Project title:

Effects of time since burn, spatial scale and post-fire treatments on rainfall thresholds to produce runoff and erosion from plot to watershed-scale

JFSP project ID number:

15-2-01-57

PI name and affiliation:

Stephanie Kampf, Department of Ecosystem Science and Sustainability, Colorado State University

Student Investigator name and affiliation:

Codie Wilson, Department of Geosciences, Colorado State University

Co-author name and affiliation:

Joe Wagenbrenner, USDA Forest Service, Pacific Southwest Research Station

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Abstract

Colorado's Front Range forested watersheds provide municipal water supplies for downstream communities. Many of these watersheds have been affected by wildfires and subsequent runoff, erosion and sedimentation of waterways. Natural resource managers need information on the frequency and duration of post-fire runoff and erosion, particularly in areas that drain to municipal water supplies. The objectives of this research are to: (1) identify whether or not runoff and erosion can be predicted by rainfall thresholds within three recent Colorado Front Range fires, (2) examine whether thresholds change with time since burn (post-fire years 0-4), spatial extent (plot-, hillslope- and watershed-scale), and post-fire treatments (i.e., mulch), and (3) develop a tool for Colorado to estimate the frequency of threshold exceedance, and therefore runoff and erosion events, in future fire areas.

We identified minimum thresholds of 60-minute rainfall intensities (MI_{60}) in the range of 0-22 mm hr^{-1} for untreated sites for years 0-2 post-fire, using subsets of data separated by fire and spatial scale; when all scales and fires were merged, these thresholds were in the range of 7-8 mm h^{-1}. Storms with rainfall intensities exceeding these thresholds generated surface runoff and erosion. Thresholds predicted 56-100% of post-fire runoff events with an average prediction accuracy of 93%. For hillslopes, threshold rainfall intensities in the first two years post-fire were similar for the High Park, Hayman, and Bobcat Fires; MI_{60} rainfall in the range of 7-12 mm h^{-1} predicted $\geq$85% of erosion events across all three fires combined. Thresholds for runoff increased substantially during the third year after fire, when MI_{60} ranged from 8-22 mm hr^{-1}. Although many factors may change the value of rainfall thresholds for runoff, we found that it is difficult to isolate the effects of a single factor. Consequently, we did not detect clear differences in rainfall thresholds with and without post-fire treatments at the plot-scale, but we did detect the

effects of treatment at the hillslope-scale, where treatments increased threshold values on average 1 mm hr^{-1} relative to untreated areas. Effects of time since burn on thresholds were detected only in the Bobcat and High Park Fires. Results indicate that spatial scale can change thresholds for runoff, but the direction of change is not consistent from plot to watershed scale.

Most of the rainfall thresholds identified have less than a 1-year return interval, indicating that post-fire runoff and erosion is likely to occur several times per year during the first two years after fire. The frequency of threshold exceedance increased with increasing elevation from 1500-2100 m; decreased from 2100-2300 m, and was relatively consistent with elevation above 2300 m. Frequency analyses indicate that rain storms with 60-minute intensities of 4 mm h^{-1} occur between 6 to $\geq$10 times per summer in Colorado, and events with intensities between 5-7 mm h^{-1} occur between 2 and 6 times per summer. Understanding the likely frequency of rainfall events that will cause runoff and erosion after fire will help resource managers plan for post-fire flooding or sediment problems and prioritize treatments to those areas with lower thresholds and higher frequencies of threshold exceedance.

Background and purpose

Large wildfires in the western United States are likely to increase in duration and frequency due to higher temperatures and earlier spring snowmelt (Westerling et al. 2006). Wildfire may already have increased in frequency and extent in Colorado's Front Range forests (Litschert et al. 2012), which are also affected by inter-annual and multi-decadal climate patterns (Sibold and Veblen 2006). Since 2000, three of Colorado's largest wildfires, the Bobcat, Hayman and High Park Fires, burned areas ranging from 330 to 560 km^2 (82,000-140,000 acres). After a fire, runoff and erosion can be up to several orders of magnitude higher than pre-fire conditions (e.g., Larsen et al. 2009; Lane et al 2011; Wagenbrenner and Robichaud 2014), leading to water quality and water treatment challenges (Hohner et al. 2016).

Post-fire runoff and erosion are driven by rain storms (Moody et al. 2013), when rainfall intensities are high enough to produce overland flow and sediment transport (Wagenbrenner and Robichaud 2014; Prosser and Williams 1998; Benevides-Solario and MacDonald 2001). To reduce runoff and erosion after fire, land managers often apply treatments such as mulch, which can increase the rainfall thresholds necessary to produce of runoff and erosion (e.g., Schmeer 2014), and reduce erosion on plots (<1 ha; 2.5 acres; Wagenbrenner et al. 2006) and hillslopes (<10 ha; 25 acres; Robichaud et al. 2013a,b). Because many downstream communities depend upon forested watersheds to provide municipal water supplies (Gunderson et al. 2009), managers need to quickly estimate the location and frequency of post-fire runoff and erosion events, and determine whether treatments will reduce sediment delivery to streams.

Prior research has found that rainfall thresholds required for runoff and sediment production increase with surface roughness (Cammeraat 2002), vegetation recovery and mulch treatments (Schmeer 2014) and spatial scale (Cammeraat 2004). Vegetation and post-fire treatments that increase surface cover may protect soil from raindrop impact and contribute to surface roughness, which may slow, retain and store overland flow (Wainwright et al. 2000; Moreno-de las Heras et al. 2010; Prosser and Williams 1998; Inbar and Wittenberg 1998). Surface roughness may increase with spatial scale, longer flow path lengths (Wagenbrenner and Robichaud 2014), and increased vegetation (Moreno-de las Heras et al. 2010) to promote infiltration and provide potential locations for storing runoff and eroded sediment (Cammeraat 2002).

The magnitude of runoff and erosion may increase with burn severity (Prosser and Williams 1998), rainfall intensity (Wagenbrenner and Robichaud 2014) and rainfall erosivity (Benevides-Solario and MacDonald 2001), where erosivity (EI_{30}) is the product of event rainfall kinetic energy and intensity (Brown and Foster 1987). Once runoff begins, detached sediment can become entrained in surface flow and transported via inter-rills and rills (Wainwright et al. 2000). Increases in runoff can elevate sediment transport capacity (Prosser and Williams 1998; Wainwright et al. 2000), disintegrate soil aggregates (Wang et al 2014), and increase sediment yields (Parsons et al. 2006).

To help land managers identify where and when rain events are likely to cause post-fire flooding or sediment problems, we aim to improve understanding of rainfall thresholds required for runoff and sediment delivery at different spatial scales. The objectives of this research are:

1. *Threshold identification:* Identify whether or not runoff and erosion can be predicted by rainfall thresholds within three recent Colorado Front Range fires.
2. *Effects of time since burn, spatial scale, and treatment on thresholds*: Compare identified thresholds for: plots (planar; <0.06 ha), hillslopes (convergent; 0.07-10 ha) and watersheds (100-1500 ha), time since burn (post-fire years 0-4), and varied levels of post-

fire treatment.

3. *Tool development:* Develop a tool for Colorado to estimate the frequency that rainfall events will exceed runoff thresholds in future fire areas.

Study description and location

Post-fire rainfall, runoff and erosion data were compiled for three recent Colorado Front Range fires: the 2000 Bobcat, the 2002 Hayman, and the 2012 High Park Fire (Figure 1). Spatial extents and burn severities include moderately to severely burned plots (<0.06 ha) and hillslopes (0.07-5.2 ha), and mixed severity watersheds (100-1500 ha). Average slopes range from 2-24° at plots, 3-31° for convergent hillslopes, and 18-24° for larger watersheds, which are comprised of multiple hillslopes (Table 1; Figure 2). Elevations range from 1700-2700 m. The dominant soil type is sandy loam in the Bobcat and High Park Fires and gravelly coarse sand in the Hayman Fire (Robichaud et al 2013a; Wagenbrenner and Robichaud 2014; BAER 2012). Treatments included mulch, contour felling and straw wattles in the Bobcat Fire; aerial and ground hydromulch, straw and wood mulch in the Hayman Fire; and straw and wood shred mulch in the High Park Fire. Aerial seeding was also applied in parts of the Bobcat and Hayman Fires, but it did not affect post-fire erosion rates (Wagenbrenner et al. 2006).

We identified rainfall thresholds for runoff and erosion for the summer thunderstorm seasons (June-Sept) of post-fire years 0-4; these months include the large majority of runoff observations, and thresholds for later years post-fire have limited data (Table 1). The effects of fire location, year post-fire and spatial scale were assessed where data were available for comparison (Figure 2). The effect of treatment is also assessed for sites with observations of surface cover.

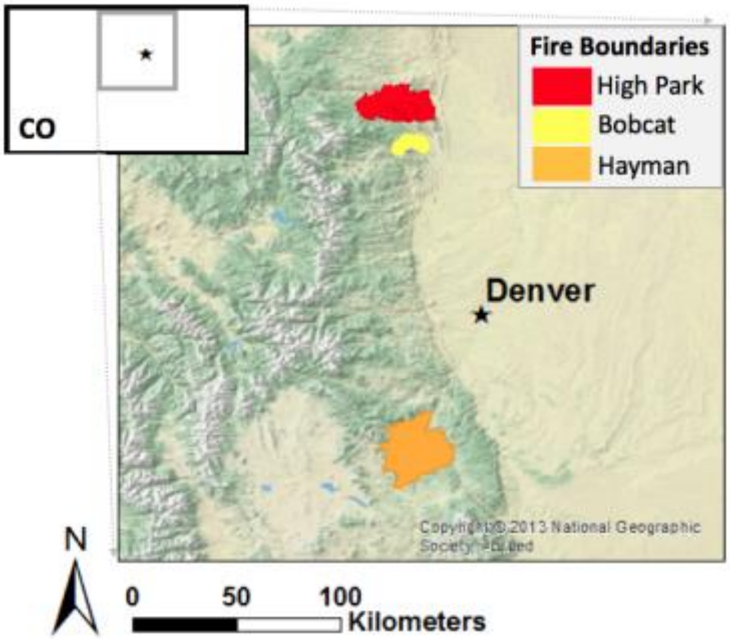

Figure 1. Location of the three recent Colorado Front Range fires of this analysis; from north to south: the 2012 High Park, 2000 Bobcat and the 2002 Hayman Fire. Imagery from ESRI (2013).

Table 1. The three recent Colorado Front Range fires, years of burn, spatial scales, area (ha), number of sites monitored, years of post-fire monitoring with 0 representing the year of the fire, and the data references.

Year, Fire	Spatial scale	Area (ha)	Sites (#)	Years post-fire	Reference
2012,	Hillslope	0.07-10	31	0-3	This study; Schmeer 2014
High Park	Watershed	100-1500	6	2-4	This study; Ryan, in preparation.
2000,	Plot	$\leq$0.06	11	0-3	Wagenbrenner et al. 2006
Bobcat	Hillslope	0.07-10	23	0-3	Wagenbrenner and Robichaud 2014
	Watershed	100-1500	2	0-2	Kunze and Stednick 2006
2002,	Plot	$\leq$0.06	32	1-4	Robichaud et al. 2013a
Hayman	Hillslope	0.07-10	32	0-4	Wagenbrenner & Robichaud 2014; Rough 2007; Robichaud et al. 2013b

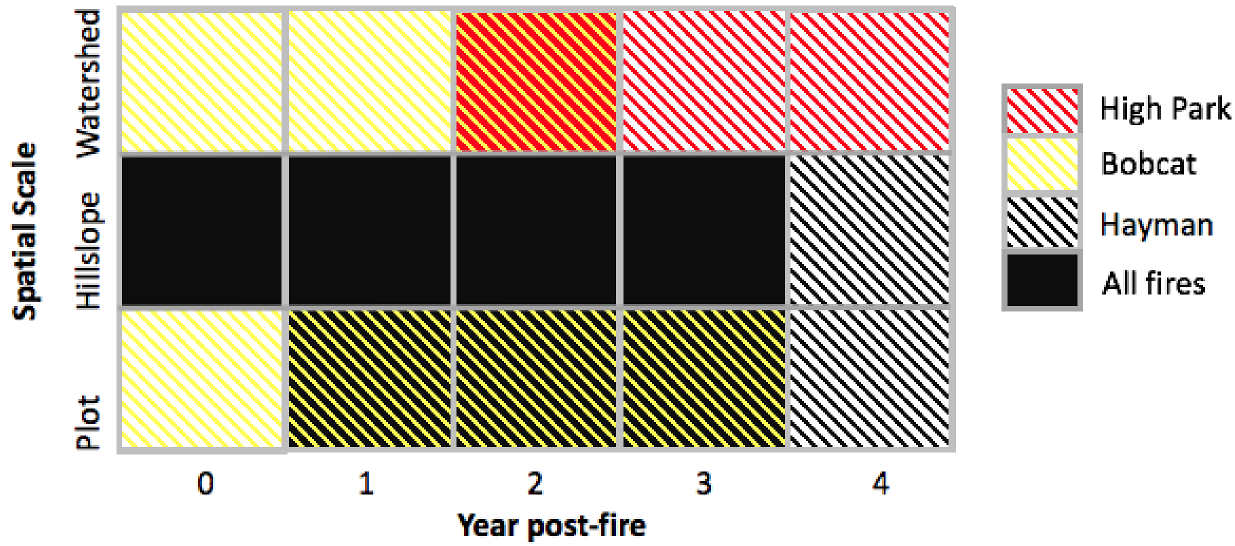

Figure 2. Sample data available for this analysis by fire location, spatial scale and year post-fire. Post-fire year 0 represents the fire year. Plot-scale data were available only for Bobcat and Hayman Fires; hillslope-scale data were available for all fires, and watershed-scale data were available only for Bobcat and High Park Fires.

Rainfall

Tipping bucket rain gauges were located adjacent to or within each of the plots, hillslopes and watersheds. Rainfall data were compiled and processed using the USDA Rainfall Intensity Summarization Tool (RIST; ARS, 2013). Rainfall events were separated by at least 6 h with <1 mm (0.05 in) of rain (Renard et al. 1997); the following rainfall metrics were calculated: the maximum intensity (mm h^{-1}) over 60-minute intervals (MI_{60}), and maximum 30-minute erosivity (EI_{30}), where EI_{30} is the product of event rainfall kinetic energy and intensity (Brown and Foster 1987). To determine thresholds, MI_{60} was chosen because initial tests of different rainfall metrics using maximum rainfall intensities over varying time intervals (5-60 minutes) produced similar results. Other studies have found that MI_{60} is somewhat better for identifying runoff thresholds than maximum intensities over shorter time intervals (c.f., Kampf et al. in review).

Runoff and erosion monitoring

Methods to monitor runoff and erosion varied by spatial scale. To monitor erosion, silt fences (c.f. Robichaud and Brown 2002) were installed at the outlets of plots (Wagenbrenner et al. 2006; Robichaud et al. 2013a) and hillslopes (Rough 2007; Wagenbrenner and Robichaud 2014; Schmeer 2014). Runoff was also monitored continuously at two hillslopes in the Hayman Fire using sediment traps with v-notch weirs (Robichaud et al. 2013b). For plots and hillslopes, flow was ephemeral, with no baseflow between storms. For locations without continuous runoff monitoring, we assumed that an observation of erosion indicated that both runoff and erosion had occurred for the event (hereafter, “runoff”). Watershed-scale sites had perennial flow and continuous monitoring of stream stage and turbidity.

Each runoff measurement location was paired with rainfall data from the nearest rain gauge. For each rainfall event, site responses were classified by the presence or absence a runoff response to rainfall. In sites without continuous runoff monitoring, any measurement of eroded sediment was assumed to be a runoff event. If there were multiple rainfall events between site visits, the rainfall event with the highest EI_{30} was assigned to the runoff producing event. For sites with continuous monitoring, runoff responses to rain events were identified from a rise in stage above baseflow that followed the characteristic shape of a hydrograph. Continuous stage data were not available for watersheds in the Bobcat Fire during year 0, so surveys of high-water marks during frequent site visits were used to identify runoff events (Kunze and Stednick 2006). Rainfall events without observations of runoff or erosion were marked as rainfall events without runoff. All rainfall data over the summer thunderstorm season of June-September were included in the threshold analysis.

Threshold identification and assessment

Rainfall events with associated runoff responses (i.e., presence or absence of runoff) at each site were compiled by fire, year post-fire, spatial scale, and treatment status (i.e., presence or absence of mulch); this produced 54 separate sample groups (Table 2). For each sample group, thresholds were identified as the range of MI_{60} values that maximized the fraction (F) of rainfall events for which the threshold correctly predicted a response in runoff. F was quantified for each sample group using the equation:

$$F = \frac{y+n}{N} \tag{1}$$

where y is the number of true positives, defined as rainfall events with $MI_{60} \geq$ the identified threshold and a runoff response; n is the number of true negatives, defined as rainfall events with $MI_{60} <$ the identified threshold, but with no runoff response, and N is the total number of rainfall events within the sample group, whether or not runoff was observed. A higher value of F indicates greater likelihood of a threshold process; we consider values of $F \geq 0.9$ to indicate very good threshold predictions of response; $0.7 \leq F < 0.9$ good predictions, and $0.5 \leq F < 0.7$ fair predictions. A value of $F < 0.5$ is a poor prediction and indicates low likelihood that runoff can be predicted accurately by a rainfall threshold.

In most cases, more than one MI_{60} value produced the same optimum F; for these cases, the range of threshold values were documented from T-min (minimum value of optimal threshold) to T-max (maximum value of optimal threshold). Thresholds and F-values were compared by fire location, time since burn, spatial scale, and treatment status to determine whether or not the runoff response depends on a rainfall threshold.

Table 2. Sample groups for threshold analysis by spatial scale, year post-fire (Year), location (Fire), and treatment status (Mulch; Y/N) with a count of rainfall events at a site June-Sept. (P; #), percent of rainfall events with runoff (Q; %), and the range and median of MI_{60} rainfall (mm h^{-1}). Bobcat, Hayman and High Park Fires abbreviated BC, HM, and HP, respectively. Blank cells are those without available data.

Spatial scale:			Plot			Hillslope			Watershed		
Year	**Fire**	**Mulch**	**P (#)**	**Q (%)**	**MI_{60} min-max (median)**	**P (#)**	**Q (%)**	**MI_{60} min-max (median)**	**P (#)**	**Q (%)**	**MI_{60} min-max (median)**
0	BC	N	80	10	2-7.6 (5.7)	78	24	2-31.3 (5.8)	11	18	2-8.2 (5.2)
		Y	2	100	5.4-31.3 (18.3)	35	14	2-31.3 (5.6)	11	18	2-31.3 (5.2)
	HM	N				1232	6	1.1-11.2 (2.8)			
		Y				143	3	1.1-11.2 (2.6)			
	HP	N				93	24	1.3-15 (2.5)			
		Y				31	19	1.2-15 (2)			
1	BC	N	210	14	1.4-13.6 (2.6)	384	21	1.2-14.1 (2.4)	27	56	1.2-13.6 (2.8)
		Y	25	16	1.2-14.1 (2.2)	134	11	1.2-14.1 (2.4)	23	22	1.2-12.1 (2)
	HM	N	186	18	1.3-23.9 (2.2)	368	27	1.1-23.3 (3.8)			
		Y	268	12	1.3-23.9 (2.2)	298	13	1.1-20 (3.8)			
	HP	N				387	22	1.3-27.1 (3.6)			
		Y				178	9	1.3-26.2 (2.8)			
2	BC	N	110	22	1.2-12 (2.8)	223	12	1.2-12 (2.4)	10	10	1.2-12 (5.6)
		Y	15	13	1.2-7.8 (2.4)	70	6	1.2-12 (2.8)	18	6	1.2-7.7 (2.3)
	HM	N	534	13	1.3-10.1 (2.8)	957	10	1.2-23.2 (2.8)			
		Y	528	11	1.3-10.1 (2.8)	377	15	1.2-23.2 (2.8)			
	HP	N				598	11	1.1-19.8 (3.3)	102	8	1.3-19.8 (2.7)
		Y				221	11	1.1-21.7 (3)	54	11	1.1-21.7 (2.3)
3	BC	N	150	2	1.2-21.5 (2.4)	255	2	1.2-21.5 (3)			
		Y	15	0	1.2-17.8 (4.4)	90	0	1.2-21.5 (2.5)			
	HM	N	47	34	1.2-11.7 (4)	37	3	1.3-9.5 (2.9)			
		Y	47	34	1.2-11.7 (4)	26	4	1.3-11.2 (3.4)			
	HP	N				486	5	1.3-18.3 (3.3)	170	5	1.3-20.3 (3)
		Y				178	9	1.3-22.9 (3.1)	83	23	1.3-22.9 (3)
4	HM	N	438	20	1.3-13.5 (3.1)	40	3	1.3-20.6 (3.5)			
		Y	438	19	1.3-13.5 (3.1)	37	3	1.3-20.6 (3.8)			
	HP	N							105	12	1.3-19 (2.5)
		Y							8	38	1.3-14.8 (2.8)

Effects of location, time since burn, spatial scale, and treatment on thresholds

To examine the effects of fire location, spatial scale, and time since burn on thresholds (Table 3), we used only untreated sites because treatment types and application rates varied by site. First, the effects of fire location (i.e., Bobcat, Hayman or High Park) on thresholds were assessed for hillslopes in post-fire years 0-3 because hillslopes were the only scale with data across all three locations (Figure 2). Second, the effects of spatial scale were assessed by fire and year post-fire. Third, the effects of treatment were assessed for plots and hillslopes by fire and year post-fire. Watersheds were excluded from the treatment analysis because none of the watersheds were treated over their full contributing area, and to our knowledge the spatial extent of treatments was not quantified over watersheds. For plots and hillslopes, sites were considered treated if mulch was applied, and treatment was categorized as either present or absent. Finally, the effects of year post-fire were assessed by fire for hillslopes because this spatial scale had data available for more than one year post-fire in all three fires.

As an additional test of the effects of fire and spatial scale, data were merged by year post-fire. For spatial scale, we grouped: (a) untreated sites with similar spatial scale across all fires, and (b) untreated sites from all spatial scales across all fires. Thresholds identified for merged datasets were then compared by year post-fire to those thresholds initially identified for discrete spatial scales and fires.

Table 3. Variables assessed for effects on threshold values. Dataset column lists the data subset used in the analysis of each variable.

Variable	Dataset
Fire	Hillslopes, Year post-fire, No treatment
Year post-fire	Fire, Hillslopes, No treatment
Spatial scale	Fire, Year post-fire, No treatment
Treatment	Fire, Year post-fire, Plots and hillslopes

Tool development

The frequency of rainfall events exceeding threshold MI_{60} values was assessed for Colorado's Front Range using data from the 47 NOAA Atlas stations with 15-minute rainfall data (Perica et al. 2013); these data span periods of 25-39 years (average of 34 years; standard deviation of 5 years). Years with >14 days of missing data between June-September were excluded because missing data caused underestimation of event frequency; events with intensity < 2.54 mm h^{-1} were also excluded because this is the precision of most of the NOAA rain gauges. The remaining events were ranked by MI_{60} magnitude. The frequency of occurrence, defined as the average number of times an event with similar MI_{60} would occur in a given summer, was calculated for each event as (Equation 2):

$$Frequency = \frac{rank}{(n+1)} \tag{2}$$

where n is the total number of summers analyzed.

For each station, a polynomial function was fit to the values of frequency v. MI_{60} for MI_{60} values in the range of 4-12 mm hr^{-1}; we chose this range based on the threshold values identified for hillslopes in years 0-2 and because most higher intensities have frequency <1 and are therefore already mapped by the NOAA atlas. These functions were used to estimate the frequency of MI_{60} values ranging from 4-20 mm h^{-1} in increments of 1 mm h^{-1}. The frequencies of threshold exceedance for each of these MI_{60} values were spatially interpolated over the state of Colorado with Simple Co-kriging in ArcGIS 10.3 (ESRI 2013) using each station's coordinates and 800 m resolution precipitation grids of average summer rainfall depths (mm; June to September of 1981-2010) from the Parameter-elevation Relationships on Independent Slopes Model (PRISM; PRISM Climate Group 2017). The frequency of events with intensities ranging from 4-12 mm h^{-1} was assessed with elevation across the Front Range forests in central Colorado.

Key findings

Rainfall event sample sizes

The number of rain events in the dataset varied by spatial scale and fire location (Table 4). Overall, over 90% of the rain events in the dataset were for hillslopes and plots; of these, most were from the Hayman Fire dataset (Table 4). Fewer rain events were recorded at watershed sites (<6%), and many of these occurred in the High Park Fire (Table 4). The percent of rainfall events with runoff ranged from 13% at hillslopes to 16% at plots and watersheds.

Table 4. Rainfall event sample size (P; #) by spatial scale showing the percent of rainfall events with runoff (Q; %) and the distribution of rainfall events by fire (P; %). Bobcat, Hayman and High Park Fires abbreviated BC, HM, and HP, respectively. Blank cells are those without available data.

Scale	P (#)	Q (%)	Fire	P (%)
Plot	3175	16	BC	19
			HM	81
Hillslope	6955	13	BC	18
			HM	50
			HP	31
Watershed	622	16	BC	16
			HP	84

Threshold identification

Across all sample groups, MI_{60} rainfall thresholds ranged from 0 to 31 mm h^{-1}. The range of reported thresholds is indicated by T-min and T-max, which bracket the MI_{60} values that produced the same maximum prediction value (F), i.e., the MI_{60} value(s) that minimized the total number of false positives and false negatives (Table 5). A minimum threshold (T-min) of 0 indicates that the highest possible prediction (F) can be obtained assuming all rainfall events produce runoff. In some cases, a maximum threshold (T-max) could not be defined (see footnote "b" in Table 5), which indicates that prediction accuracy (F) is the same for all values exceeding T-min. T-max was set to the maximum observed rainfall for sample groups with T-max greater than observed rainfall values (i.e., T-max could not be defined; see footnote "b" in Table 5). Defined threshold values ranged from 0-22 mm h^{-1} ($F \geq 0.87$) for plots, 4-31 mm h^{-1} ($F \geq 0.85$) for hillslopes, and 0-31 mm h^{-1} ($F \geq 0.56$) for watersheds. Errors in threshold predictions could be either false positives or false negatives. False positives were events without an observed response in runoff but with an MI_{60} rainfall greater than the threshold value. False negatives were events with an observed response in runoff but with an MI_{60} rainfall less than the threshold value.

To first test the causes of variability in threshold values, thresholds and F-values were compared between fire locations, years post-fire, spatial scale groups, and treatment status using ANOVA (Table 6). Thresholds (T-min and T-max) and F-values did not vary significantly by fire or by treatment, but were significantly different for years post-fire and for different spatial scale groups. Average T-min values increased from year 0 to 1, were slightly lower in year 2, and highest in year 3. Average T-min and T-max values were highest for hillslopes, then plots and watersheds; mean F-values were highest for plots, then hillslopes, followed by watersheds (ANOVA; $p \leq 0.05$; Table 6).

Table 5. Range of MI_{60} rainfall thresholds (T-min and T-max; mm h^{-1}) and the fractional value (F) of the rainfall events that correctly predicted a response in runoff by year post-fire (Year), location (Fire), treatment (Mulch; Y/N) and spatial scale. Bobcat, Hayman and High Park fires abbreviated BC, HM, and HP, respectively. Blank cells are those without available data.

	Spatial scale:		Plot			Hillslope			Watershed		
Year	**Fire**	**Mulch**	**T-min**	**T-max**	**F**	**T-min**	**T-max**	**F**	**T-min**	**T-max**	**F**
0	BC	N	7.6	7.6[c]	0.9	6.8	7.5	0.88	6.8[b]	7.6	0.82
		Y	0[a]	5.3	1	7.6	31.2	0.89	6.8[b]	31.2	0.91
	HM	N				10.9	11.1	0.96			
		Y				11.2	11.2[c]	0.97			
	HP	N				4.1	4.3	0.86			
		Y				3.5	4	0.97			
1	BC	N	6.6	7.7	0.95	6.4	7.4	0.85	0[b]	1.1	0.56
		Y	6.8[b]	7.4	0.88	11.1	13.5	0.92	5[b]	6.7	0.96
	HM	N	8.1	9.1	0.99	9.3	9.7	0.85			
		Y	8.1	9.1	1	11	11.1	0.9			
	HP	N				9.3	9.9	0.87			
		Y				16.6	18.5	0.93			
2	BC	N	4.4	6.1	0.96	7.3	7.7	0.93	12[b]	12[c]	0.9
		Y	4.6[b]	7.8[c]	0.87	12	12[c]	0.94	4.6[b]	7.7[c]	0.94
	HM	N	5.4	5.6	0.95	7.9	9.5	0.94			
		Y	7.7	7.8	0.95	8	8.8	0.92			
	HP	N				12	15.6	0.92	4.7	5	0.92
		Y				17.1	18	0.92	5.8	10.4	0.98
3	BC	N	21.5	21.5[c]	0.98	21.5	21.5[c]	0.98			
		Y	17.8[b]	17.8[c]	1	21.5	21.5[c]	1			
	HM	N	9.2	11.6	1	7.9	9.5	1			
		Y	9.2	11.6	1	11.2[b]	11.2[c]	0.96			
	HP	N				12	12.6	0.97	7.7	8.6	0.96
		Y				12.7	18.2	0.94	4.9	5.2	0.96
4	HM	N	6.3	6.3	0.92	20.6	20.6[c]	0.96			
		Y	6.3	6.3	0.92	20.6	20.6[c]	0.97			
	HP	N							5	5.7	0.93
		Y							3[a]	3.7	0.75

[a] sample size <10; [b] sample size <30; [c] thresholds where F was not bounded by T-max show highest observed P

Table 6. Comparisons of minimum and maximum rainfall thresholds (T-min and T-max, respectively) and prediction performance values (F-value) by fire, year post-fire, spatial scale and treatment shown as ANOVA p-values; bold text indicates $p \leq 0.05$.

	T-min	T-max	F-value
Fire	0.73	0.54	0.15
Year post-fire	**0.03**	0.30	**0.03**
Spatial scale	**0.001**	**0.05**	**0.03**
Treatment	0.73	0.11	0.23

Effects of fire location

The effects of fire location on threshold values were examined in greater detail for hillslopes without treatments in post-fire years 0-3. Overall, minimum rainfall thresholds required to produce a response in runoff (T-min) ranged from 4-22 mm hr^{-1} ($F \geq 0.85$), and there was no consistent tendency for thresholds to be lower or higher in certain fires (Figure 3). In post-fire year 0, T-min was lowest in the High Park Fire at 4 mm h^{-1} (F=0.86), and highest in the Hayman Fire at 11 mm h^{-1} (F=0.97); Bobcat T-min was 7 mm h^{-1} (F=0.88). In post-fire year 1, T-min was lowest in the Bobcat Fire at 6 mm h^{-1} (F=0.85), and was the same in the High Park and Hayman Fires at 9 mm h^{-1} ($F \geq 0.85$). In post-fire year 2, T-min was again lowest in the Bobcat Fire at 7 mm h^{-1} (F=0.93), slightly higher in the Hayman Fire at 8 mm h^{-1} (F=0.94), and highest in the High Park Fire at 12 mm h^{-1} (F=0.92). In post-fire year 3, T-min was lowest in the Hayman Fire at 8 mm h^{-1} (F=1), 4 mm h^{-1} higher in the High Park Fire at 12 mm h^{-1} (F=0.97), and highest in the Bobcat at 22 mm h^{-1} (F=0.98).

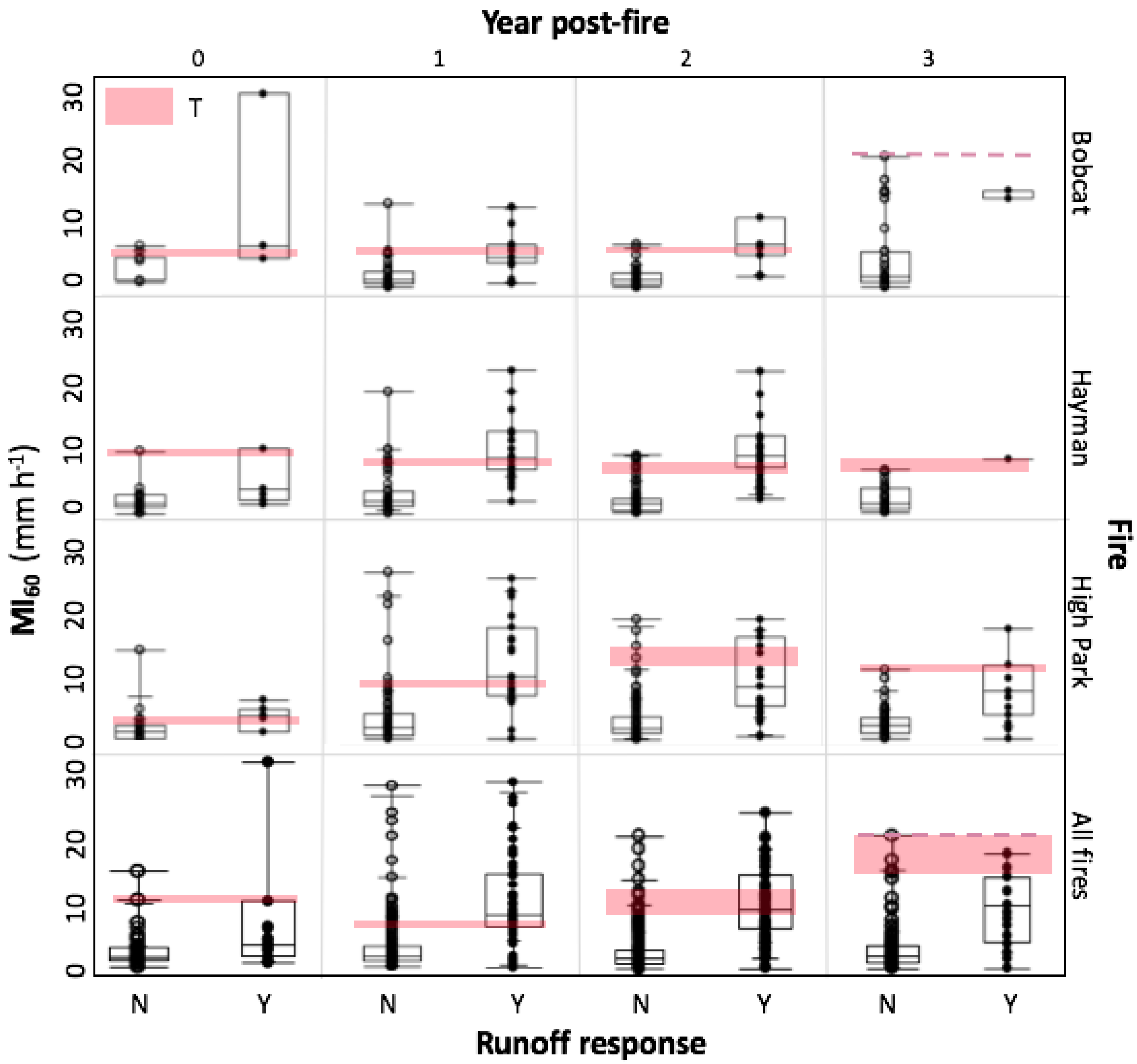

Figure 3. MI_{60} rainfall thresholds (T) by fire and year post-fire over box plots of events that either did not (N) or did produce a response (Y). All values are for hillslopes without treatment. Shaded areas correspond to the range of thresholds (T) from T-min to T-max. Dashed lines indicate the highest observed P for thresholds where T-max was undefined.

Effects of spatial scale

To examine the effects of spatial scale on threshold values, we used untreated plot, hillslope and watershed-scale data grouped by fire and year post-fire (Figure 4). For the Bobcat fire, thresholds during post-fire years 0-3 ranged from 0 to 22 mm h^{-1}; excluding the outlier value of 0, which had relatively poor threshold performance (F=0.56), the minimum threshold was 4 mm h^{-1}. Thresholds increased from plot- to hillslope- and watershed-scale in post-fire year 2 for Bobcat and Hayman Fires but not for High Park Fire (Figure 4, Table 5). Thresholds in the Bobcat Fire were similar for plots, hillslopes and watersheds in post-fire year 0 and ranged from 7-8 mm h^{-1} ($F \geq 0.82$); plot and hillslope thresholds were similar in post-fire year 1 and ranged from 6-7 mm h^{-1} ($F \geq 0.85$). For post-fire year 3, only plot and hillslope-scale data were available in the Bobcat Fire, and both scales had T-min of 22 mm h^{-1} (F=0.98). For the Hayman Fire, data were available for comparison at plots and hillslopes during post-fire years 1-3, when thresholds ranged from 5-11 mm h-1 ($F \geq 0.85$). Thresholds for plots and hillslopes within the Hayman Fire were similar in year 1 and ranged from 8-9 mm h^{-1} ($F \geq 0.85$). Thresholds increased with spatial scale at Hayman plots and hillslopes in post-fire year 2, and decreased with scale in post-fire year 3 (Figure 4; Table 5). For the High Park Fire, hillslope and watershed-scale data were available in post-fire years 2 and 3; minimum thresholds ranged from 5-12 mm h^{-1} ($F \geq 0.92$), and thresholds decreased with increasing spatial scale (Figure 4, Table 5).

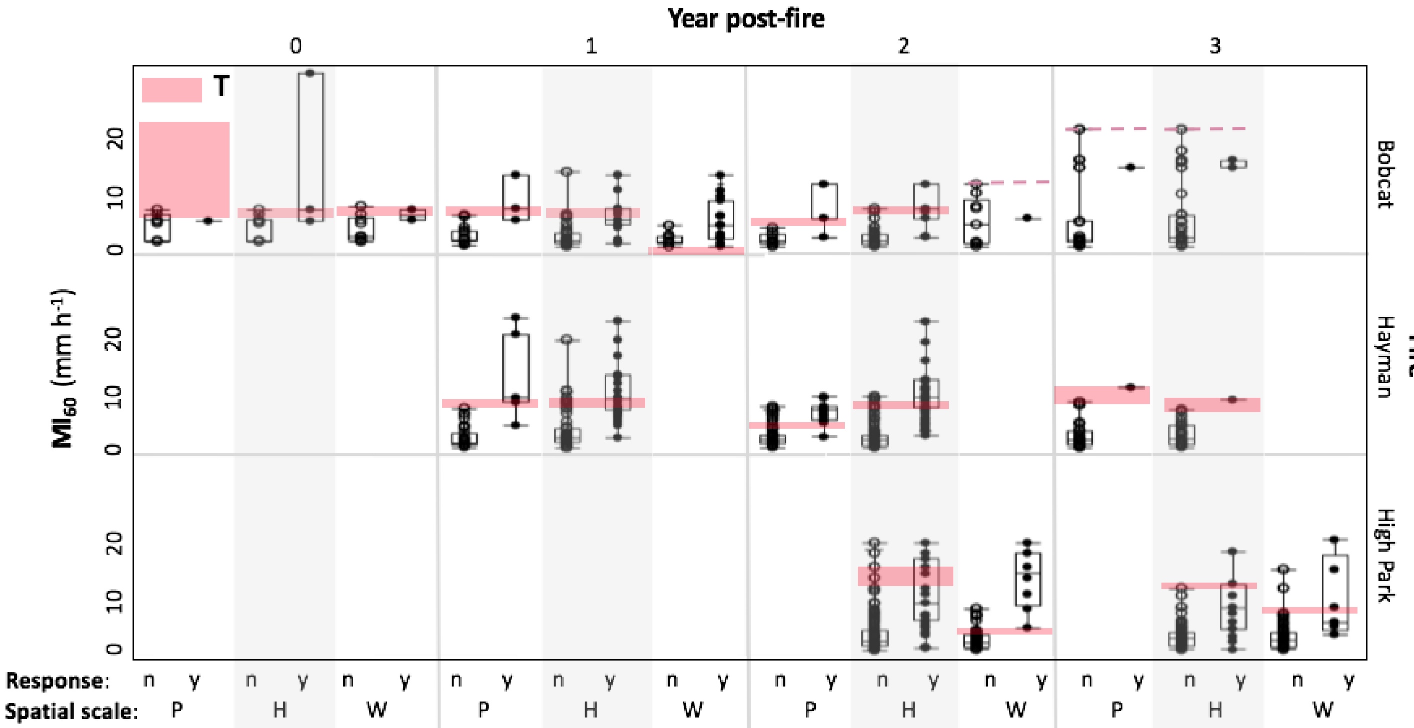

Figure 4. MI_{60} rainfall thresholds (T) by spatial scale (P: plot; H: hillslope; W: watershed), years post-fire (0-3), and fire location plotted over boxplots of events that did not (n) and did (y) produce runoff. All values are for sites without treatment. Shaded areas correspond to the range of thresholds with the highest fraction of events correctly predicted by the threshold. Dashed lines indicate the highest observed P for those thresholds where T-max was undefined.

When sites with similar spatial scale were grouped across fires, thresholds did not consistently increase or decrease with spatial scale (Table 7; Figure 5). In post-fire year 1, T-min decreased from 8 mm h^{-1} at plots (F=0.95) to 7 mm h^{-1} (F=0.85) at hillslopes. In post-fire year 2, T-min increased from 5 mm h^{-1} at plots (F=0.95) to 10 mm h^{-1} at hillslopes (F=0.94); watershed T-min was in-between at 8 mm h^{-1} (F=0.96). In post-fire year 3, T-min was 22 mm h^{-1} at plots (0.97) and 18 mm h^{-1} at hillslopes (F=0.96). When all spatial scales were grouped across all fires by year post-fire (Table 7; Figure 5), T-min values were similar for years 0-2 (7-8 mm h^{-1}) and substantially higher in year 3 (22 mm h^{-1}) (Table 7).

Table 7. Minimum and maximum MI_{60} rainfall thresholds (mm h^{-1}; T-min and T-max, respectively), prediction (F) for data grouped across fires and spatial scales by year post-fire. Bobcat, Hayman and High Park Fires abbreviated BC, HM, and HP, respectively.

Fire	Year	Scale	T-min	T-max	F
All	0	All	7.6	31.2	0.95
All	1	All	6.6	6.8	0.87
All	2	All	7.9	9.8	0.92
All	3	All	21.5	21.5[a]	0.95
All	0	Hillslope	10.9	11.1	0.94
All	1	Hillslope	6.6	7.3	0.85
All	2	Hillslope	10.2	11.5	0.93
All	3	Hillslope	17.8	21.5[a]	0.96
BC, HM	1	Plot	8.1	9.1	0.95
BC, HM	2	Plot	4.9	5.6	0.95
BC, HM	3	Plot	21.5	21.5[a]	0.97
BC, HP	2	Watershed	8.4	15.6	0.96

[a] T-max undefined, so value is highest observed P.

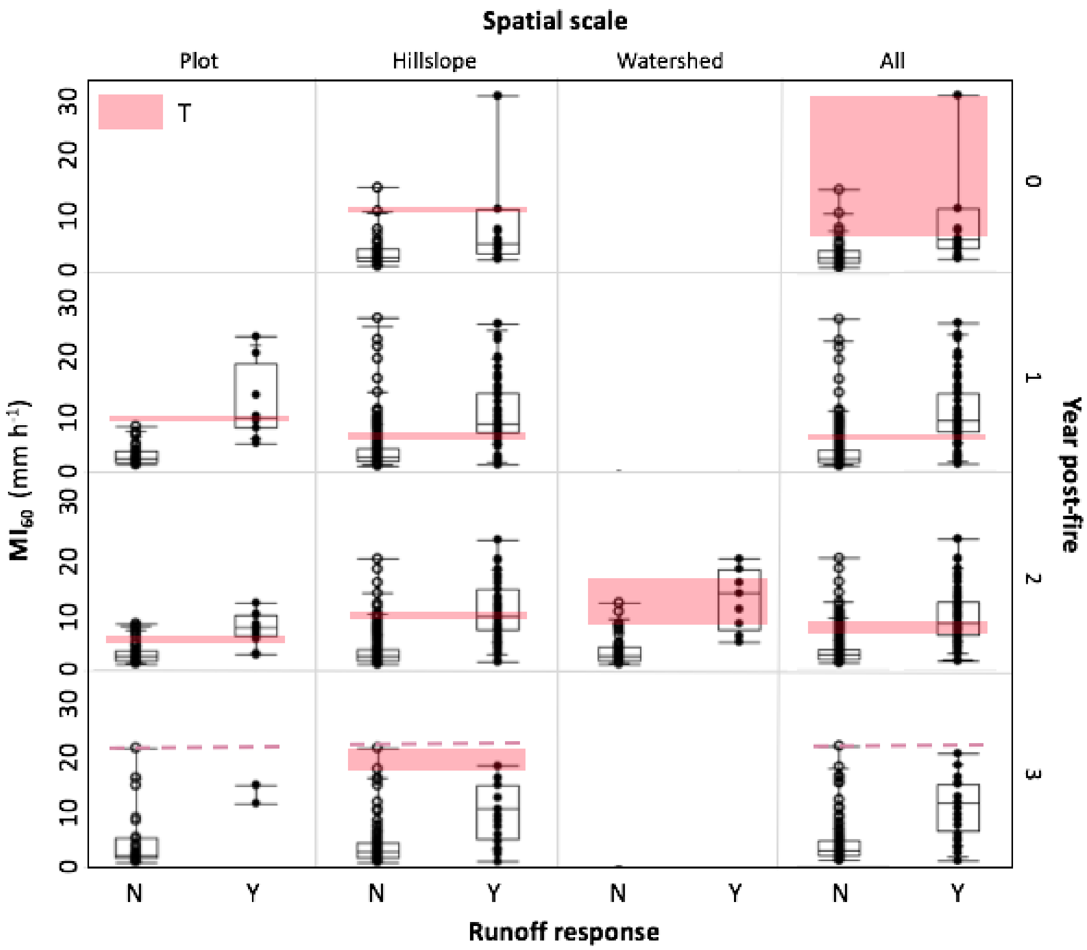

Figure 5. MI_{60} rainfall thresholds (T) for discrete spatial scales merged across fires and for all spatial scales merged across fires ("All") for post-fire years 0 to 3. Box plots show events that did not (N) and did (Y) produce runoff. All values are for sites without treatment. Shaded areas correspond to the range of thresholds (T) with the highest fraction of events correctly predicted by the threshold (F). Values included only if data were available for more than one fire. Dashed lines indicate the highest observed P for those thresholds where T-max was undefined.

Treatment effects

Plot and hillslope thresholds were compared by fire and year post-fire (Figure 6) to determine the effects of mulch treatments. Treatments increased thresholds for 63% of plot- and hillslope-scale comparisons in post-fire years 0-3. Most of these increases were at the hillslope scale, where79% of hillslope comparisons had increases in T-min or T-max from treatment compared to 36% of plot comparisons. Plot T-min and T-max were higher for sites with treatment as compared to those without in post-fire year 2 only. Within the Bobcat fire, T-min was 4 mm h^{-1} (F=0.96) at untreated plots and increased to 5 mm h^{-1} (F=0.87) with treatment. For the Hayman fire, T-min was 5 mm h^{-1} (F=0.95) for untreated plots and 8 mm h^{-1} (F=0.95) for plots with treatment (Table 5).

At the hillslope-scale, treatments increased thresholds during post-fire years 0-3, but not consistently across fires. During post-fire year 0, treatments only increased thresholds at the Bobcat Fire: T-min was 7 mm h^{-1} (F=0.88) at untreated sites and 8 mm h^{-1} (F=0.89) at sites with treatment. During post-fire year 1, treatments increased thresholds within all fires: in the Bobcat Fire, T-min values increased from 6 mm h^{-1} (F=0.85) to 11 mm h^{-1} (F=0.92) with treatment; in the Hayman Fire, T-min increased from 9 mm h^{-1} (F=0.85) to 11 mm h^{-1} (F=0.90) with treatment; and, in the High Park Fire, T-min increased from 9 mm h^{-1} (F=0.87) to 17 mm h^{-1} (F=0.93) with treatment. In post-fire year 2, treatments at hillslopes increased thresholds within both the Bobcat and High Park Fires: Bobcat T-min increased from 7 mm h^{-1} (F=0.93) to 12 mm h^{-1} (F=0.94) with treatment, and High Park T-min increased from 12 mm h^{-1} (F=0.92) to 17 mm h^{-1} (F=0.92) with treatment. In post-fire year 3, treatments increased thresholds within both the Hayman and High Park Fires: Hayman T-min increased from 8 mm h^{-1} (F=1) to 11 mm h^{-1} (F=0.96) with treatment, and High Park T-min increased from 12 mm h^{-1} (F=0.97) to 13 mm h^{-1} with treatment (F=0.94; Figure 6).

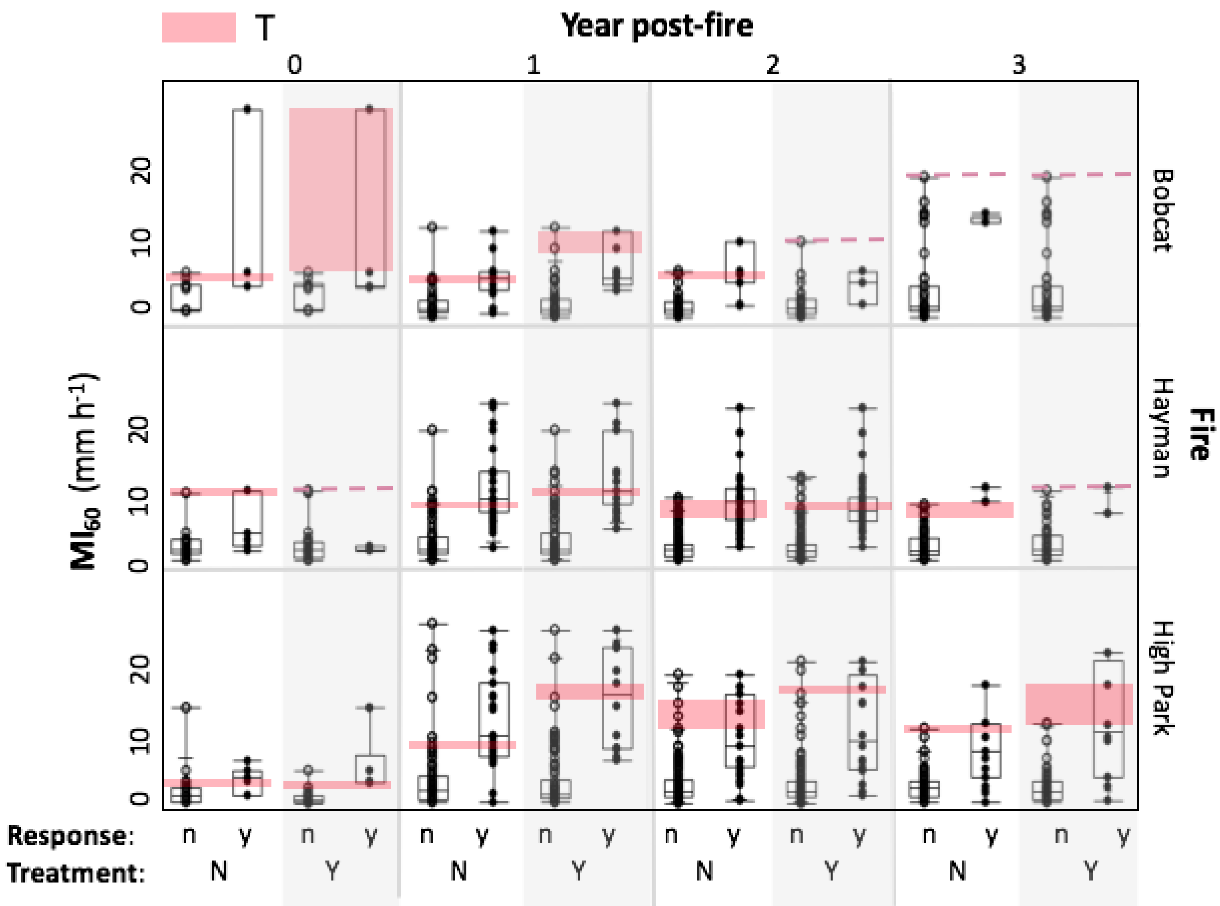

Figure 6. MI_{60} rainfall thresholds (T) for hillslopes by treatment status (N/Y), year post-fire and fire location. Box plots show events without a runoff response (n) compared to those with a runoff response (y). Shaded areas correspond to the range of thresholds (T) with the highest fraction of events correctly predicted by the threshold (F). Dashed lines indicate the highest observed P for those thresholds where T-max was undefined.

Effects of time since burn

We evaluated untreated hillslopes by fire and year post-fire to determine whether thresholds change over time (Figure 3). Overall, thresholds for post-fire year 0-3 ranged from 4-22 mm h^{-1} ($F \geq 0.85$). For the Bobcat and High Park Fires, rainfall thresholds increased with time since burn (Figure 3). T-min in the Bobcat Fire increased from post-fire year 1 to 3: from 6 mm h^{-1} in year 1 to 7 mm h^{-1} in year 2 and up to 22 mm h^{-1} in year 3. In the High Park Fire, T-min increased from post-fire year 0 to 2: from 4 mm h^{-1} in post-fire year 0 to 9 mm h^{-1} in post-fire year 1 and up to 12 mm h^{-1} in post-fire years 2 and 3. Time since burn does not appear to affect thresholds in the Hayman Fire.

When all fires were grouped by year post-fire, T-min increased from post-fire years 1-3; T-min was 11 mm h^{-1} (F=0.94) in year 0, 7 mm h^{-1} (F=0.85) in year 1, 10 mm h^{-1} (F=0.93) in year 2, and 18 mm h^{-1} (F=0.96) in year 3. While there is some evidence that thresholds tend to increase with time after fire, the effect of time since burn on thresholds appears to be site-specific and was not consistent enough across fires to allow us to define a clear separation of threshold values for each year post-fire (Figure 3).

Frequency of threshold exceedance

The frequencies of rainfall events with MI_{60} thresholds of 4-12 mm h^{-1} were calculated and mapped across Colorado (Figure 7). Most identified threshold have less than a 1-year return interval, indicating that post-fire runoff and erosion is likely to occur several times per year during the first two years after fire. The frequency of threshold exceedance increases with increasing elevation from 1500-2100 m; decreases from 2100-2300 m, and stays relatively consistent with elevation above that (Figure 8). Rain events with MI_{60} of 4 mm h^{-1} are estimated to occur between 5 to $\geq$10 times per summer in the forests affected by, and surrounding, the wildfires assessed here (Figure 7). Increasing MI_{60} decreases the event frequency, so events with MI_{60} of 5-7 mm h^{-1} are estimated to occur between 2-6 times per summer (Figure 7).

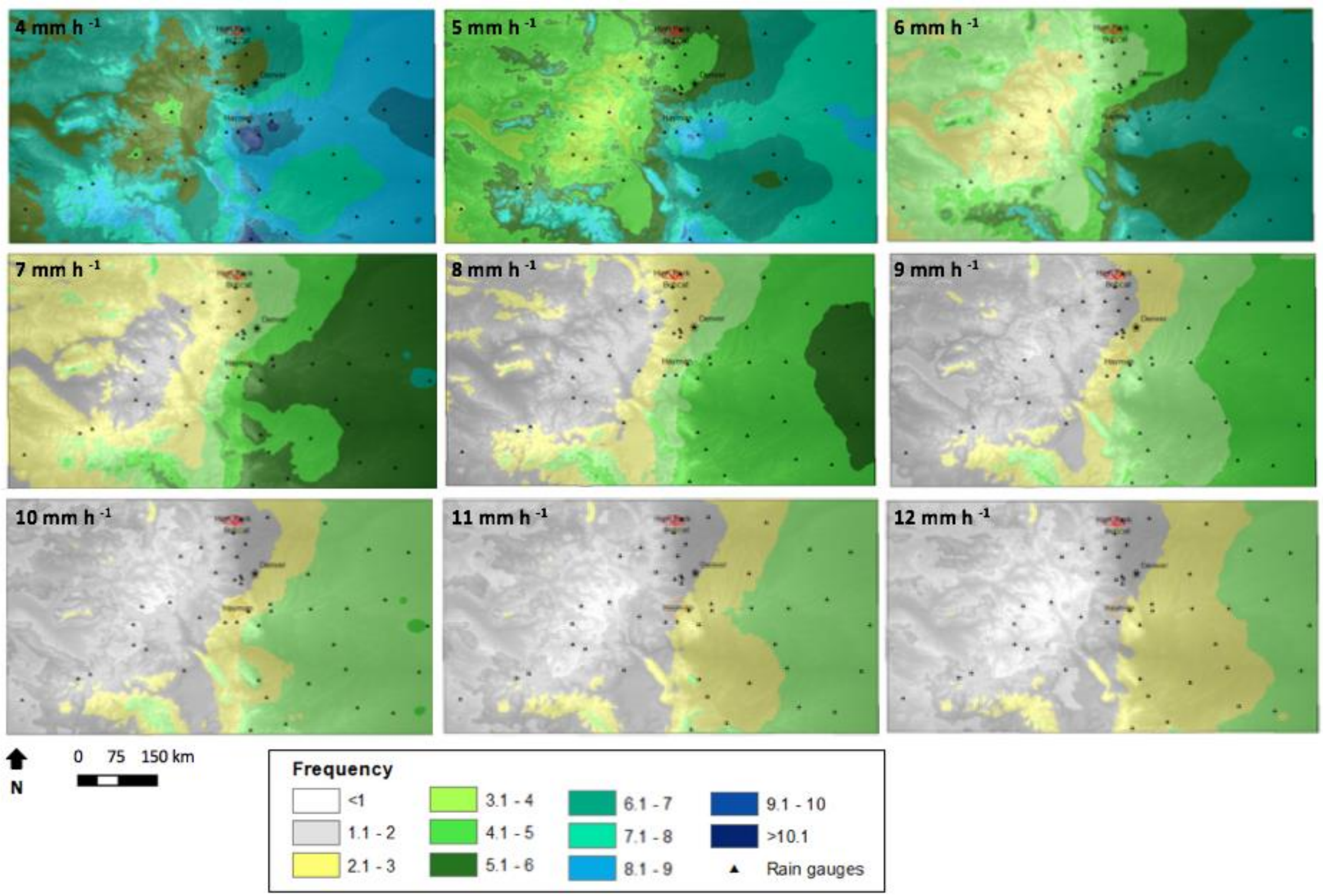

Figure 7. Frequency of exceedance in summer (June-September) for MI_{60} of 4-12 mm h^{-1} across Colorado. Data derived from NOAA rainfall gauges (Perica et al. 2013) and PRISM climate data (PRISM Climate Group 2017).

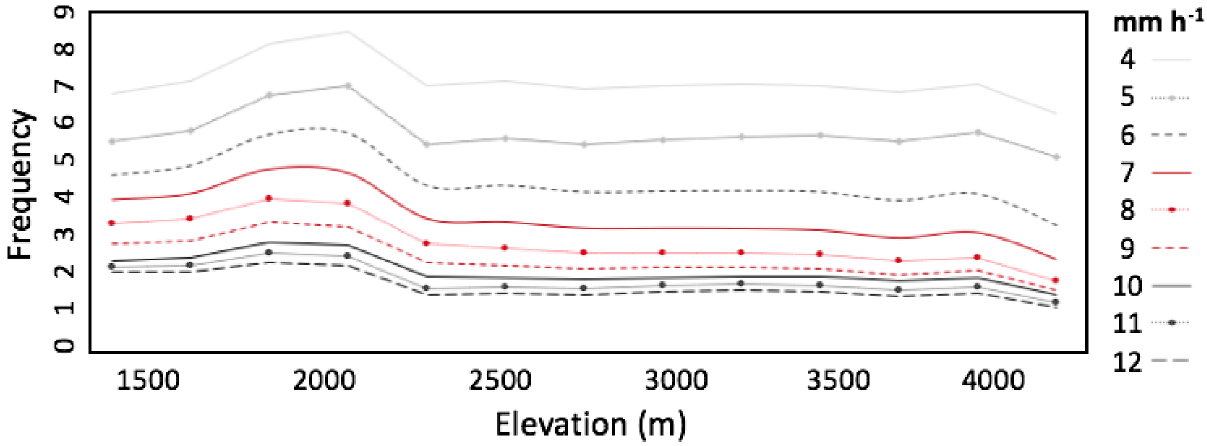

Figure 8. Average frequency of MI_{60} threshold exceedance in summer (June-Sept.) for the east slope of the Rockies in Colorado versus elevation for rainfall events with intensities from 4-12 mm h^{-1}. Data derived from NOAA rainfall gauges (Perica et al. 2013).

Management implications

Across the fires studied, rainfall thresholds overall were strong predictors of runoff occurrence (average F of 0.93). We did not find any consistent patterns in threshold variability by fire or spatial scale, so we recommend using the same thresholds throughout study region. We also recommend using threshold values identified for post-fire years 1-2 for the following reasons: (a) post-fire year 0 thresholds generally had lower sample sizes and were therefore most uncertain, (b) by post-fire year 3, recovery of vegetation appears to increase threshold values, and (c) thresholds from merged datasets were most similar to those identified by discrete fire and spatial scale during post-fire years 1-2. T-min in post-fire years 1-2 ranged from 6-12 mm h^{-1} for individual fires and from 7-10 mm h^{-1} across fires.

Many thresholds also increased with time since burn and mulch treatments. For untreated hillslopes, thresholds tended to increase with time after fire, although this effect appears to be site-specific (Figures 3 and 10). Thresholds primarily increased from post-fire year 1 to 2 (Table 7; Figures 6 and 7) with T-min of 6-9 mm h^{-1} in post-fire year 1 and 7-12 mm h^{-1} in post-fire year 2, which means a likely decrease in the frequency of runoff events. These threshold increases are likely due to vegetation recovery, as vegetation growth reduces exposure of the soil to rainfall and overland flow (Moreno-de las Heras et al. 2010), particularly in later years post-fire. The rate of vegetation recovery may vary by fire; for example, vegetation recovery for the Hayman Fire has been slower than for the other fires due to coarse granite-derived soils. In the Hayman Fire, similar intensities as those identified with runoff in post-fire years 0-2 occurred in later years without producing runoff responses, but higher intensities (MI_{60}>43 mm hr^{-1}) in post-fire year 7 did produce a runoff response (Robichaud et al. 2013b). Once vegetation grows back sufficiently, runoff generation may no longer be a threshold process because most or all rainfall can infiltrate into soils.

Treatments increased thresholds primarily at the hillslope scale in post-fire years 1-2; (Figures 6 and 9), and this treatment effect declined over time. In post-fire year 1, untreated hillslope T-min was 6-9 mm h^{-1} and increased to 11-17 mm h^{-1} with treatment; in post-fire year 2, T-min was 7-12 mm h^{-1} at untreated sites and 12-17 mm h^{-1} at sites with treatment; in post-fire year 3, T-min was 8-12 mm h^{-1} at untreated sites and 11-13 mm h^{-1} at sites with treatment (Table 5; Figure 9). Therefore, mulch is most effective in reducing runoff frequency in year 1, but reductions in mulch cover over time along with vegetation recovery will diminish differences in runoff between mulched and unmulched areas.

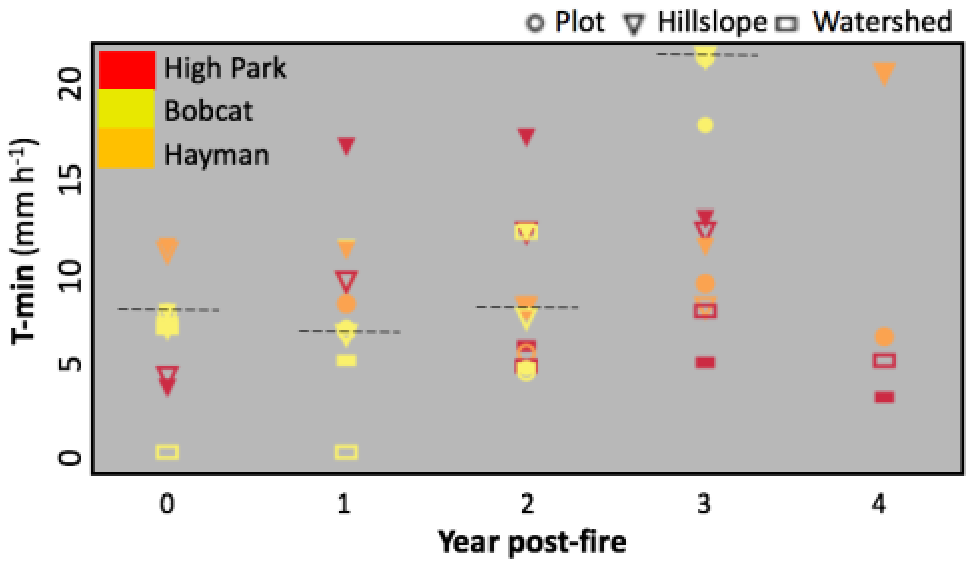

Figure 9. Summary of T-min values by fire year post-fire 0-4 and spatial scale. Filled symbols are those sample groups with treatment. Dashed lines represent thresholds identified across all fires and all spatial scales (Table 7).

BAER teams have very limited time to complete assessments and design treatments, and the frequency mapping tool will allow for rapid estimation of the number of runoff-producing storms likely during the post-fire summer seasons. The tool will also help other disaster response managers allocate resources for post-fire response, as the frequency values are an indication of how often roads or other infrastructure may experience flooding and sedimentation in the first two years after fire.

The rainfall thresholds for runoff presented here can be used to identify design storms that may cause erosion and sedimentation problems after fire. In the past, design storms represented extreme storms with return intervals of 5- to 25-years. Our work shows that runoff occurs at a much lower rainfall intensities in the CO Front Range, and the range of MI_{60} thresholds we identified nearly all have <1-year return interval, as estimated from the NOAA

Atlas (Perica et al. 2013). Thresholds of 7-8 mm h^{-1} are likely to be exceeded 2-7 times each summer; along the Colorado Front Range, frequency increased with elevation from 1500-2100 m, decreased from 2100-2300 and was relatively constant above 2300 m (Figure 8). The frequency maps can be used to identify likely storm patterns in different burn areas. The maps are most reliable in areas with high NOAA station density in central and eastern Colorado; there were no stations with 15-minute data in northwestern Colorado to generate the frequency analysis, so those values in the map are the most uncertain.

Although many factors may affect thresholds, e.g., surface cover (Wainwright et al. 2000; Moreno-de las Heras et al. 2010; Prosser and Williams 1998; Inbar and Wittenberg 1998), spatial scale (Cammeraat 2002) or flow path lengths (Wagenbrenner and Robichaud 2014), we found that it is difficult to isolate the effects of a single factor. Consequently, we did not detect clear differences in rainfall thresholds with treatment at the plot-scale, for scale of measurement, nor consistently with time since burn. We recommend that managers use the same tool for all areas as a starting point to estimate the frequency of post-fire runoff, but a range of threshold values should be considered to address uncertainties in site-specific thresholds. The thresholds presented here indicate only a binary (yes/no) response to rainfall, and do not indicate the magnitude of erosion. Smaller erosion events (<0.05 Mg ha^{-1}) account for 70% of the erosion events at the hillslope-scale within the three fires investigated here, meaning that some threshold-exceeding storms do not produce large quantities of erosion.

Relationship to other recent findings and ongoing work on this topic

Rainfall thresholds for runoff and erosion post-fire have been mentioned in previous papers (Moody 2002; Schmeer 2014; Pietraszek 2006), but they have not been analyzed in the detail presented here. Most of these prior studies reported thresholds as maximum 30-minute rainfall intensity (MI_{30}) values. MI_{30} and MI_{60} rainfall data from the three Front Range fires in our analysis were correlated to determine the values of MI_{60} that correspond to reported MI_{30} values from the literature (Figure 10; Equation 3).

$$y = 0.5548x + 0.516 \tag{3}$$

where y is an MI_{60} rainfall value and x is the corresponding MI_{30} rainfall value from the three Front Range fires of our analysis (n=2532; r^2=0.94; Figure 11).

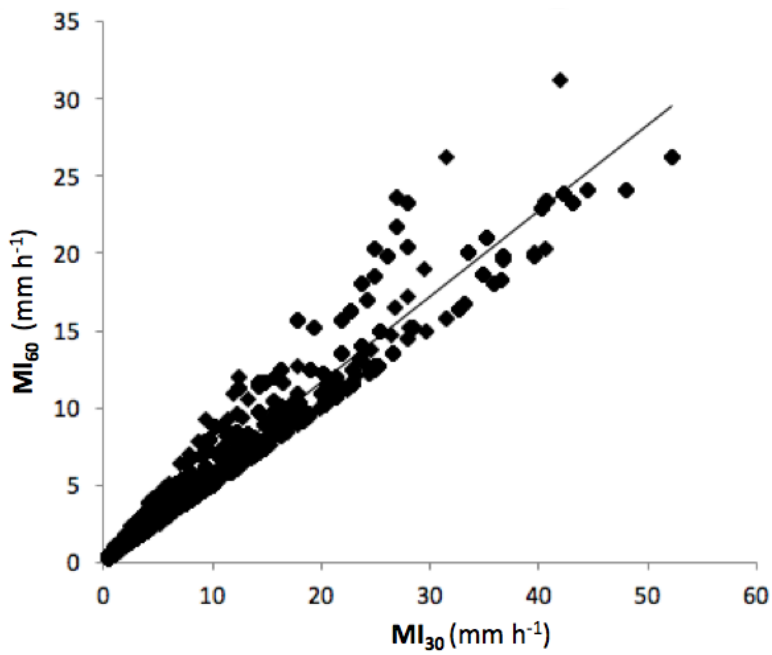

Figure 11. The relationship between MI_{30} and MI_{60} rainfall intensities for the three Front Range fires of our analysis (n=2532; r^2=0.94).

Sediment production identified for hillslopes within the Hayman Fire by Pietraszek (2006) was initiated by MI_{30} of 8-10 mm h^{-1}; converting to MI_{60} using Equation 3 results in thresholds between 5-6 mm h^{-1}, slightly lower than the range of Hayman hillslope thresholds identified here (Table 5). The MI_{30} thresholds to initiate a response in runoff/erosion during post-fire years 1 and 2 within the Spring Creek basin (2680 ha) of Colorado's 1996 Buffalo Creek Fire were reported at 5-9 mm h^{-1} (Moody 2002), resulting in MI_{60} values between 3-6 mm h^{-1}. MI_{30} thresholds for other basins across the western U.S. (220-2170 ha) were 8 mm h^{-1} for post-fire years 0-1, and 11 mm h^{-1} for post-fire year 2 (Moody 2002), corresponding to MI_{60} of 5-7 mm h^{-1}, respectively. These thresholds are consistent with the range we reported. The thresholds are also similar to those reported for an Australian fire, where MI_{30} rainfall $\geq$7 mm h^{-1} initiated erosion on a 5 ha (13 acre) burned site, and erosion increased substantially when MI_{30} was above 13 mm h^{-1} (Prosser and Williams 1998). However, threshold values may differ for other study regions, so we do not recommend applying these outside the area mapped without further data analysis.

Future work needed

We recommend further analysis of spatial scale and treatment effects on thresholds at other locations to determine how thresholds for the Colorado Front Range compare to those for other types of climates and soils. Fine spatial resolution rainfall data would help reduce uncertainties in threshold definition. We also recommend continuous monitoring of runoff at all spatial scales, including areas with ephemeral runoff because this reduces uncertainty in connecting rain event characteristics to runoff response. To determine effects of treatments on erosion, we recommend including the following in rainfall-runoff investigations by year post-fire: (a) bare soil, basal surface cover, and/or vegetative cover (%), and (b) methods to quantify and track surface cover across watershed, such as fine resolution aerial photography. Future work could also explore the relationship between vegetation recovery and runoff processes. Threshold analysis could also be expanded to changes in magnitude of runoff and erosion with different rain storm characteristics. With data from more locations, the tool we presented here could be expanded into an interface that allows rainfall frequency mapping across US. Information on rainfall thresholds presented here could also be incorporated into existing rapid assessment tools (e.g., Miller et al. 2015) and other online models (e.g., ERMiT, disturbed WEPP, etc.). Rainfall frequency information could also be linked with analyses of intensification of rainfall under future climate to determine how post-fire runoff and erosion may be affected by changes in storm frequency.

Deliverables crosswalk table

All deliverables identified in our proposal and the status of each, plus additional deliverables created are in Table 8.

Table 8. Deliverables, descriptions and dates delivered

Deliverable Type	Description	Delivery Dates
Presentation	Present findings at a wildland fire conference	December 2016
Webinar	Present webinar to Southern Rockies Fire Science Network	Aug. 9, 2017
Annual report	Performance reports complete	Feb. 17 & Sept. 28, 2017
Final report	Final report complete	Nov. 3, 2017
Refereed publication	Submitted to journal of Forest Ecology and Management	Nov. 3, 2017

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