CSIRO PUBLISHING

International Journal of Wildland Fire **2014**, *23*, 929–944
http://dx.doi.org/10.1071/WF13192

A synthesis of post-fire Burned Area Reports from 1972 to 2009 for western US Forest Service lands: trends in wildfire characteristics and post-fire stabilisation treatments and expenditures

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Abstract. Over 1200 post-fire assessment and treatment implementation reports from four decades (1970s–2000s) of western US forest fires have been examined to identify decadal patterns in fire characteristics and the justifications and expenditures for the post-fire treatments. The main trends found were: (1) the area burned by wildfire increased over time and the rate of increase accelerated after 1990; (2) the proportions of burned area assessed as low, moderate and high burn severity likely have remained fairly constant over time, but the use of satellite imagery that began *c*. 2000 increased the resolution of burn severity assessments leading to an apparent decreased proportion of high burn severity during the 2000s; (3) treatment justifications reflected regional concerns (e.g. soil productivity in areas of timber harvest) and generally reflected increased human encroachment in the wildland–urban interface; (4) modifications to roads were the most frequently recommended post-fire treatment type; (5) seeding was the most frequently used land treatment, but declined in use over time; (6) use of post-fire agricultural straw mulch has steadily increased because of proven success; and (7) the greatest post-fire expenditures have been for land treatments applied over large areas to protect important resources (e.g. municipal water sources).

Additional keywords: BAER, Burned Area Emergency Response, erosion control, post-fire assessment, rehabilitation, treatment expenditure, values-at-risk.

Received 15 November 2013, accepted 19 May 2014, published online 4 September 2014

Introduction

Wildfires have always been part of important natural processes that contribute to the ecology of the western US. In recent decades, substantial increases in wildfire activity have resulted in greater wildfire frequency, longer wildfire durations and seasons (Westerling *et al.* 2006), and greater area burned per fire (Stephens 2005), compared to historic fire regimes. There is a strong link between climate and area burned (Littell *et al.* 2009; Holz *et al.* 2012). Driven by recent global climate change and, in several ecosystems, high levels of fuel accumulation due to past wildfire suppression policy (Mouillot and Field 2005) and beetle-killed trees, the trend in western US forest fires is towards larger and more catastrophic events (Keane *et al.* 2002; Stephens 2005; Running 2006; Westerling *et al.* 2006; NIFC 2013). However, in the woody sagebrush scrublands that dominate large portions of the Great Plains and canyon lands of the western US, no overall upward trend in area burned has occurred (Baker 2013).

High-severity fires not only consume or deeply char all vegetation, but also affect the physical properties of soil. These changes alter watershed responses to rainfall, causing increased runoff, erosion and downstream sedimentation (DeBano *et al.* 1998; Neary *et al.* 2005; Úbeda and Outeiro 2009). The magnitude of these post-fire runoff and erosion responses is a function of soil burn severity, topography and the occurrence of hydrologic events. When a major, and particularly high-intensity, rainfall event follows a large, high burn severity fire, the runoff, peak flows, flooding and erosion are likely to be orders of magnitude greater than the pre-fire response to the same rain event (DeBano *et al.* 1998; Neary *et al.* 1999, 2005; Moody and Martin 2001). Mitigating the threats to public safety, property, infrastructure, cultural sites, natural resources and water quality from these secondary fire effects is an integral part of wildfire response in the western US (Robichaud and Ashmun 2013). Efforts to predict and mitigate the risks from secondary fire effects are catalogued in the US

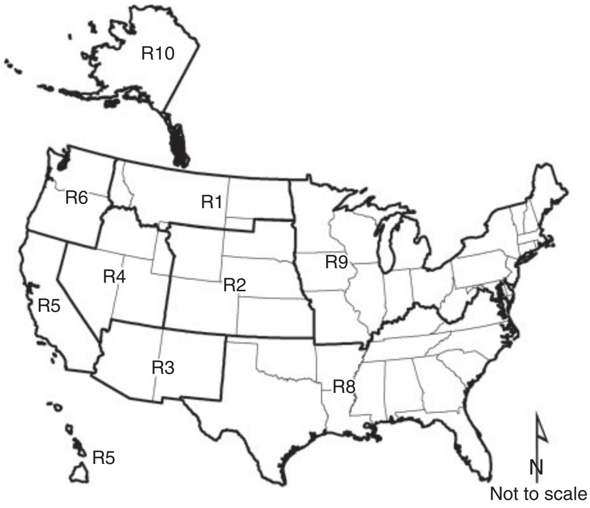

Fig. 1. USDA Forest Service administrative regions (modified from USDA Forest Service 2013).

Forest Service (USFS) Burned Area Reports that have been made over the past four decades.

The first Burned Area Reports on post-fire emergency watershed stabilisation and rehabilitation were prepared in the 1960s and early 1970s. The funds for these early post-fire watershed rehabilitation projects were obtained from fire suppression accounts, emergency flood control programmes or appropriated watershed restoration accounts. In 1974, a formal authority for post-fire rehabilitation activities, the Burned Area Emergency Rehabilitation (BAER) programme, was authorised to evaluate burn severity and treatment options, and established funding request procedures. In 1988–89, BAER policies and procedures were codified in the Forest Service Manual and the BAER Handbook, which standardised the assessments and reports filed within the programme.

The current Burned Area Emergency Response (BAER – same acronym with a new, more accurate word for the letter 'R') programme is an interagency effort involving four land management agencies within the US Department of Interior and US Department of Agriculture, Forest Service. The post-fire assessment protocols and Burned Area Reports examined in this study are specific to the USFS implementation of the BAER programme in the western US because the majority of the wildfires that have been evaluated through the BAER programme occurs on USFS land and of these, 1246 out of 1260 Burned Area Reports were from USFS Regions 1–6 (Fig. 1).

The BAER programme supports a limited range of post-fire activities: (1) identify post-wildfire threats to human life and safety, property and critical natural or cultural resources, and (2) take appropriate, immediate action to manage risks (FSM 2523.02, USDA Forest Service 2012). Assessments are conducted on burned areas following wildfires larger than 200 ha in size (FSM 2523.03, USDA Forest Service 2012), and are then summarised and reported using the Burned Area Report (US government form FS-2500–8). Burned area assessments are intended neither to provide a comprehensive evaluation of all fire and suppression damages nor to identify long-term rehabilitation and restoration needs (FSM 2523.1, USDA Forest Service 2012). Emergency stabilisation actions are normally temporary short-term measures that require little or no maintenance or that can be removed after objectives have been met (FSM 2523.2, USDA Forest Service 2012). BAER funds can be used only for emergency stabilisation for up to 1 year after fire containment, with the exception of monitoring treatment effectiveness, and maintaining, repairing or replacing emergency treatments where failure to do so would place significant risk on critical values, which can continue for up to 3 years following a fire (FSM 2523.03, USDA Forest Service 2012). This approach ensures that emergency stabilisation measures are effective and working as planned, but it precludes using the funding for longer-term rehabilitation.

Post-fire assessments and recommendations for actions and treatments are completed by *ad hoc* BAER teams that may include soil scientists, hydrologists, foresters, ecologists, engineers, archaeologists and other specialists as dictated by the location of the fire and values-at-risk. Once assembled, BAER teams: (1) assess fire-induced changes in the burned area; (2) estimate the risk for loss or damage posed by the post-fire conditions to the identified values-at-risk; (3) recommend cost-effective treatments to reduce the risk where possible and economically justified; and (4) implement selected treatments. BAER teams work under strict time constraints to accomplish the first three tasks within 2 weeks of fire containment, as public safety protection and burned area stabilisation measures need to be put into place as rapidly as possible. Their assessments, analyses, treatment recommendations and cost estimates are included in the Initial FS-2500–8 Burned Area Report (see sample Burned Area Report in the Supplementary material available online at http://www.publish.csiro.au/?act=view_file&file_id=WF13192_AC.pdf), which accompanies the request for funding of proposed treatments if needed. Because treatment implementation can take up to 1 year to complete, a BAER implementation team (separate from the BAER assessment team, although some members may be on both) oversees the treatment installation process. Inevitably, especially on large fires, the implementation process requires adjustments in terms of areas treated, contract costs and material substitutions. As changes affect costs, additional Interim FS-2500–8 Burned Area Reports may be filed. After 3 years, a Final FS-2500–8 Burned Area Report is filed, which contains the final costs, areas treated, implementation report and results of treatment effectiveness monitoring. The initial assessment information is included in all subsequent Burned Area Reports. Thus, the most complete post-fire assessment and treatment information is in the Final FS-2500–8 Burned Area Report, which is the Burned Area Report we used whenever possible for this study.

The Burned Area Report form includes fire characteristics, post-fire threats, values-at-risk, management objectives, treatment recommendations and cost estimates, analysis of expected treatment effectiveness, and a monitoring plan (FSM 2523.1, USDA Forest Service 2012). Although the Burned Area Report form has changed over the years, nearly all versions contain the fire name, location, dates of fire start and containment, size of the burned area and suppression cost. The affected watershed(s) is identified and described in terms of vegetation, soils, geology and stream channels. The post-fire conditions are generally described as the proportions of burned area designated as low, moderate and high burn severity and the estimated proportion of water-repellent soil (Parsons *et al.* 2010). Erosion hazard ratings based on a 2–5-year design storm and estimates of potential runoff, peak flows, erosion and sediment yields are made using various prediction models (Robichaud and Ashmun 2013). Values-at-risk for damage – specifically life, property, threatened and endangered species, water quality and soil productivity – are identified. The Burned Area Report describes the watershed emergency and justifies the need (or not) for immediate stabilisation treatments, as well as the estimated probabilities of their success. The report also provides treatment costs and an economic rationale for treatment implementation by estimating the costs of the potential losses that may occur if no action is taken (see sample Burned Area Report in the Supplementary material).

Burned Area Report information selected for analysis

The breadth of information contained in the Burned Area Reports, particularly in the forms used for the past 15 years, is extensive and not easily examined within a single study. We decided to focus on changes over time in fire size and burn severity, post-fire treatment selections and expenditures incurred in post-fire assessment and treatments.

Fire size and burn severity

The area within the fire perimeter generally has been reported as representing the fire size although this area is not burned throughout to the same degree. Instead, most wildfires leave a mosaic of unburned as well as low, moderate and high severity burned areas in various proportions and with variable levels of ‘patchiness’, or variation in spatial distribution within the fire’s perimeter (Lentile *et al.* 2006).

In recent years, an attempt has been made to standardise severity definitions and classifications as they pertain to fire and its effects (Parsons *et al.* 2010). The term ‘severity’ is often used inconsistently, and fire severity and burn severity are regularly used interchangeably when describing wildfire effects on post-fire environments (Jain 2004; Lentile *et al.* 2006; French *et al.* 2008). Fire severity is defined as a measure of the immediate and direct effects of fire on the environment (Lentile *et al.* 2006; French *et al.* 2008); whereas burn severity is defined by the degree to which an ecosystem has changed owing to the fire (Morgan *et al.* 2001; Lentile *et al.* 2006; French *et al.* 2008). Although post-fire assessments and Burned Area Reports use the term ‘burn severity’ to describe the magnitude of ecological change caused by fire, newer resources, such as the ‘Field Guide for Mapping Post-fire Soil Burn Severity’ (Parsons *et al.* 2010), focus on the condition of the soil to classify burn severity. Burn severity is often assessed by comparing pre- and post-fire vegetative and soil characteristics using satellite imagery and ground measurements (Parsons *et al.* 2010). Near-infrared and mid-infrared bands from the Landsat satellite sensor are used to calculate the Normalised Burn Ratio (NBR) for pre- and post-fire satellite images and the differences in the pre- and post-fire NBR values to determine the dNBR of each pixel in the image (Orlemann *et al.* 2002). The dNBR values are categorised into unburned, low, moderate and high burn severity and shown on a Burned Area Reflection Classification (BARC) map (Clark and Bobbe 2006). Ground assessments include post-fire vegetative characteristics, such as aboveground vegetation consumption, mortality and scorch, together with an estimate of potential recovery (Morgan *et al.* 2001), and soil characteristics, based on char depth, ash colour, bare soil exposed, organic matter and fine root loss, altered soil structure, reduced infiltration and soil water repellency (Ryan and Noste 1985; DeBano *et al.* 1998; Neary *et al.* 1999, 2005; Parsons *et al.* 2010). Given that the soil components of burn severity affect post-fire runoff, erosion and sedimentation potential more than the vegetative components, the BAER teams focus more specifically on assessing *soil* burn severity (Robichaud and Ashmun 2013).

Post-fire treatment justifications and selections

Treatments are categorised into four groups: (1) protection of public safety, (2) land, (3) channel and (4) road and trail (Napper 2006). All treatments aim to mitigate adverse effects from the burned area on values-at-risk, such as life, property, and critical natural and cultural resources. Public safety treatments, such road closures, flood warning systems and signage are used to protect the public from hazards such as flooding, dangerous trees, falling rocks and landslides. Land treatments stabilise burned soils by providing ground cover, reducing erosion and trapping sediment, and may also be implemented to minimise an influx of invasive plants. Channel treatments reduce channel down-cutting, slow water velocity, trap sediment and help maintain channel characteristics. Road and trail treatments improve the drainage capacity to handle potential increased flows and debris from burned areas.

Not all treatments are equally effective and their effectiveness can vary by region. In the 2000s, many treatment effectiveness studies were carried out (e.g. Beyers 2004; Raftoyannis and Spanos 2005; Robichaud *et al.* 2006; Wagenbrenner *et al.* 2006; Yanosek *et al.* 2006; deWolfe *et al.* 2008; Robichaud *et al.* 2008; Dodson and Peterson 2009; Foltz and Copeland 2009; Foltz *et al.* 2009; Robichaud *et al.* 2010; Stella *et al.* 2010; Prats *et al.* 2012; Robichaud *et al.* 2013*a*, 2013*b*). The findings from these and other studies support the development of new post-fire treatment products and application techniques, which in turn are evaluated for their effectiveness (Table 1) (Napper 2006).

Post-fire assessment and treatment costs

Although it is known that expenditures within the BAER programme have increased over time, there has been little analysis of the driving factors. Given the much larger costs of fire suppression compared to post-fire response costs it is not surprising that fire suppression expenditures, which have steadily increased since the mid-1980s, are much better understood (Calkin *et al.* 2005; Prestemon *et al.* 2008; Abt *et al.* 2009). The increase in suppression costs is mostly due to the increase in area burned, not the increase in suppression cost per unit area (Calkin *et al.* 2005; Liang *et al.* 2008). In addition, a small number of large fires are generally responsible for most of the area burned (Cramer 1959; Minnich and Chou 1997; Heyerdahl *et al.* 2001; Rollins *et al.* 2001) and consequently the amount of money spent on suppression. Although there is an expectation that post-fire response expenditures are increasing for the same reasons as the suppression costs, this has not been well studied.

Robichaud *et al.* (2000) compiled a database (BAERDAT) of Burned Area Reports from 470 fires (321 had post-fire treatments) that occurred in 1973–98 in the western US (USFS

Table 1. Frequently used post-fire treatments by category
Robichaud *et al.* (2000); Napper (2006); Foltz and Copeland (2009); Robichaud *et al.* (2010)

Category	Treatment	Description
Road	Armouring	Covering road, hillslope surface or ditch with aggregates and rocks to protect the surface
	Culvert modifications	Upsizing existing culverts; armouring inlet and outlet areas; attaching metal end sections
	Culvert removal	Removing cross-drain culverts that are too small (≤60 cm (24 inch)) for expected increased flows
	Culvert risers	Vertical extension of upstream culvert to sieve debris and to allow passage of water
	Debris racks or deflectors	Barrier (trash rack) across stream channel to hold debris and keep culverts open
	Low-water stream crossing	Temporary fords and low-water overflows when culverts cannot handle increased flows
	Out-sloping	Shaping a road surface to divert water off the surface to the road fill
	Overflow structures	Structures to control runoff across the road surface and to protect the road fill
	Road closure	Closing roads with gates, jersey barriers, barricades, signs and closure enforcement
	Rolling dips or water bars	Road grade reversal to direct surface flow across the road
	Storm patrol	Checking and cleaning drainage structure inlets between or during rain events
Land	Contour-felled logs (LEB)	Burned tree trunks installed on slope contour to trap sediment
	Silt fences	Geotextile fabric installed to form an upright fence to trap sediment
	Mulching	Materials spread over burned soil using aerial or ground application technologies
	Agricultural straw mulch	Wheat, barley and rice straw are most frequently used for post-fire mulching
	Hydromulch	Fibrous material (wood, paper, etc.), tackifiers and optional materials mixed with water into slurry for application; hydromulch adheres to the soil surface after it dries
	Wood shreds	Green or burned trees shredded by a horizontal grinder to produce a coarse mulch
	Wood strands (WoodStraw[A])	Narrow slats of wood of various lengths manufactured from scrap veneers
	Seeding (and fertilising)	Plant seeds spread over burned area; usually applied aerially; occasionally with added fertiliser
	Slash spreading	Trees and brush scattered over burned area
	Soil scarification or drilling	Tilling burned soils with a rake or disc to break up water-repellent soil layer
Channel	Channel-debris clearing	Removal of woody debris from channels
	Channel deflectors	Structures that direct stream flow away from unstable banks or high values-at-risk
	Check dams	Small structures placed perpendicular to the flow that store sediment on the upstream side; made of logs, straw bales, rocks, etc.
	Debris basins	Constructed basin to trap and hold sediment and debris
	Grade stabilisers	Structures installed at channel grade to decrease incision; made of rocks, logs and wood
	In-channel tree felling	Felled trees placed at a diagonal angle along channel reaches to slow flow and trap sediment
	Stream bank armouring	Rock reinforcement of the stream bank

[A]In this study, the wood strand material (WoodStraw) was produced by Forest Concepts, Inc., Auburn, WA.

Regions 1–6; Fig. 1). They found that USFS BAER programme expenditure increased by US$48 million (in 1998 dollars) from 1991 to 1998 primarily due to several large fires, whereas in the early 1980s annual expenditures were less than $2 million. Peppin *et al.* (2011) reviewed 380 Burned Area Reports from fires in the western US occurring between 1970 and 2007, primarily to analyse post-fire seeding trends. They found that 2000 to 2007 expenditures for post-fire seeding increased by 192% compared to the average spent during the previous 30 years. Although the percentage of burned area seeded decreased from 21% in the 1970s to only 4% during 2000–07, the cost per unit area seeded increased greatly due to the high costs of flight time for aerial seeding and specialised seed.

The objectives of this study were to review all available USFS Burned Area Reports from wildfires in the western US to determine trends in fire size, burn severity, treatment justification, types of treatments used, and expenditures on post-fire assessment and treatments. By examining post-wildfire trends we show how changes in the post-fire assessment process influenced treatment decisions and expenditure.

Methods

The existing BAERDAT (created in Microsoft Access) database used in Robichaud *et al.* (2000) was updated with the USFS Burned Area Reports database from 1999 to 2009. The resulting BAER Burned Area Reports contained a total of 1246 Burned Area Reports that were filed during 1972–2009 (http://forest.moscowfsl.wsu.edu/BAERTOOLS/baer-db, accessed 28 August 2013). We used accomplishment (after treatments were implemented) or final (when project is completed) Burned Area Reports whenever possible, to ensure that the treatments actually implemented were analysed. If no accomplishment or final Burned Area Report was available for a fire, an initial or interim Burned Area Report was used.

The elements of the Burned Area Reports that were analysed included: (1) total area burned and the proportional area of each burn severity class (low, moderate and high); (2) the identified values-at-risk (life, property, threatened and endangered species, water quality and soil productivity) and the economic justification of the post-fire treatments; (3) expenditure by three treatment (land, channel and road) and other (assessment, administrative and monitoring) categories; (4) expenditure by specific land treatment (contour-felled logs, agricultural straw mulch, hydromulch, wood strand mulch and seeding); and (5) a separate analysis of the 10 fires with the greatest expenditures for post-fire assessment and treatment. We included all Burned Area Reports, regardless of any treatment recommendations, for burned area, burn severity and economic justification analyses (points 1 and 2 above). Only the Burned Area Reports with actual treatment expenditures were analysed for post-fire expenditures, individual land treatments and most expensive fires (points 3, 4, and 5 above). To compare expenditures over time, all costs were converted to 2009 US dollars using the Consumer Price Index (Federal Reserve Bank of Minneapolis, see www.minneapolisfed.org, accessed 17 April 2014).

Burned area and burn severity

The reported fire areas were summed annually. The proportions of the areas burned according to each of the three burn severity classifications compared to the total area burned were calculated to determine the percentage of burned area in each burn severity class (low, moderate and high) for each fire. The decadal mean percentages of area burned in each burn severity classification were calculated and analysed for changes over time. The BAER protocol for determining soil burn severity changed in 2000 when quantitative analysis of satellite imagery replaced aerial observations. Satellite imagery data used in the Monitoring Trends in Burn Severity (MTBS) project (Eidenshink *et al.* 2007; MTBS Project, www.mtbs.gov/dataaccess.html, accessed 28 August 2013) were also compared to the values derived from the Burned Area Reports.

Justification of post-fire treatment needs

Post-fire treatments are justified by comparing the cost of no action given a damaging storm event (i.e. the economic value of damage or loss to the identified values-at-risk) *v.* the cost of the proposed treatment and expected reduction of damage or loss if a damaging storm event occurs. The percentage of Burned Area Reports that cited each of the five value-at-risk categories (life, property, threatened and endangered species, water quality and soil productivity) was compared by decade. The total post-fire expenditure was compared to the projected economic loss if no action was taken and these data were compared by decade to discern changes over time; however, this comparison was limited to approximately half (602 of the 1246) of the Burned Area Reports used in the study because only those reports that included monetary values for both the values-at-risk and treatment expenditures could be included.

Post-fire treatment expenditure by category

BAER programme treatment expenditures were categorised into road, land or channel treatments (Table 1), or other (assessment, monitoring and administration). Treatment category frequency (the percentage of all the Burned Area Reports that prescribed treatment(s) of each category), total treatment category expenditures, and treatment category expenditure per fire and per unit area were calculated. Mean treatment category values were calculated by decade for land, channel and road categories and analysed for changes over time.

Individual land treatment expenditures

When the Burned Area Reports from the 1970s–1998 were analysed, Robichaud *et al.* (2000) found that over two-thirds of the treatment expenditures were for land treatments, with the greatest expenditures being made for contour-felled logs, agricultural straw mulch and seeding treatments. Since 2000, new

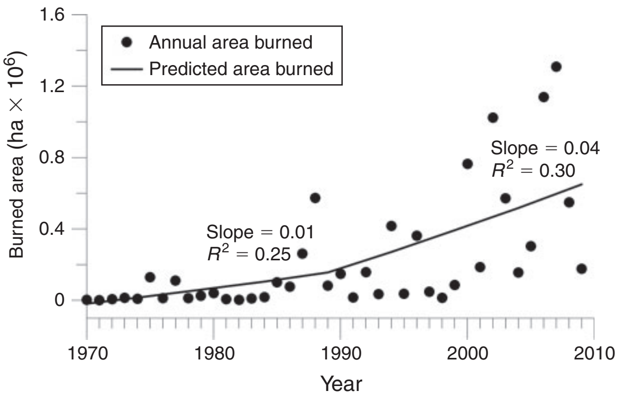

Fig. 2. Total burned area by year from 1970 to 2009 as reported in Burned Area Reports. Note the predicted (loess fit) line for the 1970–89 data has a slope of 0.01 and the predicted (loess fit) line for 1990–2009 data has a four-times-greater slope of 0.04.

land treatments have been introduced, such as hydromulch and wood strand mulch, and changes in techniques for producing and applying treatments, such as aerial application of mulches, have influenced the use and expense of land treatments. For this study, contour-felled logs (also called log erosion barriers, or LEBs), agricultural straw mulch, hydromulch, wood strand mulch and seeding (occasionally combined with fertiliser) were selected for investigation. Frequency of use, total expenditure, and expenditure per individual fire and per unit area were calculated for each of the individual treatments. Individual treatment costs per year and per unit area were calculated and decadal means were compared to determine changes over time.

Most expensive fires for treatment expenditure

The 10 fires on USFS lands with the highest BAER programme costs were analysed separately to determine the influence of these large fires on the overall BAER programme. The area burned, total BAER expenditure and proportion of the total annual BAER expenditure that was encompassed by the individual fire's BAER expenditure were compared from these 10 fires. Pearson correlation coefficients were calculated between the area burned and expenditure for the top 10 most expensive fires (SAS 2003).

Statistical analyses

Annual area burned was plotted using a loess fit (locally-weighted quadratic least-squares regression) to estimate the trend in annual burned area. In addition, the data were frequently divided into decadal groupings to compare changes over time. Differences among decadal mean values were compared using the least-squares means. A Tukey adjustment was used to compare multiple least-squares means at a significance level of $\alpha = 0.05$ (SAS 2003).

Results and discussion

Burned area and severity

The annual total area burned by wildfire has increased over time, with the rate of increase from 1990 to 2009 being nearly three times greater than from 1970 to 1989 (Fig. 2). Similar wildfire trends have been reported by other researchers working with

Table 2. Proportions of land classified as unburned, low, moderate and high burn severity within fire perimeters in the western US by decade

Data from the Monitoring Trends in Burn Severity (MTBS) project were used to calculate the proportions for all fires on western US lands and for fires on western US Forest Service lands (www.mtbs.gov, accessed 28 August 2013). Unburned area within the fire perimeter was not reported in the Burned Area Reports and was generally included as low burn severity

Decade	Unburned (%)	Low (%)	Moderate (%)	High (%)
Based on MTBS summary data for all fires[A] on western US lands				
1984–89	24	40	22	14
1990–99	20	45	24	11
2000–09	20	39	26	15
Based on MTBS summary data for fires[A] on western US Forest Service lands				
1984–89	27	29	22	22
1990–99	25	39	22	14
2000–09	18	39	27	16
Based on the Burned Area Reports from western US Forest Service fires assessed by BAER teams[B]				
1980–89		35[A]	33[A]	32[A]
1990–99		41[A]	30[A]	29[A]
2000–09[C]		51[A]	33[A]	16[A]

[A]All fires ≥405 ha (1000 acres) included.

[B]Decadal mean values for the Burned Area Reports within a column (within a burn severity class) followed by the same superscript letter are not significantly different based on Tukey comparisons ($P < 0.05$).

[C]Burn severity assessment methodology changed *c*. 2000 when BAER teams began to use burn severity maps derived from pre- and post-fire satellite data as the starting point for burn severity assessments.

other data sources and time divisions. For example, Stephens (2005) reported an increase in area burned from 1940 to 2000 and Westerling *et al.* (2006) reported that the annual area burned during 1987–2003 was more than six and a half times the average for 1970–1986.

The proportion of burned area in each burn severity class, as reported in the Burned Area Reports, was similar in the 1980s and 1990s (Table 2). However, when comparing the change from the 1990s to the 2000s, the proportion of low burn severity significantly increased from 41 to 51% and the proportion of high burn severity significantly decreased from 29 to 16%, whereas the proportion of moderate burn severity was virtually unchanged (Table 2). Until the last decade, BAER assessment teams mostly relied on low-level aerial survey (helicopter) to map general areas of concern followed by some ground survey and observation when possible. In addition, there was no consistent definition of 'severity' or standardised methods for determining the burn severity (Lentile *et al.* 2006). Since 2000, the BAER programme has refined the process used to classify burn severity within the perimeter of a wildfire to take advantage of the BARC maps produced from satellite imagery (Orlemann *et al.* 2002). BAER teams use field observations and measurements to make needed adjustments in the classification parameters used to produce the BARC map so that the final burn severity map more closely reflects the 'soil burn severity' (Parsons *et al.* 2010). The change in methodology from broad visual assessments to quantitative analysis of remotely sensed data made it incongruous to compare the pre- and post-2000 proportions of burned area in each burn severity class reported in the Burned Area Reports.

Recently, the MTBS Project – a joint venture of between the Earth Resources Observation Systems (EROS) Data Center (USDI Geological Survey) and the Remote Sensing Applications Center (RSAC) (USDA Forest Service) – has used archived satellite data to map the burn severity within fires across all lands of the US since 1984 (Eidenshink *et al.* 2007; www.mtbs.gov/dataaccess.html). Given that the same methodology for classifying burn severity was applied to all these data, changes over time can be quantitatively assessed. Using the MTBS data, the proportion of burned area classified as unburned, low, moderate or high burn severity were determined for each decade available (1984–89, 1990–99, and 2000–09) for all fires greater than 405 ha (1000 acres) in the western region of the US and specifically for fires that burned western US Forest Service lands (Table 2). A data summary provided by the MTBS Project reported that (a) there was no consistent trend towards more high severity across all fires and (b) that large fires (>20 230 ha [50 000 acres]) had slightly higher proportions of high burn severity in the last decade (MTBS Project 2009). Given the consistent methodology applied to create the MTBS data, the changes in the proportions of low and high burn severity after wildfires in the last decade were more accurately assessed by the MTBS data than by the Burned Area Reports.

The proportions of burned area in each of the burn severity classifications reported in the Burned Area Reports after 2000 were not directly comparable to MTBS data for the same period despite being generated by a similar analysis of pre- and post-fire satellite data. The satellite images used to generate the MTBS data were taken at different times relative to the fire (pre-fire high growth period and the first post-fire high growth period – generally ~1 year after the fire) than those used to create the BARC maps for the BAER teams (pre-fire high growth compared to immediate post-fire). In addition, the MTBS database, even when filtered for USFS lands only, includes more fires than those assessed by USFS BAER teams. BAER teams are not called in to assess small fires, prescribed

Table 3. The proportion of Burned Area Reports that selected each of the five values-at-risk categories as justification for post-fire treatment expenditures by decade or by region

Burned Area Reports often place values-at-risk in more than one justification category, such that the sum of the percentages may exceed 100%. Regional values are for the four decades combined. Values in bold highlight those individual values that are greater than the mean of the six regional values. T and E species, Threatened and Endangered species

	Values-at-risk category				
	Life (%)	Property (%)	T and E species (%)	Water quality (%)	Soil productivity (%)
Decade					
1970s	3	41	1	39	24
1980s	2	36	6	40	31
1990s	16	45	19	44	42
2000s	42	61	25	40	63
Region					
1	48	**28**	39	**61**	24
2	43	4	35	55	17
3	42	11	25	40	23
4	**58**	**29**	36	**63**	**36**
5	**59**	16	**45**	45	**32**
6	**56**	**26**	**59**	**64**	**31**
Mean	51	19	40	55	27

burns or fires that pose little risk of damage from post-fire responses, but these fires were included in the MTBS data. Consequently, greater proportions of unburned and low burn severity were, as expected, reported in the MTBS Project data as compared to the Burned Area Reports. In the 2000s, the MTBS data showed that the combined proportion of unburned and low burn severity was 59% on all western fires and 57% on USFS fires, both of which were slightly more than the 51% low burn severity from the Burned Area Reports. However, the proportion of high burn severity was the same (16%) for the MTBS data for USFS lands and the Burned Area Reports (Table 2), which reflects the fact that BAER teams assessed nearly all the fires that included areas burned at high severity.

Justification of post-fire treatment expenditure

Of the five value-at-risk categories (life, property, threatened and endangered species, water quality and soil productivity), property, water quality and soil productivity were consistently cited as justification for treatment expenditures during the four decades of the study (Table 3). Although both property and soil productivity were cited more often in the last decade, water quality has been consistently named as a value-at-risk in ~40% of the Burned Area Reports in all decades. Comparing the 2000s to the previous three decades, more wildfires occurred in or near the wildland–urban interface (WUI) (Calkin *et al.* 2005; Prestemon *et al.* 2008) and there was a four-fold increase in the number of fires receiving treatments (from 157 to 642) whereas the number of fires with no-treatment recommendations only increased by ~50% (from 75 to 130) (Fig. 3). Although protection of property and soil productivity were the primary justifications for treatment expenditures in the 2000s, protection

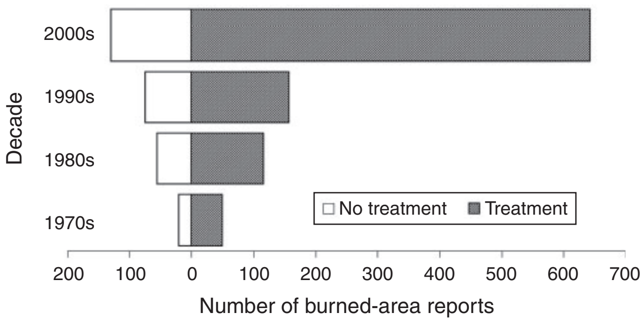

Fig. 3. The number of Burned Area Reports recommending no post-fire treatment (no shading, left-facing bar) and treatments (shading, right-facing bar) in each of the four decades of this study.

of life (public safety) increased 24%, rising from 16% in the 1990s to 42% in the 2000s (Table 3).

Threatened and endangered species was least frequently cited as a value-at-risk to justify post-fire treatments, but this varied significantly among USFS Regions. USFS Region 6 (Oregon and Washington) justified post-fire treatments for protection of threatened and endangered species in 59% of their reports – the highest of any region – and USFS Region 5 (California) was second with 45% (Table 3). Several species of salmonid fish are listed as threatened or endangered in the Pacific salmon habitats of the western US (excluding Alaska), which are mostly located in Oregon, Washington and northern California (Augerot and Foley 2005). Protection of bull trout (*Salvelinus confluentus*), a threatened salmonid species mostly found in Idaho, Montana, Nevada, Oregon and Washington, influenced post-fire treatment justifications in USFS Regions 1,4 and 6, which encompass most of their habitat (USDOI Fish and Wildlife Service 2013). Bull trout have exacting habitat demands, such as cold water temperatures and very low amounts of silt, both of which can be affected by wildfire. Protection of bull trout habitat likely contributed to the frequent selection of water quality as a treatment justification in the three regions (Table 3).

As part of the economic justification for post-fire treatments, their costs were compared to the expected monetary loss if no action was taken. Most (98%) of the Burned Area Reports showed the monetary value of the potential loss or damage to values-at-risk was more than 15 times greater than the total treatment expenditures ($y = 15.5x$, $R^2 = 0.48$) (Fig. 4). Some values-at-risk, such as life and public safety, were too important to be subjected to economic justification. Other non-market values-at-risk, such as water quality, habitat for threatened and endangered species, and culturally significant areas, were not easily assigned a value in economic terms. Generally, members of the assessment team, sometimes with the help of an economist, used their collective professional judgment to assign a monetary value to a non-market value-at-risk for comparison in the treatment cost evaluation.

Of the nearly 600 Burned Area Reports that contained monetary value of both the values-at-risk and the treatments implemented to protect them, 15 had treatment costs that exceeded (by 6–500% or US$5000–$3.5 million) the cost reported for the value-at-risk (Fig. 4); ten of the 15 Burned Area

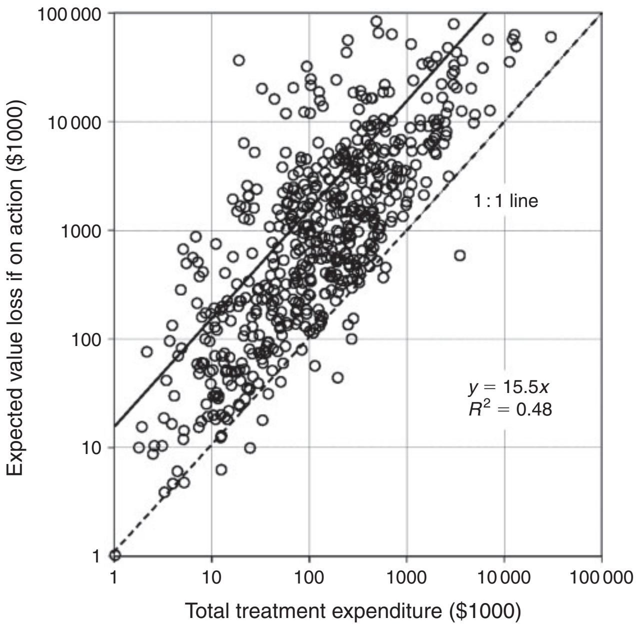

Fig. 4. The costs of post-fire treatments were compared to those of the potential damage or loss to the identified values-at-risk if no action (no treatment) was taken. The dashed 1 : 1 line indicates equal cost of treatment and loss of values-at-risk. The solid regression line indicates that values-at-risk amounted to 15 times the cost of treatments. In only 15 (2%) of the Burned Area Reports were recommended treatments more expensive than the assessed value of the values-at-risk (data point below the 1 : 1 line). All monetary values are converted to 2009 US dollars. Logarithmic scale is used for both axes.

Reports were for fires that occurred in the 2000s. Given that approval of any post-fire treatment implementation plan is based on the justification, values-at-risk, expected value loss and estimated treatment expenditure, the justifications for these treatments had to carry more weight than the economics alone for the treatment projects to be approved. Common elements among these 15 reports were: (1) high costs of monitoring (mostly for noxious weeds); (2) high assessment and administration costs because of high public interest; and (3) difficulty in applying monetary values for risk factors. Recently, there have been efforts to develop guidelines to systematically formulate an implied minimum value of non-market values-at-risk in the post-fire environment (Calkin *et al.* 2007, 2008); however, these economic tools were unavailable during the years considered in this study.

Post-fire treatment expenditure

Frequency of implementing post-fire treatments increased during the study period and 91% of the Burned Area Reports had some post-fire treatment expenditure in the 2000s – up from 65 to 70% of the reports in the three prior decades. Total post-fire treatment expenditure followed the same trends and increased dramatically from one decade to the next with the largest decadal increase occurring in the 2000s (Table 4). Total expenditure per fire followed a slightly different trend: BAER spending per fire was approximately the same in the 1970s and 1980s, increased by ~50% from the 1980s to the 1990s (US$296 000–$433 000 per fire), and remained approximately the same in the 2000s (Table 4). Given that the number and treated area of fires tended to increase over time and that post-fire expenditure per fire stayed nearly the same during the 1990s and 2000s, it is not surprising that the post-fire expenditure per unit area decreased in the same interval (Table 4). This was likely due to a combination of more standardised assessment procedures, more rigorous education of post-fire assessment teams and the restricted budgets of the last decade. The particularly high expenditure per unit area in the 1970s (Table 4) resulted from the uncharacteristically intense treatment of 4000 ha for two 1976 fires – Crum Canyon (Okanogan–Wenatchee NF, Washington) and Skinner Mill (Shasta–Trinity NF, California) – which was motivated by severe post-fire flooding in nearby areas having occurred a few years earlier.

BAER assessment

It is difficult to determine the BAER assessment expenditures (i.e. BAER team costs) in the 1970s and 1980s as they were not reported separately from other categories. Starting in the 1990s, more than 70% of the Burned Area Reports included 7–10% of the post-fire expenditure to pay for the work and support of the BAER team (Table 4). Average expenditure of BAER assessment per fire peaked in the 1990s (US$57 000 per fire), but as budgets were reigned in during the past decade the cost per fire dropped to ~$37 000 per fire even though the total BAER costs tripled (Table 4). In the 2000s, it is likely that per fire BAER team expenditures were reduced by the use of satellite imagery for post-fire burn severity mapping, which decreased the amount of helicopter flight time and BAER team member time committed to burn severity mapping. Increased training and experience of many BAER team members has also increased the efficiency and expertise of BAER team members.

Public safety

Although protection of life and safety has always been the highest priority for BAER teams, treatments aimed at public safety never exceeded 5% of the decadal BAER expenditures. The proportion of Burned Area Reports that included public safety recommendations rose from 17% in the 1990s to 45% in the 2000s (Table 4), which coincides with the rapid expansion of the WUI in the western US. Public safety treatments often include mechanisms to restrict public access to areas that pose danger, provision for adequate warning of impending floods, and removal of hazardous trees from areas around trails, roads and recreation areas. Despite the importance of this category of treatments, the costs of implementing road closures, installing fences, gates and flood warning systems, and removing hazardous trees have been significantly less than for other treatments. Arguably, treatments that reduced flooding and erosion also contributed to public safety; however, this category was mostly applied to those treatments designed to reduce public exposure to hazards in the post-fire environment.

Land treatments

During all four decades covered by this study, land treatments were applied most often and accounted for the largest proportion of post-fire treatment expenditures (57–72%).

Table 4. The proportion of Burned Area Reports, expenditure, percent of total expenditure and mean expenditure by fire disaggregated by treatment category and decade

All expenditures reported in 2009 US dollars. Among treatment categories not all treatment categories were used in the Burned Area Reports before 2000; this is indicated by n.a. (i.e. not available)

Treatment category		Decade			
		1970s	1980s	1990s	2000s
Total	Proportion[A] (%)	66	65	71	91
	Total expenditure ($)	11 100 000	32 900 000	71 000 000	310 800 000
	Expenditure per fire ($)	242 000	296 000	433 000	444 000
	Expenditure per unit area ($ ha^{-1})	73	46	88	72
BAER assessment	Proportion of reports[B] (%)	n.a.	n.a.	74	84
	Category expenditure ($)	n.a.	n.a.	6 900 000	21 700 000
	Portion of total expenditure (%)	n.a.	n.a.	10	7
	Category expenditure per fire ($)	n.a.	n.a.	57 000	37 000
Public safety	Proportion of reports (%)	n.a.	n.a.	17	45
	Category expenditure ($)	n.a.	n.a.	700 000	16 100 000
	Portion of total expenditure (%)	n.a.	n.a.	1	5
	Category expenditure per fire ($)	n.a.	n.a.	24 000	52 000
Land	Proportion of reports (%)	98	91	82	73
	Category expenditure ($)	6 300 000	23 800 000	48 000 000	188 300 000
	Portion of total expenditure (%)	57	72	68	61
	Category expenditure per fire ($)	140 000	235 000	356 000	371 000
Road	Proportion of reports (%)	33	58	55	64
	Category expenditure ($)	2 700 000	6 100 000	9 000 000	69 200 000
	Portion of total expenditure (%)	24	19	13	22
	Category expenditure per fire ($)	179 000	95 000	100 000	155 000
Channel	Proportion of reports (%)	37	49	51	24
	Category expenditure ($)	2 100 000	2 600 000	6 300 000	7 800 000
	Portion of total expenditure (%)	19	8	9	3
	Category expenditure per fire ($)	122 000	48 000	76 000	46 000
Monitoring (implementation)	Proportion of reports (%)	n.a.	n.a.	n.a.	68
	Category expenditure ($)	n.a.	n.a.	n.a.	7 700 000
	Portion of total expenditure (%)	n.a.	n.a.	n.a.	2
	Category expenditure per fire ($)	n.a.	n.a.	n.a.	16 000

[A]Percentage of Burned Area Reports that included treatment expenditures.
[B]Percentage of Burned Area Reports that included this particular treatment category.

However, the proportion of Burned Area Reports that included land treatments decreased in each successive decade (98–73%), whereas total post-fire land treatment expenditures and mean expenditure per fire increased each decade (Table 4). These trends reflect the transition in terms of treatment from broadcast seeding, a relatively inexpensive land treatment and virtually the only land treatment used in the 1970s, to the use of both seeding and contour-felled log erosion barriers (higher cost due to labour-intensive installation) throughout the 1980s and 1990s, and the increasing use of more expensive aerially applied mulches in the past decade.

Road treatments

Road treatments were second in terms of treatment expenditure after land treatments, and unlike the latter, the proportion of Burned Area Reports that included recommendations for road treatments generally increased between the 1970s (33%) and the 2000s (64%). Total road treatment expenditures also increased between the 1970s (US$2.7 million) and the 2000s ($69.2 million) (Table 4). However, the proportion of decadal post-fire expenditure (24% in the 1970s and 22% in the 2000s) did not follow the same trend. Expenditures on road treatments increased from $9 million in the 1990s to $69 million in the 2000s; yet road treatment expenditures per fire only increased by ~50% over the same two decades (Table 4). This suggests that the increasing number and extent of wildfires of the past decade drove the increased spending on post-fire road treatments. The post-fire treatments implemented on the 2006 Tripod Complex Fires (Washington) cost over $30 million, the most spent on any one fire in this study; over $6.9 million (23%) of those expenditures were for road treatments.

Forest roads were generally unaffected by wildfire, but the increased runoff and peak flows that often occur after a fire led to damaged road water passage structures, such as culverts, and the road structure itself. Thus, the purpose of most post-fire road treatments was to improve the road drainage capacity to handle increased flows and debris from burned areas (Foltz *et al.* 2009). Given that road treatment costs and the potential losses to the values-at-risk (the roads) were based on well-known road construction costs, it was fairly straightforward to propose, justify and approve road treatment recommendations.

Channel treatments

Channel treatments were recommended in almost half of the Burned Area Reports in the 1980s and 1990s, but less than 10% of the post-fire expenditures were used for channel treatments (Table 4). In the 2000s, only a quarter of the Burned Area Reports recommended channel treatments and just 3% of the expenditures were used for them (Table 4). Expenditures per fire for channel treatments decreased from the 1990s to the 2000s (from US$76 000 to $46 000 per fire), yet the large increase in the number of fires resulted in increased channel treatment expenditures (from $6.3 to $7.8 million) during the same period.

The limited research on the effectiveness of emergency treatments to stabilise channels has been inconclusive (Robichaud *et al.* 2000). Check dams made of straw bales or log structures were found to be less costly and relatively easy to install, but were prone to failure and quickly filled with sediment, negating their effectiveness (Goldman *et al.* 1986; Collins and Johnston 1995; Storrar 2013). Larger, sturdier structures such as rock dams and gabions were generally more effective long-lived stabilisers, but were more costly and difficult to install (Heede 1970, 1981; Chiun-Ming 1985). In the past decade, as land treatments evolved to include aerial mulching, BAER teams often decided to treat hillslopes rather than channels. They reasoned that keeping the sediment on the hillslopes and out of the channels would be more successful and cost effective than installing channel treatments. As a result, there were more land treatments and fewer channel treatments in the 2000s.

Monitoring

Monitoring was not separately budgeted for until the last decade when more than two-thirds of Burned Area Reports included monitoring expenditures that totalled US$7.7 million (Table 4). Application of treatments, particularly land and road treatments, often involved multiple contractors and contracts with complex and geographically diverse specifications. Costs were incurred in administering these contracts and inspecting the materials used and the treated areas for contract compliance. The time needed for the processes of contracting, treating and verifying compliance extended beyond the tenure of the BAER assessment team and required personnel to be hired for these tasks. In addition, treatments were monitored for up to 3 years after the fire to ensure that they were maintained and performed as expected. Prior to 2000, post-fire treatment performance and effectiveness reports often consisted of images and qualitative descriptions of the treatment and treatment effectiveness (e.g. good ground cover, little rilling observed) (Robichaud *et al.* 2000). Given that quantitative evaluation of treatment effectiveness required measurement of rainfall characteristics and responses (e.g. amount of sediment per unit area) over several years, BAER teams often collaborated with research personnel to determine treatment effectiveness.

Individual land treatment expenditure

Seeding

Seeding was the most frequently used land treatment in each decade of the study. In the 1970s and 1980s more than 75% of all fires that received any treatment were seeded (Table 5). The proportion of fires treated with seeding fell to 68% in the 1990s and then decreased to 30% in the 2000s (Table 5). In the late 1990s, researchers and land managers began questioning the effectiveness of seeding for hillslope stabilisation, especially in the first post-fire year, when erosion and flooding are usually greatest. Several studies found that seeding reduced year 1 post-fire erosion for less than 25% of the rain events, but when favourable rainfall allowed the seeds to germinate and grow, seeding could effectively reduce erosion for 1 to 2 years (Dean 2001; Robichaud *et al.* 2006; Wagenbrenner *et al.* 2006; Groen and Woods 2008; Dodson and Peterson 2009; Peppin *et al.* 2011). Because of this research and the availability of stabilisation treatments that were more likely to be successful, seeding was recommended by BAER teams less often in the 2000s compared to earlier decades (Table 5). Despite being more selectively used, seeding remained the most implemented post-fire land treatment over the entire study period. Seeding's long history of use, relatively low cost and perceived success in reducing erosion from burned hillslopes made it an easy choice for remote hillslopes that qualified for post-fire treatment, especially in the early part of the decade when aerial application of mulches was not well proven.

Expenditures for seeding increased through the 1980s, decreased slightly in the 1990s and increased again in the 2000s. The large expenditures in the 1980s were due to the abnormally high cost of aerial seeding after two 1988 fires; US$2.3 million was spent to treat 9300 ha after the Clover Mist Fire in Wyoming and $1.1 million was spent to treat 8100 ha after the Brewer Fire in Montana. In the 2000s, seeding was prescribed for less than a third of the treated fires, yet total expenditures for seeding nearly doubled from the 1990s (Table 5). This increased expenditure for seeding treatments reflected the combined effects of the four-fold increase in the number of fires receiving post-fire treatments (Fig. 3) and a doubling of the cost of post-fire seeding per unit area in the 2000s compared to the 1990s (Table 5). This increase in cost per unit area was due to the high costs of flight time for aerial seeding and specialised seed mixtures.

Fertiliser and seeding

Fertiliser, when used as a post-fire treatment, was always applied in combination with seeds (but not *vice versa*). This treatment was used most often in the 1970s (20%) and decreased over time to less than 1% in the 2000s with expenditures being commensurate (Table 5). Fertilisation to facilitate seeded plant growth was never shown to be effective and did not justify the additional cost (Dean 2001; Robichaud *et al.* 2006; Dodson and Peterson 2009); thus, the treatment fell into disuse unless a specific need was known to exist.

Contour-felled logs

Contour-felled logs, also known as LEBs, were widely used in the 1990s; one-third of Burned Area Reports with treatment expenditures included contour-felled logs and 60% of the total land treatment expenditures (US$28.6 million of $48 million) were spent to apply contour-felled logs (Table 5). In 1994, $15.3 million (53% of the decadal total expenditure) was spent on contour-felled log treatment for two fires – Rabbit Creek

Table 5. The proportion (%) of Burned Area Reports that included the treatment category, the total expenditure on the treatment category, the mean expenditure per fire and per unit area disaggregated by treatment category and decade

All expenditures reported in 2009 US dollars. Among land treatment categories only the Burned Area Reports from fires that included post-fire treatment expenditures were analysed. Not all treatments were available in all decades; this is indicated by n.a. (i.e. not available)

Land treatment category		Decade			
		1970s	1980s	1990s	2000s
Seeding	Proportion of reports[A] (%)	76	78	68	30
	Total expenditure ($)	3 500 000	13 500 000	12 100 000	21 100 000
	Expenditure per fire ($)	99 000	155 000	108 000	100 000
	Expenditure per unit area ($ ha^{-1})	280	340	230	470
Fertiliser and seeding[B]	Proportion of reports (%)	20	11	4	<1
	Total expenditure ($)	2 200 000	2 900 000	1 300 000	1 418 000
	Expenditure per fire ($)	243 000	243 000	179 000	1 418 000
	Expenditure per unit area ($ ha^{-1})	290	210	110	280
Contour-felled logs	Proportion of reports (%)	2	19	33	7
	Total expenditure ($)	211 000	6 300 000	28 600 000	8 300 000
	Expenditure per fire ($)	211 000	300 000	529 000	173 000
	Expenditure per unit area ($ ha^{-1})	n.a.	800	920	1520
Agricultural straw mulch	Proportion of reports (%)	2	10	15	18
	Total expenditure ($)	<100 000	200 000	3 400 000	79 700 000
	Expenditure per fire ($)	4000	18 000	142 000	618 000
	Expenditure per unit area ($ ha^{-1})	150	3290	3000	2570
Hydromulch	Proportion of reports (%)	n.a.	n.a.	n.a.	5
	Total expenditure ($)	n.a.	n.a.	n.a.	41 000 000
	Expenditure per fire ($)	n.a.	n.a.	n.a.	1 171 000
	Expenditure per unit area ($ ha^{-1})	n.a.	n.a.	n.a.	5980
Wood strand mulch[C]	Proportion of reports (%)	n.a.	n.a.	n.a.	3
	Total expenditure ($)	n.a.	n.a.	n.a.	2 900 000
	Expenditure per fire ($)	n.a.	n.a.	n.a.	163 000
	Expenditure per unit area ($ ha^{-1})	n.a.	n.a.	n.a.	8390
Total land	Total expenditure ($)	6 300 000	23 800 000	48 000 000	188 300 000
	Expenditure per fire ($)	140 000	235 000	356 000	371 000

[A]Percentage of Burned Area Reports that included this particular treatment category.
[B]No fertiliser treatment was prescribed without seeding. Expenditure amounts include both the fertiliser and the seed.
[C]In this study, the wood strand material (WoodStraw) was produced by Forest Concepts, Inc., Auburn, WA, and was shipped to the sites where it was used.

Complex in Idaho ($9.3 million to treat nearly 13 000 ha) and Tyee Creek Complex in Washington ($6.0 million to treat 6100 ha). In the 2000s, contour-felled logs were prescribed for only 7% of the treated fires and most of these were in the early years of the decade. The precipitous decline in contour-felled log use was in response to research based on post-fire observations from nine wildfires in western US that occurred between 1998 and 2002, which showed contour-felled logs to be fairly effective as a post-fire runoff and erosion mitigation treatment for lower-intensity rainfall events but ineffective for high-intensity rainfall events (Wagenbrenner *et al.* 2006; Robichaud *et al.* 2008). Additionally, Robichaud *et al.* (2008) found that greater care was needed during installation, such as adding end berms and backfilling underneath each log, thus increasing the time per log and associated unit area costs in the 2000s (Table 5). These research findings were disseminated before formal publication through BAER team meetings and technical training sessions, and drastically reduced the use of contour-felled logs after 2003.

Agricultural straw mulch

The use of agricultural straw mulch as a post-fire stabilisation treatment has continuously increased from the 1970s to 2000s (2% to 18%), and in the last decade, only seeding was prescribed more frequently. Agricultural straw mulch has been found to be a highly effective post-fire stabilisation treatment (Kay 1983; Miles *et al.* 1989; Edwards *et al.* 1995; Wagenbrenner *et al.* 2006; Groen and Woods 2008; Robichaud *et al.* 2013*a;* 2013*b*), but its increase in the last decade was the result of not only its proven effectiveness in reducing runoff and erosion but also, and perhaps more importantly, the development of aerial application techniques for dry mulch material (Robichaud *et al.* 2010). Prior to 2000, the application rate for straw mulch was considered 'slow' as it depended on ground-based dispersal (Miles *et al.* 1989) and seeding was the only post-fire land treatment that could be aerially applied on remote and inaccessible hillslopes. However, when straw mulch was successfully applied by helicopters on some fires in 2000, it became a viable treatment for the inaccessible burned areas that are frequently encountered in the western US (Robichaud *et al.* 2010). With the increased use of agricultural straw mulch in burned areas it became apparent that even certified weed-free straw can bring non-native plant seeds into the burned area (Olliff *et al.* 2001; Graham 2003) and the resulting plants could be invasive and pervasive, and compete with native vegetation (Beyers 2004; Kruse *et al.* 2004).

Table 6. The 10 fires on USFS lands with the greatest post-fire expenditures

The name of the fire, location by state, year it occurred and burned area are included as well as the total post-fire expenditure for the individual fire and the proportion of the total annual post-fire treatment expenditure that was spent on the individual fire (%). All expenditures reported in 2009 US dollars

Fire name	State	Year	Burned area (ha)	Expenditure (US$)	Proportion of annual expenditure (%)
Tripod Complex	Washington	2006	60 200	30 100 000	59
Hayman	Colorado	2002	47 300	24 900 000	30
Cerro Grande	New Mexico	2000	10 400	15 300 000[A]	35
Rodeo Chediski Complex	Arizona	2002	71 800	13 300 000	16
Foothills	Idaho	1992	56 600	12 600 000	79
Rabbit Creek	Idaho	1994	38 400	12 200 000	43
Valley–Skalkaho Complex	Montana	2000	76 300	12 200 000[B]	28
Biscuit	Oregon	2002	197 900	11 000 000	13
Tyee Creek Complex	Washington	1994	42 700	8 900 000	31
Gap	California	2008	1900	7 000 000	29

[A]Excludes additional expenditures made by the US Department of Energy to protect critical values-at-risk.
[B]Based on additional BAER expenditure information from Regional BAER coordinator not included in the Burned Area Report.

Although the cost of applying agriculture straw mulch has declined over time (from US\$3290 ha^{-1} in the 1980s to \$2570 ha^{-1} in the 2000s and even less in 2013 – \$1200–\$1600 ha^{-1}), aerial seeding was always less expensive. Consequently, in the last decade, 42% of the total land treatment expenditure was committed to agricultural straw mulching ($80 million of $188 million), despite seeding being prescribed more often. In addition, agricultural straw mulch accounted for most of the hillslope treatment expenditures associated with the most expensive fires (Table 6). Given that the use of agricultural straw mulch increases the need for weed monitoring, some forest managers have suggested that the cost of monitoring should be included in the overall cost of using straw mulch when comparing post-fire treatment costs.

Hydromulch

Hydromulch comprises a mixture of wood or paper fibres, tackifiers, suspension agent, soil stabiliser and often seeds, combined with water and applied as a slurry on the soil surface. The components of a hydromulch formulation can be modified to enhance specific performance characteristics and some companies are striving to produce a mix for post-fire applications that will stabilise burned hillslopes for more than 1 year. It was first used for post-fire hillslope stabilisation in 2000 and infrequently since then. Only 5% of the Burned Area Reports from the 2000s included hydromulch as a prescribed treatment (Table 5), but the expense per unit area (~US\$6000 ha^{-1}) resulted in $41 million (27% of the total land treatment expenditures) being spent on hydromulch. Because it was used on only a few fires, the average expenditure per fire ($1.2 million) was higher than for any other land treatment. In addition to the high cost, the hydromulch mixes that have been tested were found to be short lived on the soil surface – often disappearing within months of their application – and failed to significantly reduce erosion (Hubbert *et al.* 2012; Robichaud *et al.* 2013*a*, 2013*b*). On the other hand, preliminary data from a hydromulch effectiveness study in southern California suggest that the paper-based hydromulch applied after three wildfires (occurring 2007–09) was moderately successful in reducing erosion (P. Wohlgemuth, pers. comm.).

Wood strands

The wood strand mulch used in the 2000s was a manufactured material (WoodStraw; Forest Concepts, Inc., Auburn, WA) made from veneer and wood manufacturing waste (Foltz and Dooley 2003; Foltz 2012). Wood strand mulch was first used in 2005 and had limited use on 18 fires included in this study. The expense of manufacturing and shipping wood strand mulch adds to the treatment cost, making the expenditure per unit area (US\$8390 ha^{-1}) the greatest among all land treatments (Table 5). Wood strand mulch has been found to be at least as effective as agricultural straw mulch in mitigating post-fire erosion (Foltz and Dooley 2003; Yanosek *et al.* 2006; Foltz 2012; Robichaud *et al.* 2013*a*) without the risk of introducing non-native plant seeds. In addition, wood strands remain on the soil surface longer (i.e. have greater persistence) and have less tendency to be displaced by the wind than agricultural straw (Copeland *et al.* 2009; Foltz 2012; Robichaud *et al.* 2013*a*). There is high interest in developing wood-based mulches that embody the positive characteristics of wood strand mulch but at a lower cost. Wood shreds, a wood product that can be produced on or near a burned area from burned or green trees, has been tried and has shown promise as a post-fire mulch treatment (Foltz and Copeland 2009; Foltz 2012; Robichaud *et al.* 2013*c*, 2013*d*).

Most expensive fires for treatment expenditure

The post-fire treatments that were implemented on the 2006 Tripod Complex fires (Washington) were the most expensive of any fire and cost over US$30 million – 59% of the total annual BAER expenditure on National Forest Service lands that year (Table 6). Three of the 10 most expensive post-fire treatment fires occurred in the 1990s with the other seven in the 2000s (Table 6). Although seeding was generally applied to the largest area, it was the high-cost treatments, such as contour-felled logs in the 1990s and aerial straw mulching in 2000s that pushed these particular fires into the top 10 in terms of BAER expenditure. In addition, these costly fires often were those with the highest BAER expenditure for the year in which they occurred (Table 6). Although a small number of large fires generally accounted for most of the area burned in any given year (Cramer 1959; Strauss *et al.* 1989; Calkin *et al.* 2005), the largest fires did not always result in the largest BAER expenditure; in fact there was no statistical relationship between fire size and BAER expenditure ($r = -0.03$, $P = 0.93$) for the 10 fires with the highest BAER expenditures. BAER expenditures were not driven by amount of area burned, but rather by the values-at-risk for damage or loss. Protecting source water areas for municipal drinking water supplies has justified large expenditures for post-fire treatments throughout the western US. For example, in the 2002 Hayman Fire, a large proportion of the Denver municipal water supply was threatened when a large, steep area surrounding a major reservoir was burned at high severity. Protection of the water quality draining into the reservoir was a prominent component of the post-fire treatment plan (Graham 2003).

Conclusions

The 1246 Burned Area Reports analysed for this synthesis related to fires on National Forest lands in the western US that occurred over four decades (early 1970s through the year 2009). Although they were not the only wildfires that occurred, the reports cover the majority evaluated through the BAER programme.

We found that the annual total area burned has increased over time, and the rate of increase accelerated *c*. 1990, such that the decadal total area burned in the 2000s was four times as much as that in the 1990s. Similar wildfire trends were reported by other researchers working with other data sources and time divisions. Burned Area Report data showed that in the 1980s and 1990s the proportion of burned area classified as low, moderate and high burn severity remained relatively stable with approximately half of the burned area classified as unburned or low severity and the remaining half fairly evenly divided between moderate and high severity. The BAER programme protocol for classifying burn severity was improved *c*. 2000 when low-level aerial surveys were replaced with an analysis of pre- and post-fire satellite imagery. The quantitative analysis of remote sensing products was applied at a high resolution over the entire burned landscape, and as a result, was not comparable to the more subjective assessments of the previous two decades.

Treatment justifications generally reflected regional concerns, such as protection of aquatic habitat for threatened and endangered species in the Pacific Northwest, protection of soil productivity in areas that support a robust timber industry and protection of municipal water supplies where fires surrounded source water watersheds. In the last decade, BAER treatments were more often justified using life and property values-at-risk compared with the earlier three decades, which reflected the overall increase in number and the area of wildfires and the expansion of development into the WUI, where people and property are more at risk from wildfires.

Road treatments were the most frequently recommended category of treatments, yet the largest decadal treatment expenditures were for land treatments. In the 2000s, US$188 million was spent on post-fire land treatments in the western US. Seeding was the most frequently used treatment during all four decades of the study, particularly in the 1970s and 1980s when it was used on 96 and 89% of the treated fires. However, as post-fire treatment effectiveness research showed that seeding only reduced erosion ~20–25% of the time (and rarely in the first post-fire year when erosion rates were often greatest), the frequency of post-fire seeding decreased to 72% in the 1990s and to 30% in the 2000s. Even though agricultural straw mulch was more expensive than seeding, its use continuously increased from the 1970s to the 2000s (2 to 18%). In the last decade, 42% of the total land treatment expenditure was used to aerially apply straw mulch on hillslopes burned at high severity. Unlike seeding, straw mulch has been found to be quite effective at reducing post-fire erosion, which has led to the development and use of other mulches, such as hydromulch and wood strands, for post-fire stabilisation. The unit costs of hydromulch and wood strands were respectively 2.3 and 3.3 times more than agricultural straw mulch. High-cost land treatments applied over large areas to protect values-at-risk, such as municipal drinking water sources, were generally responsible for the majority of expenditures in the 10 most expensive fires for the BAER programme. Five of the ten most expensive fires occurred in the last decade and each had large expenses for aerial mulching.

The trends discerned in the Burned Area Reports fit into the broader explanations of wildfire trends coming from global research efforts, which couples with our increased understanding of the effects of climate change on potential wildfire, wildfire behaviour and post-fire vulnerabilities. This information is needed for planning the most appropriate and effective post-fire management response.

Acknowledgements

The authors acknowledge the assistance and support of the national and regional coordinators from the US Department of Agriculture, Forest Service BAER Program and Richard Jones (retired) who helped update BAER Burned Area Reports database from the previous study with newly acquired USFS Burned Area Reports from 1999 to 2009 placed online by Conrad Albright. We also acknowledge contributions from Louise Ashmun, Annette Parsons (retired) and Bruce Sims (retired) from the US Department of Agriculture, Forest Service and from Richard Schwab at the US Department of the Interior, National Park Service for their reviews and comments.

References

Abt KL, Prestemon JP, Gerbert KM (2009) Wildfire suppression cost forecasts for the US Forest Service. *Journal of Forestry* **107**, 173–178.

Augerot X, Foley DN (2005) 'Atlas of Pacific Salmon: the First Map-based Status Assessment of Salmon in the North Pacific.' (State of the Salmon: Portland, OR)

Baker WL (2013) Is wildland fire increasing in sagebrush landscapes of the western United States? *Annals of the Association of American Geographers. Association of American Geographers* **103**, 5–19. doi:10.1080/00045608.2012.732483

Beyers JL (2004) Postfire seeding for erosion control: effectiveness and impacts on native plant communities. *Conservation Biology* **18**, 947–956. doi:10.1111/J.1523-1739.2004.00523.X

Calkin D, Gebert KM, Jones JG, Neilson RP (2005) Forest Service large fire area burned and suppression expenditure trends, 1970–2002. *Journal of Forestry* **103**, 179–183.

Calkin DE, Hyde KD, Robichaud PR, Jones JG, Ashmun LE, Loeffler D (2007) Assessing postfire values-at-risk with a new calculation tool. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-205. (Fort Collins, CO)

Calkin D, Jones G, Hyde K (2008) Nonmarket resource valuation in the postfire environment. *Journal of Forestry* **106**, 305–310.

Chiun-Ming L (1985) Impact of check dams on steep mountain channels in northeastern Taiwan. In 'Soil Erosion and Conservation' (Eds SA El-Swaify, WC Moldenhauer, A Lo) pp. 540–548. (Soil Conservation Society of America: Ankeny, IA)

Clark JT, Bobbe T (2006) Using remote sensing to map and monitor fire damage in forest ecosystems. In 'Understanding Forest Disturbance and Spatial Patterns: Remote Sensing and GIS Approaches'. (Eds MA Wulder, SE Franklin) Ch. 5, pp. 113–132. (Taylor & Francis: London)

Collins LM, Johnston CE (1995) Effectiveness of straw bale dams for erosion control in the Oakland Hills following the fire of 1991. In 'Brushfires in California Wildlands: Ecology and Resource Management'. (Eds JE Keeley, T Scott) pp. 171–183. (International Association of Wildland Fire: Fairfield, WA)

Copeland NS, Sharratt BS, Wu JQ, Foltz RB, Dooley JH (2009) A wood-strand material for wind erosion control: effects on total sediment loss, PM_{10} vertical flux, and PM_{10} loss. *Journal of Environmental Quality* **38**, 139–148. doi:10.2134/JEQ2008.0115

Cramer OP (1959) Relation of number and size of fires to fire-season weather indexes in western Washington and western Oregon. USDA Forest Service, Pacific and Northwest Forest and Range Experiment Station, Research Note 175. (Portland, OR)

Dean AE (2001) Evaluating effectiveness of watershed conservation treatments applied after the Cerro Grande fire, Los Alamos, New Mexico. MSc thesis, University of Arizona.

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

deWolfe VG, Santi PM, Ey J, Gartner JE (2008) Effective mitigation of debris flows at Lemon Dam, La Plata County, Colorado. *Geomorphology* **96**, 366–377. doi:10.1016/J.GEOMORPH.2007.04.008

Dodson EK, Peterson DW (2009) Seeding and fertilization effects on plant cover and community recovery following wildfire in the Eastern Cascade Mountains, USA. *Forest Ecology and Management* **258**, 1586–1593. doi:10.1016/J.FORECO.2009.07.013

Edwards L, Burney J, DeHaan R (1995) Researching the effects of mulching on cool-period soil erosion control in Prince Edward Island, Canada. *Journal of Soil and Water Conservation* **50**, 184–187.

Eidenshink J, Schwin B, Brewer K, Zhi-Liang Z, Quayle B, Howard S (2007) A project for monitoring trends in burn severity. *Fire Ecology* **3**(1), 3–21. doi:10.4996/FIREECOLOGY.0301003

Foltz RB (2012) A comparison of three erosion control mulches on decommissioned forest road corridors in the northern Rocky Mountains, United States. *Journal of Soil and Water Conservation* **67**, 536–544. doi:10.2489/JSWC.67.6.536

Foltz RB, Copeland NS (2009) Evaluating the efficacy of wood shreds for mitigating erosion. *Journal of Environmental Management* **90**, 779–785. doi:10.1016/J.JENVMAN.2008.01.006

Foltz RB, Dooley JH (2003) Comparison of erosion reduction between wood strands and agricultural straw. *Transactions of the American Society of Agricultural Engineers* **46**, 1389–1396.

Foltz RB, Robichaud PR, Rhee H (2009) A synthesis of postfire road treatments for BAER teams: methods, treatments effectiveness, and decision-making tools for rehabilitation. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-228. (Fort Collins, CO)

French NH, Kasischke ES, Hall RJ, Murphy KA, Verbyla DL, Hoy EE, Allen JL (2008) Using Landsat data to assess fire and burn severity in the North American boreal forest region: an overview and summary of results. *International Journal of Wildland Fire* **17**, 443–462. doi:10.1071/WF08007

Goldman SJ, Jackson K, Bursztynsky TA (1986) 'Erosion and Sediment Control Handbook' (McGraw-Hill: San Francisco, CA)

Graham RT (Ed.) (2003) Hayman Fire case study. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-114. (Ogden, UT)

Groen AH, Woods SW (2008) Effectiveness of aerial seeding and straw mulch for reducing post-wildfire erosion, north-western Montana, USA. *International Journal of Wildland Fire* **17**, 559–571. doi:10.1071/WF07062

Heede BH (1970) Design, construction and cost of rock check dams. USDA Forest Service, Rocky Mountain Forest and Range Experimental Station, Research Paper RM-20. (Fort Collins, CO)

Heede BH (1981) Rehabilitation of disturbed watershed through vegetation treatment and physical structures. In 'Proceedings, Interior West Watershed Management Symposium', 8–10 April 1980, Spokane, WA. (Ed. DM Baumgartner) pp. 257–268. (Washington State University Cooperative Extension: Pullman, WA)

Heyerdahl EK, Brubaker LB, Agee JK (2001) Spatial controls of historical fire regimes: a multiscale example from the Interior West, USA. *Ecology* **82**, 660–678. doi:10.1890/0012-9658(2001)082[0660:SCOHFR]2.0.CO;2

Holz A, Kitzberger T, Paritsis J, Veblen TT (2012) Ecological and climate controls of modern wildfires activity patterns across southwestern South America. *Ecosphere* **3**, art103. doi:10.1890/ES12-00234.1

Hubbert KR, Wohlgemuth PM, Beyers JL (2012) Effects of hydromulch on post-fire erosion and plant recovery in chaparral shrublands of southern California. *International Journal of Wildland Fire* **21**, 155–167. doi:10.1071/WF10050

Jain TB (2004) Tongue-tied. Wildfire (July–August), 22–26.

Kay BL (1983) Straw as an erosion control mulch. University of California Agricultural Experiment Station, Agronomy Progress Report 140. (Davis, CA)

Keane RE, Veblen T, Ryan KC, Logan J, Allen C, Hawkes B (2002) The cascading effects of fire exclusion in the Rocky Mountains. In 'Rocky Mountain Futures: an Ecological Perspective'. (Ed. J Baron) pp. 133–153. (Island Press: Washington, DC)

Kruse R, Bend E, Bierzychudek P (2004) Native plant regeneration and introduction of non-natives following postfire rehabilitation with straw mulch and barley seeding. *Forest Ecology and Management* **196**, 299–310. doi:10.1016/J.FORECO.2004.03.022

Lentile LB, Holden ZA, Smith AMS, Falkowski MJ, Hudak AT, Morgan P, Lewis SA, Gessler PE, Benson NC (2006) Remote sensing techniques to assess active fire characteristics and post-fire effects. *International Journal of Wildland Fire* **15**, 319–345. doi:10.1071/WF05097

Liang J, Calkin DE, Gebert KM, Venn TJ, Silverstein RP (2008) Factors influencing large wildland fire suppression expenditures. *International Journal of Wildland Fire* **17**, 650–659. doi:10.1071/WF07010

Littell JS, McKenzie D, Peterson DL, Westerling AL (2009) Climate and wildfire area burned in western U.S. *Ecological Applications* **19**, 1003–1021. doi:10.1890/07-1183.1

Miles SR, Haskins DM, Ranken DW (1989) Emergency burn rehabilitation: cost, risk, and effectiveness. In 'Proceedings of the Symposium and Fire and Watershed Management', 26-28 October 1988, Sacramento, CA (Ed. NH Berg) USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, General Technical Report PSW-GTR-109, pp. 97–102. (Berkeley, CA)

Minnich RA, Chou YH (1997) Wildland fire patch dynamics in the chaparral of southern California and northern Baja California. *International Journal of Wildland Fire* **7**, 221–248. doi:10.1071/WF9970221

Moody JA, Martin DA (2001) Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms* **26**, 1049–1070. doi:10.1002/ESP.253

Morgan P, Hardy CC, Swetnam T, Rollins MG, Long LG (2001) Mapping fire regimes across time and space: understanding coarse and fine-scale fire patterns. *International Journal of Wildland Fire* **10**, 329–342. doi:10.1071/WF01032

Mouillot F, Field CB (2005) Fire history and the global carbon budget: a 1° × 1° fire history reconstruction for the 20th century. *Global Change Biology* **11**, 398–420. doi:10.1111/J.1365-2486.2005.00920.X

MTBS Project (2009) Monitoring Trends in Burn Severity Project presentation. Available at http://www.mtbs.gov/ProjectDocsAndPowerpoints/MTBS_FSGeospatial09.pdf [Verified 28 August 2013]

Napper C (2006) Burned Area Emergency Response treatments catalog. USDA Forest Service, National Technology and Development Program, Watershed, Soil, Air Management, 0625 1801–SDTDC. (San Dimas, CA) Available at ftp://165.235.69.100/pub/incoming/fire_repair/Post%20Fire%20Erosion%20References/USFS%20BAER%20Treatment%20Catelog/TOContents.pdf [Verified 9 July 2014]

Neary DG, Klopatek CC, DeBano LF, Ffolliott PF (1999) Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management* **122**, 51–71. doi:10.1016/S0378-1127(99)00032-8

Neary DG, Ryan KC, DeBano LF (Eds) (2005) Wildland fire in ecosystems: effects of fire on soils and water. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-42-vol. 4. (Ogden, UT)

NIFC (2013) Total wildland fires and acres (1960–2013). (National Interagency Fire Center) Available at http://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html [Verified 17 April 2014]

Olliff T, Renkin R, McClure C, Miller P, Price D, Reinhart D, Whipple J (2001) Managing a complex exotic vegetation program in Yellowstone National Park. *Western North American Naturalist* **61**, 347–358.

Orlemann A, Saurer M, Parsons A, Jarvis B (2002) Rapid delivery of satellite imagery for burned area emergency response (BAER). In 'Proceedings of the Ninth Forest Service Remote Sensing Applications Conference: Rapid Delivery of Remote Sensing Products', 8–12 April 2002, San Diego, CA. (Ed. JD Greer) (CD-ROM) (American Society of Photogrammetry and Remote Sensing: Bethesda, MD)

Parsons A, Robichaud P, Lewis S, Napper C, Clark J (2010) Field guide for mapping post-fire soil burn severity. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-243. (Fort Collins, CO)

Peppin DL, Fulé PZ, Sieg CH, Beyers JL, Hunter ME, Robichaud PR (2011) Recent trends in post-wildfire seeding in western US forests: costs and seed mixes. *International Journal of Wildland Fire* **20**, 702–708. doi:10.1071/WF10044

Prats SA, MacDonald LH, Monteiro M, Ferreira AJD, Coelho COA, Keizer JJ (2012) Effectiveness of forest residue mulching in reducing post-fire runoff and erosion in a pine and a eucalypt plantation in north-central Portugal. *Geoderma* **191**, 115–124. doi:10.1016/J.GEODERMA.2012.02.009

Prestemon JP, Abt K, Gerbert K (2008) Suppression cost forecasts in advance of wildfire seasons. *Forest Science* **54**, 381–396.

Raftoyannis Y, Spanos I (2005) Evaluation of log and branch barriers as post-fire rehabilitation treatments in a Mediterranean pine forest in Greece. *International Journal of Wildland Fire* **14**, 183–188. doi:10.1071/WF04031

Robichaud PR, Ashmun LE (2013) Tools to aid post-wildfire assessment and erosion-mitigation treatment decisions. *International Journal of Wildland Fire* **22**, 95–105. doi:10.1071/WF11162

Robichaud PR, Beyers JL, Neary DG (2000) Evaluating the effectiveness of postfire rehabilitation treatments. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-63. (Fort Collins, CO)

Robichaud PR, Lillybridge TR, Wagenbrenner JW (2006) Effects of postfire seeding and fertilizing on hillslope erosion in north-central Washington, USA. *Catena* **67**, 56–67. doi:10.1016/J.CATENA.2006.03.001

Robichaud PR, Wagenbrenner JW, Brown RE, Wohlgemuth PM, Beyers JL (2008) Evaluating the effectiveness of contour-felled log erosion barriers as a postfire runoff and erosion mitigation treatment in the western United States. *International Journal of Wildland Fire* **17**, 255–273. doi:10.1071/WF07032

Robichaud PR, Ashmun LE, Sims BD (2010) Post-fire treatment effectiveness for hillslope stabilization. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-240. (Fort Collins, CO)

Robichaud PR, Lewis SA, Wagenbrenner JW, Ashmun LE, Brown RE (2013*a*) Post-fire mulching for runoff and erosion mitigation. Part I. Effectiveness at reducing hillslope erosion rates. *Catena* **105**, 75–92. doi:10.1016/J.CATENA.2012.11.015

Robichaud PR, Wagenbrenner JW, Lewis SA, Ashmun LE, Brown RE, Wohlgemuth PM (2013*b*) Post-fire mulching for runoff and erosion mitigation. Part II. Effectiveness in reducing runoff and sediment yields from small catchments. *Catena* **105**, 93–111. doi:10.1016/J.CATENA.2012.11.016

Robichaud PR, Jordan P, Lewis SA, Ashmun LE, Covert SA, Brown RE (2013*c*) Evaluating the effectiveness of wood shred and agricultural straw mulches as a treatment to reduce post-wildfire hillslope erosion in southern British Columbia, Canada. *Geomorphology* **197**, 21–33. doi:10.1016/J.GEOMORPH.2013.04.024

Robichaud PR, Ashmun LE, Foltz RB, Showers CG, Groenier JS, Kesler J, DeLeo C, Moore M (2013*d*) Production and aerial application of wood shreds as a post-fire hillslope erosion mitigation treatment. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-307. (Fort Collins, CO)

Rollins MG, Swetnam TW, Morgan P (2001) Evaluating a century of fire patterns in two Rocky Mountain wilderness areas using digital fire atlases. *Canadian Journal of Forest Research* **31**, 2107–2123. doi:10.1139/X01-141

Running SW (2006) Is global warming causing more, larger wildfires? *Science* **313**, 927–928. doi:10.1126/SCIENCE.1130370

Ryan KC, Noste NV (1985) Evaluating prescribed fires. In 'Proceedings of the Symposium and Workshop on Wilderness Fire', 15–18 November 1983, Missoula, MT. (Eds JE Lotan, BM Kilgore, WC Fischer, RW Mutch) USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-GTR-182, pp. 230–238. (Ogden, UT)

SAS (2003) SAS 9.1 TS Level 1M2. (Cary, NC: SAS Institute, Inc.)

Stella KA, Sieg CH, Fulé PZ (2010) Minimal effectiveness of native and non-native seeding following three high-severity wildfires. *International Journal of Wildland Fire* **19**, 746–758. doi:10.1071/WF09094

Stephens SL (2005) Forest fire causes and extent on US Forest Service lands. *International Journal of Wildland Fire* **14**, 213–222. doi:10.1071/WF04006

Storrar KA (2013) Effectiveness of straw bale check dams at reducing post-fire sediment yields from ephemeral channel catchments. MSc thesis, University of Montana (Missoula, MT)

Strauss D, Bednar L, Mees R (1989) Do one percent of forest fires cause ninety-nine percent of the damage? *Forest Science* **35**, 319–328.

Úbeda X, Outeiro LR (2009) Physical and chemical effects of fire on soil. In: 'Fire Effects on Soils and Restoration Strategies' (Eds A Cerdà, PR Robichaud) pp. 105–132. (Science Publishers: Enfield, NH)

USDA Forest Service (2012) Forest Service Manual 2523 – Emergency Stabilization – Burned Area Emergency Response (BAER). (USDA Forest Service: Washington DC)

USDA Forest Service (2013) Regional areas of the Forest Service. Available at http://www.fs.fed.us/contactus/regions.shtml [Verified 17 April 2014]

USDOI Fish and Wildlife Service (2013) Species profile, bull trout (*Salvelinus confluentus*). Available at http://ecos.fws.gov/speciesProfile/profile/speciesProfile.action?spcode=E065 [Verified 17 April 2014]

Wagenbrenner JW, MacDonald LH, Rough D (2006) Effectiveness of three post-fire rehabilitation treatments in the Colorado Front Range. *Hydrological Processes* **20**, 2989–3006. doi:10.1002/HYP.6146

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. *Science* **313**, 940–943. doi:10.1126/SCIENCE.1128834

Yanosek KA, Foltz RB, Dooley JH (2006) Performance assessment of wood strand erosion control materials among varying slopes, soil textures, and cover amounts. *Journal of Soil and Water Conservation* **61**, 45–51.