and especially likely to fail during the short duration high intensity rainfall events common in the Southwest as they do not provide ground cover and tend to channelize flow (Robichaud et al. 2010).

Mulch

The use of postfire mulching has increased dramatically in recent years, as it has proven to be effective at reducing hillslope erosion (Robichaud et al. 2010; Fig. 3). Robichaud et al. (2010) reviewed studies on the effectiveness of three types of commonly used materials: 1) hydromulch, 2) agricultural straw mulch, and 3) wood shred mulch. Additionally, soil tackifiers such as polysaccharides or polyacrylamides have been applied as hillslope treatments either on their own or in conjunction with mulches (Robichaud et al. 2010).

Trends in Southwestern BAER Funding

To compare trends in BAER hillslope and channel erosion treatment funding allocation over time, we compiled treatment requests for the 30 most expensive wildfires in the Southwest region using the BAER burned area reports database (Robichaud et al. (2014); Figs. 3 and 5). Selecting the most expensive fires created a focus on the treatment used when risks to important values were high and large expenditures justified. Usually, only a fraction of each original request is funded but data on final costs were not available. The first major takeaway is that BAER expenditures can be many millions of dollars, making it important to use the most cost-effective treatments when possible. Throughout this publication, we connect changes in expenditures with effectiveness results to show how management strategies and scientific results have interacted in the last 20 years.

Hydromulch and Soil Tackifiers

Hydromulching can be applied via aircraft or adjacent to roads using vehicles. It consists of water, fiber mulch, and a tackifier mixed into a slurry and sprayed onto the soil surface. Hydromulch is expensive at $1,684 to $4,348 per acre, breaks down quickly after application, and can concentrate flows on longer slope lengths (Napper 2006). Two studies at catchment scales in Colorado and California showed that hydromulch cover was less than 10 percent, 2.5 and 5 months after application, following a series of high intensity rainfall events from initial cover values of 64 percent and 21 percent, respectively (Robichaud et al. 2013c). Furthermore, hydromulching did not reduce erosion or runoff during that

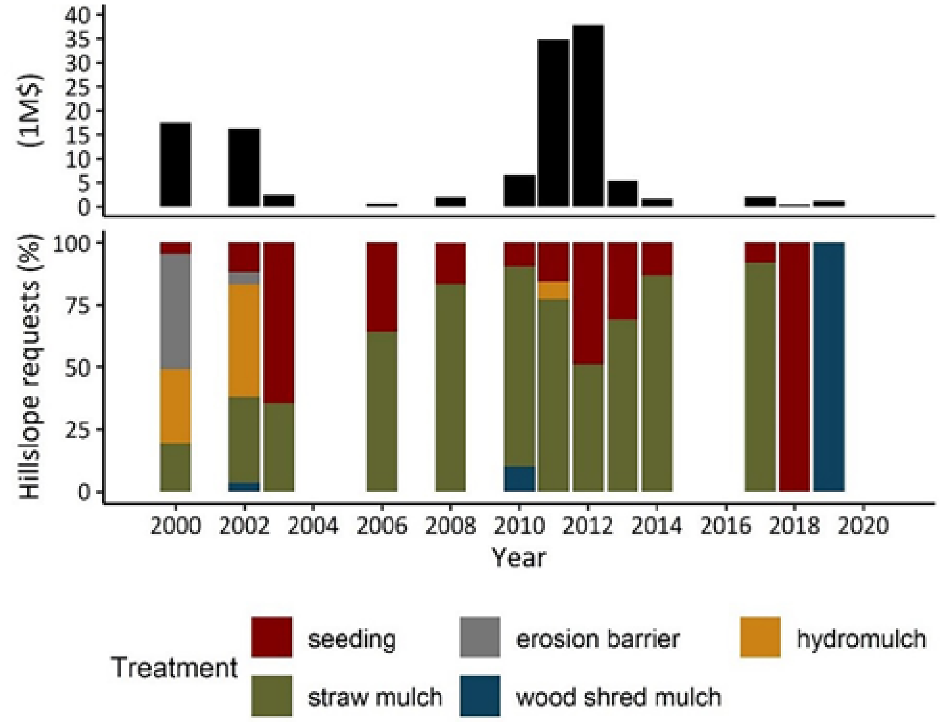

Figure 3. Total funding requests for hillslope treatments and percentages by treatment for the 30 largest BAER funding requests in the Forest Service Southwestern Region, 2000–2019. Dollar values are in millions and are adjusted for inflation to 2019 values.

time (Robichaud et al. 2013c). Polyacrylamide was tested on two sets of paired watersheds in southern California but also did not reduce erosion rates (Wohlgemuth and Robichaud 2007). Hydromulch and soil tackifiers are not recommended or widely used due to their high cost and low effectiveness compared to straw and wood shred mulches.

Straw Mulch

Agricultural straw mulching has become a widely used postfire erosion mitigation tool due to its effectiveness at reducing erosion and runoff, relatively low cost, and speed of installation (Napper 2006, Fig. 3). These attributes make straw mulching an effective tool at mitigating risks to even the most important values, such as human life and safety and public property, by reducing runoff peak flows and erosion that can damage infrastructure. Its relatively low cost per acre compared to wood shred mulching also make it useful when less critical values are at risk, such as municipal water sources (Table 1). Finally, straw mulch can be bought and shipped economically, and because of its low density is quickly installed, an important consideration in the Southwest where damaging storms can arrive days to weeks after fires burn. Potential risks of straw mulching are the

Table 1. Postfire erosion and runoff hillslope treatment comparison adapted from Napper (2006) and Robichaud et al. (2010). Treatments shown are currently the most widely implemented. Costs are from the 30 highest BAER funding requests in the southwestern US.

Hillslope treatment attribute	Wood Shred Mulch	Straw Mulch	Seeding
Effectiveness high intensity rainfall	High	Moderate	Low
Effectiveness low intensity rainfall	High	High	Moderate-Low
Effectiveness on slopes (40–65%)	High	Moderate	Low
Function 0-1 year	High	High-Moderate	Low-Very Low
Function 1-3 year	High	Moderate	Depends on establishment
Function 3+ years	High	Low	Depends on establishment
Resistance to wind displacement	High	Low	Moderate
Resistance to water displacement	High	Moderate	Very Low pre-germination
Implementation speed	Slow	Fast-Moderate	Fast
Risk of invasive species	Very low	High-Moderate	Moderate
Impact on native species	Positive-Neutral	Positive-Neutral	Negative/Unknown
Cost per acre: Avg (Range)	Acre: $1,486 ($357–2,100)	Acre: $930 ($206–1,868)	Acre: $103 ($12–833)

introduction of non-native species onto burned areas (Beyers 2004), as well as its potential for wind to transport it off hillslopes, greatly reducing its effectiveness in some situations (Copeland et al. 2009, Robichaud et al. 2013a).

Robichaud et al. (2013b, 2013c) studied straw mulching treatment effectiveness on four fires throughout the western US at hillslope scales and on one fire at small watershed scales. On the 2002 Hayman Fire in Colorado and the 2003 Hot Creek Fire in southern Idaho, straw mulch did not reduce hillslope erosion on slopes of 41 and 55 percent, respectively, during high intensity storms the first year postfire (Wagenbrenner et al. 2006, Robichaud et al. 2013b). Straw mulch decreased hillslope erosion on two fires in southeastern Washington and northern Idaho with slopes of 50 and 65 percent, respectively. Researchers attributed this difference in effectiveness to greater vegetation recovery on the mulched plots in the successful fires, which held mulch in place and reduced bare soil cover. On the Hayman Fire, straw mulch was effective at reducing both erosion and runoff peak flows at larger catchment scales (Robichaud et al. 2013c). Straw mulching also decreased soil surface temperature by 12°F compared to unmulched locations on the 2000 Cerro Grande Fire in New Mexico, reducing evaporation and increasing plant growth (Robichaud et al. 2010). This highlights straw mulching's ability to expedite postfire vegetation recovery and the importance of post-treatment monitoring (Robichaud et al. 2013b).

One consideration of straw mulching is providing enough cover to effectively reduce erosion without suppressing native vegetation. In a review of straw mulching studies, a ground cover of 60 percent, or roughly 1 ton per acre, was the minimum application rate to reduce erosion (Prosdocimi et al. 2016). In Washington state, mulching depths less than 3 cm had positive effects on plant recovery; however, when depths exceeded 5 cm recovery was strongly inhibited (Dodson and Peterson 2010). On the 2012 High Park Fire in Colorado, researchers found a slight positive effect of straw mulching on serotinous lodgepole pine (*Pinus contorta*) regeneration three years after the fire (Wright and Rocca 2017).

The introduction of non-native species via straw mulching is a common concern in burned areas of the western US. Due to its origin in agricultural fields, straw mulch can contain many non-native species, which take advantage of open ecological niches postfire. On the 1999 Megram Fire in northern California, Kruse et al. (2004) found that mulching significantly increased the number of non-native species present and impeded native species recovery. Practitioners now take care to buy certified weed-free straw mulch with mixed results. On the 2013 Rim Fire in California, weed-free rice straw mulch increased non-native forb and grass cover and non-native species richness (Shive et al. 2017). In two years of monitoring following the 2013 Silver Fire in New Mexico, there was no indication that mulching had introduced non-native species (Natharius 2015). Straw mulching effects on vegetative recovery at six wildfires in the interior Northwest and Rocky Mountains 9 to 13 years postfire were generally neutral or positive (Bontrager et al. 2019). Mulch had no significant effect on understory plant diversity, species richness, or cover and non-native cover was low across the study. Mulching did increase Douglas-fir (*Pseudotsuga menziesii*) over ponderosa pine establishment but did not change overall seedling density (Bontrager et al. 2019).

Wood Shred Mulch

Wood shred mulch, also known as wood strand or wood straw, consists of linear wood fragments usually generated on site from burned low-value timber (Fig. 4). Wood shred mulch is a new treatment but has gained popularity due to its effectiveness at reducing erosion, longevity on hillslopes, resistance to wind erosion, and local availability of materials, thus decreasing the possibility of invasive species encroachment (Table 1, Fig. 3). This comes at a high average cost of implementation of $1,486 per acre and a relatively slow implementation time of ≈35 acres/helicopter/day, due to its high density (Robichaud et al. 2013a).

Figure 4. Wood shred mulch grinding and spreading via helicopter, Stickpin Fire, WA. *Photo credit: Jason Jimenez, Colville NF.*

Because studies widely recognize it as the most effective hillslope treatment, practitioners use wood shred mulch when risks are high to important values, such as human life and safety and property.

On indoor rainfall and concentrated flow simulations, wood shred mixes with greater than 98 percent of fragments longer than 2 inches and less than 1 inch wide were the most effective at reducing both runoff and erosion on 40 percent slopes (Foltz and Wagenbrenner 2010). Favorable results were found for both 50 percent and 70 percent cover, leading researchers to recommend lower cover values (Foltz and Wagenbrenner 2010). Two Southwest fires confirmed the importance of long and narrow fragments when, on the 2002 Indian Fire in Arizona, small wood chips were transported off 30–40 percent hillslopes but longer fragments on the 2010 Schultz Fire remained on hillslopes of 30–65 percent. This difference was attributed to the ability for longer fragments to interlock, thus reducing their redistribution via runoff (Riechers et al. 2008, Robichaud et al. 2013a). On the Hayman Fire, wood shred mulch at 51 percent cover on 23 percent slopes effectively reduced hillslope erosion from 8.5 to 1.2 tons/acre during a high-intensity storm the first year postfire (Robichaud et al. 2013b). The higher density of wood shred has an added benefit of resisting wind transport (Copeland et al. 2009), making it more effective than wheat straw on steeper, more exposed hillslopes, and hillslopes where plant recovery may be slow. Wood shred had more than twice the residence time as wheat straw on three fires where both were applied to adjacent hillslopes (Robichaud et al. 2013b). The effectiveness of wood shred mulching for reducing runoff has not been tested at catchment scales, but one study found a 50-percent reduction on small (2.7 ft2) and large hillslope (1,076.4 ft2) scale plots during the first postfire year at mulching rates of 77–87 percent cover (Prats et al. 2016).

Few studies have examined the longer-term ecological impacts of wood shred mulching, but short-term studies have shown generally positive outcomes. In Portugal, researchers found that wood shreds reduced organic matter loss by 88 percent; however, these gains were not statistically significant due to low replication (Prats et al. 2016). On the 2012 High Park Fire, wood shred mulching did not change understory recovery or plant available nitrogen but increased lodgepole pine regeneration four years after fire (Jonas et al. 2019).

Postfire Seeding

Postfire seeding is a widely used hillslope treatment due to its relatively low cost per acre, ease of rapid installation, and perceived effectiveness (Table 1). Seeding treatments in many parts of the western US have declined; however, it was still relatively common within the Southwest region from 2000–2009, accounting for 32 percent of total Forest Service seeding costs (Peppin et al. 2011). Our more recent examination of seeding versus mulching cost requests in the Southwest points to an increased use of mulch over time, while seeding expenditures have remained relatively flat (Fig. 3). Because seeding has a lower chance of success than mulching treatments, teams only recommend it in situations where risks to values are low or values are less critical, such as soil productivity. Often in these cases, natural regeneration is a viable and more cost-effective option.

Reviews of postfire seeding effectiveness in the western US show that seeding is unlikely to reduce postfire erosion and runoff (Robichaud et al. 2000, Beyers 2004, Peppin et al. 2010). Peppin et al. (2010) found that when using more robust effectiveness monitoring methodologies (replicated randomized experiments), 0 out of 16 seeding treatments reduced erosion. Unpublished BAER monitoring reports found that seeding efforts in the Southwest region on the 2013 Silver and 2014 Signal fires on the Gila National Forest were successful at establishing seeded species in mixed-conifer and ponderosa pine forest types with elevations from 7,200 to 9,600 ft. Seed mixes for both fires consisted of a majority of barley (*Hordeum vulgare*) and native graminoid species. On the 2013 Silver Fire, seeding increased canopy cover more than 50 percent and significantly decreased percent bare soil when compared to unseeded sites (Natharius 2015). Seeding on the 2014 Signal Fire increased graminoid cover by 40 percent and total species richness the first year postfire but suppressed native forb cover the second year postfire (Koehler and Keisow 2016). Bare soil cover was similar on seeded (63 percent) and untreated sites (68 percent) the first fall postfire but had diverged to 28 and 63 percent, respectively, by year three. These changes correlate with changes in erosion rates on paired seeded and untreated north-facing hillslopes with 50 percent slopes (Koehler and Keisow 2016). Erosion rates averaged 15.5 and 29 tons/acre in 2014 and 0.6 and 6 tons/acre by 2016 on treated hillslope and untreated hillslopes, respectively. These successes were likely driven by low intensity rainfall directly after seeding, which allowed seedlings to establish and not get washed away by subsequent higher intensity rainfall (Natharius 2015, Koehler and Keisow 2016). Observational BAER effectiveness monitoring has also shown seeding establishment on the 2012 Little Bear and 2015 Slide fires, but no effects on hillslope erosion were measured (Anna Jaramillo, Southwest Region BAER Coordinator, personal communication).

These results contrast with those of many fires where seeding efforts have failed. On the 2010 Schultz Fire, seeding was not recommended by the BAER team due to concerns about the lack of effectiveness and potential negative effects on native recovery, but was ultimately implemented as a treatment (Coconino National Forest 2010). High rainfall intensity of 0.95 inches in 10 min directly after seeding caused seeds to be washed off of hillslopes (Neary et al. 2012). Conversely, when low precipitation rates occurred after the 2000 Bobcat Fire in Colorado, seeded species did not germinate, resulting in no change in ground cover or erosion (Wagenbrenner et al. 2006). One study examined seeding on randomized plots on three fires in ponderosa pine ecosystem types in northern Arizona across a range of slopes (5–25 percent) and aspects (Stella et al. 2010). Non-native cereal grains, common wheat (*Triticum aestivum*) and annual ryegrass (*Lolium multiflorum*), along with a native seed mix of graminoids and forbs were tested against controls (Stella et al. 2010). Although postfire precipitation was at or above yearly average, cereal gains only established on one fire which had the highest elevation (7,874 ft) and annual precipitation (25.4 in) resulting in 13 percent and 10 percent higher canopy cover on ryegrass and wheat seeded plots respectively compared to unseeded controls. This suggests that if the main goal for postfire rehabilitation is erosion reduction, seeding can provide cover and potentially reduce erosion when low rainfall intensity storms predominate on hillslopes favorable to recovery. Seeding is a less reliable hillslope treatment than wheat straw or wood shred mulching and thus teams recommend it only when those options are not practical (Table 1). Furthermore, current drought conditions combined with climate projections for the southwestern US point to weakening of the North American monsoon, increasing the likelihood of seeding failure (Pascale et al. 2017, Williams et al. 2020).

Additional management considerations of postfire seeding are the potential of seeded species outcompeting and suppressing native plant recovery, increasing non-native plant establishment, or introducing genetically different non-local seeds into mixes (Beyers 2004, Peppin et al. 2010, 2014). Cereal grains or sterile hybrids that are intended to have short (<3 year) residence times have been used recently to decrease effects on native recovery (Peppin et al. 2011). Monitoring on the 1996 Dome Fire indicated that when using short-lived cereal grains, detrimental impacts on native forbs and overstory plant recovery can persist after grasses decline (Barclay et al. 2004). Conversely, seeding successfully reduced non-native species cover in moderate to high burn severities both one- and two-years postfire. In six out of 11 studies on forested regions in the western US, seeding reduced non-native species establishment (Peppin et al. 2010). Research and monitoring of the effects of postfire seeding on native and non-native plant establishment most often occurs between one- and three-years postfire, making it difficult to determine longer-term ecological impacts. A better understanding of the legacy impacts of postfire seeding at relevant timescales requires long-term replicated studies.

Channel Erosion Treatments

Channel treatments range from removing debris and culverts to installing check dams, large debris basins, and trash racks (Napper 2006). Removal of debris such as logs is a widely used and effective channel treatment (Fig. 5, Table 2). Debris removal reduces log and sediment entrainment in runoff, which can increase channel peak flows and erosion through plugging and subsequent failure of downstream infrastructure. Removal allows for the passage of runoff through the built environment and is useful in reducing threats to life and safety on roadways as well as threats to the infrastructure itself. Installation of channel treatments was popular until the early 2000s but is not common now due to its low effectiveness compared to mulching treatments and potential for negative downstream impacts (Fig. 5).

Check dams consist of channel-width low dams placed at consistent intervals perpendicular to the channel. Straw bale check dams are commonly installed in steeper headwater channels; however, effectiveness is limited by storage capacity and failure. On the 2010 Twitchell Canyon Fire in southern Utah, the effectiveness of straw bale dams was evaluated on a series of paired treated and untreated catchments (Robichaud et al. 2019). Directly after installation of dams at a rate of 1.6 per acre of watershed, high rainfall intensity combined with slow plant recovery and erodible soils created erosion rates of 8.7 to 11.5 tons/acre. Check dams were filled quickly and trapped only 10–50 percent of sediment per catchment, resulting in no significant treatment differences (Robichaud et al. 2019). If the potential for debris flows and channel plugging still exists after channel clearing, trash racks, deflectors, and debris basins are other options on low slope alluvial fans. These treatments are usually expensive, require clearing of debris after runoff events, and are difficult to install quickly, making them a last resort for postfire erosion and runoff mitigation to be used when risks to values are high and other options are not available (Napper 2006).

Alluvial Fan Repair and Protection

In some extreme examples of postfire runoff and erosion, such as the 2010 Schultz Fire in Arizona and the 2012 Waldo Canyon Fire in Colorado, channel erosion extended onto relatively low slope (<10 percent) alluvial fans where deposition of sediment from steeper hillslopes would normally

Table 2. Postfire erosion and runoff hillslope treatment comparison adapted from Napper (2006). Treatments shown are currently the most widely implemented. Costs are obtained from the 30 highest BAER funding requests in the southwestern US.

Channel treatment	Check dam	Channel clear	Deflector	Debris basin	Trash rack
Effectiveness high runoff	Low	High	High	Moderate	Moderate
Effectiveness low runoff	Moderate	High	High	High	High
Function 0-1 year	Moderate	High	High	Need maintenance	Need maintenance
Function 1-3 year	Low	High	High	Need maintenance	Need maintenance
Function 3+ years	Low	Moderate	Moderate	Need maintenance	Need maintenance
Implementation speed	Moderate	Fast	Slow	Slow	Slow
Potential for failure	High	Low	Moderate	Moderate	Moderate
Cost per unit: Avg. (Range)	Each: $745 ($112-1,364)	Mile: $16,350 ($1,020-83,333)	Each: $10,456 ($227-22,681)	Each: $4,992 ($1,137-8,889)	Each: $9,840 ($595-34,091)

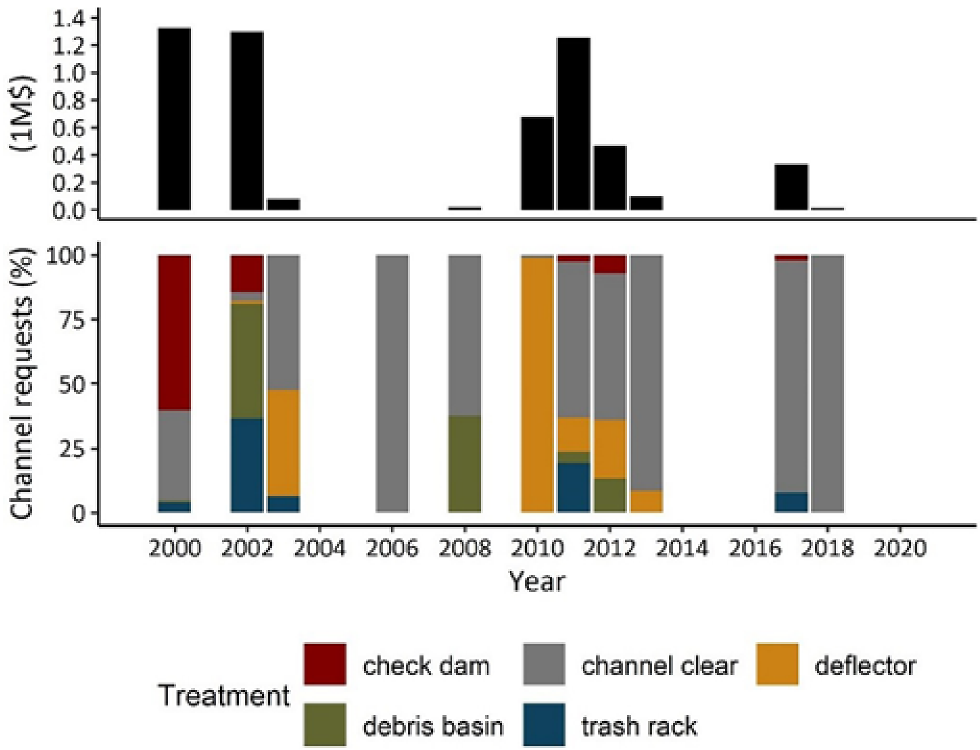

Figure 5. Total funding requests for channel treatments and percentages by types for the 30 largest BAER funding requests in the Forest Service Southwestern Region between 2000 and 2018. Dollar values are in millions and are adjusted for inflation to 2019 values.

occur. This caused runoff and sediment to be transported into neighborhoods well downstream of the burned area (Neary et al. 2012). Although no controlled comparisons of treatment effectiveness were made, alluvial fans were restored on both fires to mitigate flows and sediment deposition that were impacting downstream resources (Rosgen and Rosgen 2013). By removing incisions and armoring alluvial fans, runoff can spread over a wider area, reducing flow speeds and stream power and allowing for increased infiltration and sediment settling (Allen Hayden, Natural Channel Design, personal communication). These circumstances are beyond the scope of the BAER program and are often funded using NRCS emergency watershed protection program resources.

On the 2019 Museum Fire in Arizona, postfire mitigation consisted of proactively reducing channel incision and increasing infiltration and sediment deposition on low slope alluvial fans (Allen Hayden, Natural Channel Design, personal communication). This involved armoring steeper (≈10 percent) channel sections with cross vane rock weirs, also known as grade stabilizers, a technique most often used in stream restoration (Napper 2006, Yochum 2014). Robichaud et al. (2000) reviewed these features previously and rated them good to fair by three survey respondents. Currently, monitoring of this technique is ongoing; however, its relatively low cost and rapid installation could make it a valuable tool for postfire restoration when risks to values are high.

Road Treatments

Where roads meet channel crossings, teams often anticipate damage to culverts and roads. One common road treatment in the Southwest is to temporarily remove culverts and close roads to allow unhindered passage of flows until postfire hydrology has recovered (Foltz et al. 2009). Ditch clearing and armoring is another common postfire treatment and involves upgrading roadside drainage ditches by removing debris and adding protective rocks to prevent culvert plugging (Napper 2006). Other techniques for protecting roads at channel crossings include increasing culvert size, armored rolling dips, end walls, or outsloping (see Napper 2006 for a comprehensive list). Their effectiveness has not been tested systematically during high runoff events and is beyond the scope of this publication (Foltz and Robichaud 2013).

Conclusions and Management Recommendations

Erosion and runoff can increase dramatically postfire in the Southwest when high burn severity, high rainfall intensity, and steep slopes converge. When treatments are needed, encouragingly, postfire funding over the last 20 years has shifted toward the increased use of more effective mitigation techniques. While these tools can reduce the risk of flooding and erosion, they do not eliminate risk and can become overwhelmed under adverse conditions.

- In many instances, BAER program management goals, to protect values at risk before the first damaging storm, are achieved by closing burned areas and allowing for natural recovery. This action is often preferable due to its low cost and relative ease of implementation.

- When important values are at high risk, wood shred mulching or straw mulching are most effective at reducing hillslope erosion but costs, speed of implementation, wind redistribution, and natural recovery should be considered.

- The most effective methods for reducing risks using channel treatments involve removing debris. This can prevent debris from becoming entrained in runoff, thus reducing the likelihood of downstream infrastructure plugging and failure.

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