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Post-fire mulching for runoff and erosion mitigation Part II: Effectiveness in reducing runoff and sediment yields from small catchments

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ABSTRACT

Agricultural straw, hydromulch, and wood shred or wood strand mulches increasingly are being used as post-fire hillslope treatments, but the differences in effectiveness among these mulch treatments are not fully understood. Following the 2002 Hayman fire in central Colorado and the 2003 Cedar fire in southern California, matched catchments were monitored for five to seven post-fire years to determine the effectiveness of wheat straw mulch (Hayman fire only) and hydromulch in reducing post-fire runoff, peak flow rates, and sediment yields from natural rainfall. Measured runoff and sediment yields were caused by short duration high intensity summer storms at the Hayman fire and long duration winter rains at the Cedar fire.

The wheat straw mulch treatment significantly reduced peak flow rates and sediment yields at the Hayman fire. The annual peak flow rates in the first two post-fire years in the straw mulch catchment were 4.5 and 3.9 $m^3\ s^{-1}\ km^{-2}$ (respectively) as compared to 4.3 and 7.1 $m^3\ s^{-1}\ km^{-2}$ (respectively) in the control. In post-fire years one and two, the maximum event sediment yields in the straw mulch catchment were 7.2 and 10 $Mg\ ha^{-1}$, respectively, which were less than half of the maximum event sediment yields in the control catchment (19 and 24 $Mg\ ha^{-1}$, respectively). The straw mulch catchment had no detectable runoff or sediment yield after the second post-fire year, but the control catchment continued to have measurable runoff and sediment yields through the seventh post-fire year. The straw mulch treatment effect in runoff reduction was not significant in the statistical model. Total ground cover was 80% immediately after the application of straw mulch, and decreased to 10% by the end of first post-fire year, yet total ground cover values remained high as litter and vegetation, including invasive cheatgrass, increased.

The hydromulch cover at both fires declined rapidly and provided less than 10% of the ground cover within 2.5 months after application at which point the catchment was presumed to be untreated. Due to differences in precipitation, the three catchments at the Cedar fire had significantly different hydrologic responses during the presumed untreated portion of the study, which precluded evaluation of treatment effectiveness during the short treated period. The peak flow responses from the hydromulch and control catchments at the Hayman fire were also different during the presumed untreated period and were not tested. Although the runoff and sediment yields did not differ during the presumed untreated period and were tested for treatment effects, the Hayman hydromulch treatment did not significantly affect either response during the first post-fire year—the presumed treated period.

Unit-area sediment yields from the catchments were similar to those measured on hillslope plots at both the Hayman and Cedar fires in the first post-fire years, but in later years the sediment yields from the catchments were at least double the sediment yields measured on hillslope plots. The longer periods of greater erosion rates in the catchments likely reflect the addition of channel erosion processes and a difference in hydrologic connectivity at the catchment scale.

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1. Introduction

Post-wildfire increases in hydrologic and geomorphic responses often increase the risk of damage to valued resources within and downstream of burned areas. Land treatments, such as mulches, may be applied to burned areas to mitigate increases in post-fire responses, and thereby reduce the risk of damage to public safety, property, infrastructure, and natural habitats and landscapes (Robichaud et al., 2010). Post-fire mulches and application techniques have rapidly evolved over the past decade (Robichaud et al., 2000, 2010), and the evaluation of the efficacy of these materials and methods at

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mitigating hydrologic responses and their long-term effects have not kept pace.

Characteristics of climate, topography, soils, vegetation, degree and extent of soil burn severity, and channel proximity create high variability in post-fire responses and recovery rates (Baker, 2003; Beschta, 1990; DeBano et al., 1998; Robichaud, 2000). More specifically, post-fire runoff, peak flow rates, and erosion rates are highly dependent on rainfall intensity and amount as well as the magnitude and spatial distribution of fire-induced soil disturbances. Fire effects on soil include decreases in soil organic matter and surface litter, reduction in soil aggregates resulting in less soil structure, loss of interceptive and transpiring vegetation, changes in hydraulic roughness, and alteration or formation of water repellent soil conditions (Certini, 2005; DeBano et al., 1998; Doerr et al., 2009; Moody and Martin, 2001; Shakesby and Doerr, 2006). High severity fires tend to be larger and have more homogenous patches of soil disturbance than low or moderate severity fires (Keane et al., 2008). Increased spatial extent, or patch size, of disturbed soil may result in greater overland flow, increased potential for rilling, and larger amounts of sediment transport (Moody et al., 2008).

Post-fire mulch treatments can protect the soil from raindrop impact, increase the flow path length and reduce the kinetic energy of overland flow, and increase the hydraulic roughness and soil moisture retention (Bautista et al., 1996; Foltz and Wagenbrenner, 2010; Robichaud et al., 2010; Wagenbrenner et al., 2006). Post-fire mulching has been shown to decrease erosion and increase the amount of live vegetation when compared to untreated burned areas (Bautista et al., 2009; Wagenbrenner et al., 2006). However, thick clumps of mulch have been shown to suppress revegetation recovery in burned areas (Bautista et al., 2009; Dodson and Peterson, 2010). The specific characteristics of the applied mulch, such as strand length, ground cover amount, and thickness (depth) of application, can affect the ability of mulch to reduce erosion (Bautista et al., 1996; Robichaud et al., 2010). In some studies, 60 to 70% ground cover has been shown to reduce hillslope erosion rates (Benavides-Solorio and MacDonald, 2005; Pannkuk and Robichaud, 2003).

Studies have shown that straw mulch can be effective at reducing post-fire sediment yields immediately after burning and for up to three post-fire years (Bautista et al., 1996; Groen and Woods, 2008; Robichaud et al., 2013; Wagenbrenner et al., 2006). However, straw mulch can introduce undesirable non-native seeds to remote areas (Beyers, 2004) and can be easily moved by high winds (Copeland et al., 2009). Although there are reports of straw mulch being washed downslope when applied in steep mountainous environments, Wagenbrenner et al. (2006) found post-fire straw mulch treatments effectively reduced erosion when applied to slopes averaging 54% in the Colorado Front Range. In areas where high winds tend to redistribute straw mulch into clumps against burned vegetation or into depressions and channels, hydromulch has been used as a post-fire mulch treatment. Hydromulches are composed of fibrous material (wood, paper, etc.), tackifiers (synthetic or natural polymers), and other components such as seed, polyacrylamide (PAM), and fertilizer, which are mixed with water to form a slurry and then sprayed on the soil from truck or aircraft mounted sprayers (Robichaud et al., 2010). Hydromulch treatments have varied in composition and application rate, which likely contributes to the inconsistency in reported effectiveness among the few available post-fire studies (Robichaud et al., 2010).

Erosion processes and interactions between processes vary with scale (Allen, 2007). Infiltration and rain splash and sheet (interrill) erosion processes are generally observed and measured on small plots ($\leq 1 \text{ m}^2$) as they are difficult to isolate and measure at larger scales (Benavides-Solorio and MacDonald, 2001; Wainwright et al., 2000). Given that several meters of runoff are generally needed before flow concentrates and rills begin to form, longer hillslope plots are needed to observe rilling (Benavides-Solorio and MacDonald, 2005). Hillslope erosion by water is primarily controlled by raindrop and surface flow processes which are modified by the soil, vegetation, and topographical characteristics. As area increases to include convergent slopes, hillslope runoff converges to rill and channel flow thereby involving a wider range of hydrologic processes and a greater level of complexity and interaction (Wainwright et al., 2000). Channel processes, such as bed and bank scour and sediment transport and storage, may dominate the geomorphic responses in steep areas and larger spatial scales (Moody and Martin, 2001; Moody and Martin, 2009). Other factors that impact erosion rates such as rainfall, infiltration and sub-surface flow rates, soil properties, vegetation, and fire-induced effects (burn severity, soil water repellency, loss of organic matter) have spatial variation that occurs at relatively small scales, and the cumulative effects may be more easily discerned when measured at the catchment scale.

Post-fire treatment decisions are generally made and executed at the watershed scale, so knowledge of treatment effectiveness at the watershed scale would be most applicable to post-fire management. However, effectively measuring runoff and erosion at this scale is labor-intensive and monitoring equipment is expensive to install and maintain (Robichaud, 2005). It is unclear if estimates of potential sediment per unit area can be extrapolated between spatial scales, and much of the available post-fire erosion and post-fire treatment effectiveness research data come from planar hillslope measurements. Further, few studies have measured runoff and/or erosion rates beyond three years post-fire, and studies addressing mulch effectiveness at reducing post-fire responses, especially, are rare (Robichaud et al., 2010).

This paper is the second part of a two-part study of post-fire mulch treatment effectiveness. Part I of the study used hillslope plots (20 to 331 m^2) to compare sediment yields from burned areas treated with mulches (wheat straw, wood strands, and wood-based hydromulch) to untreated control plots in the same fires (Robichaud et al., 2013). When data were analyzed by fire, wood strand mulch reduced sediment yields at both fires where it was tested and the wheat straw mulch reduced sediment yields at two of the four fires where it was tested; hydromulch did not reduce sediment yields on either fire where it was tested. The sediment yields were strongly related to 10-min maximum rainfall intensity rather than total rainfall. Erosion rates were highest in the first post-fire year and decreased as vegetation recovery occurred.

This study, Part II, compared runoff, peak flow rates, and sediment yields from matched mulch-treated and untreated (control) catchments (1.5 to 5.2 ha) at two fires (Hayman and Cedar). The Hayman fire was included in both parts of this study and we used the results from Part I as well as published results from a hillslope plot study done on the Cedar fire (Hubbert et al., 2012) to compare sediment yields at two different spatial scales. The goals of the current study were to evaluate the effectiveness of two post-fire mulch treatments at reducing runoff and erosion at the small catchment scale and to gain insight as to the underlying processes that control post-fire runoff and erosion. Specific objectives were to: 1) determine the effects of straw mulch and hydromulch on runoff amounts, peak flow rates, and sediment yields in small catchments in the first post-fire year and in subsequent years; 2) quantitatively describe processes affected by mulch treatments that may explain the results; and 3) compare erosion rates at the hillslope (as measured in Part I) and catchment scales over all study years at the Hayman fire and for the for the first two post-fire years at the Cedar fire using hillslope plot sediment yield data from Hubbert et al. (2012).

2. Methods

2.1. Site description

Matched catchment study sites were established following the 2002 Hayman (central Colorado; on the Pike-San Isabel National Forest) and 2003 Cedar (southern California; on the Capitan Grande Indian

Reservation and Cleveland National Forest) fires to test the effectiveness of wheat straw mulch and hydromulch in reducing post-fire runoff and erosion (Fig. 1). Both fires are located in semi-arid areas and receive an average of about 400 mm of precipitation annually. The Hayman fire has a monsoonal climate with about 70% of the yearly precipitation occurring between April and September, and the Cedar fire, with a Mediterranean climate, receives most of its precipitation as winter rain (Table 1). Data from the Manitou Experimental Forest weather station were used to determine the long-term average and annual precipitation values at the Hayman fire. At the Cedar fire, the long-term average precipitation value was determined from the Alpine City weather station (Table 1), but precipitation data were missing for more than 50 days during some years of the study and data were not available after 2005. Thus, annual precipitation values for the study years were taken from the Alpine remote automated weather station (RAWS) that has been operating since 2001. The Alpine RAWS is located 10 km southeast of the Cedar study sites at the Descanso Ranger Station of the Cleveland National Forest (elevation 622 m).

The soils at both fires were derived from granitic parent materials, but the gravelly texture of the surface soil at the Hayman fire contributes to its high erodibility and low soil water holding capacity. The dominant pre-fire vegetation differed between these two fires in response to the climate differences (Table 1). The Hayman fire burned through dry forest dominated by ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Psuedotsuga menziesii*) with common juniper (*Juniperus communis*) and kinnikinik (*Arctosaphylos uva-ursi*) in the understory. The Cedar fire was located in a chaparral-dominated landscape with an overstory of chamise (*Adenostoma fasiculatum*) and cupleaf ceanothus (*Ceanothus greggii*) and an understory dominated by Cleveland sage (*Salvia clevelandii*) and chaparral yucca (*Hesperoyucca whipplei*) (Table 1).

2.2. Experimental design

At each fire, three small catchments located in areas of high soil burn severity (USDA Forest Service, 2002, 2003) were selected to minimize differences in climate, soils, pre-fire vegetation, land use, topography (elevation, aspect, and slope), and burn severity (Fig. 1) (Hewlett, 1971). At the Hayman fire, the catchments were adjacent with the control catchment in the center and the straw mulch and the hydromulch treated catchments on opposite sides; each treated catchment shared a common ridge with the untreated control (Table 2; Fig. 1). The catchments were selected and instruments installed in August and September 2002 (the year of the fire or "post-fire year 0"), 2–3 months after burning and immediately before the treatments were applied. Two of the three catchments at the Cedar fire were adjacent (fully treated and control), and the partially treated catchment was located about 2 km to the southeast (Fig. 1). The catchments were selected and instruments installed in January and February 2004 (post-fire year 0), 3–4 months after burning and 1 month after the hydromulch was applied.

The outlet elevations of the Hayman fire catchments were nearly the same—around 2430 m. At the Cedar fire the non-adjacent, partially treated catchment outlet was more than 200 m higher (1015 m) than the outlets of the control (795 m) or the fully treated (785 m) catchments (Table 2). The Hayman catchments generally faced east, but the aspects of the Cedar catchments were more varied with the control and fully treated catchments generally facing west and the partially treated catchment facing south (Table 2). The Hayman catchments had moderately steep slopes (28–35%) and 39–68% of the catchment areas had slopes greater than 30%. In contrast, the Cedar catchments had gentler slopes of 18–20%, and only 2–7% of the catchment areas had slopes greater than 30% (Table 2).

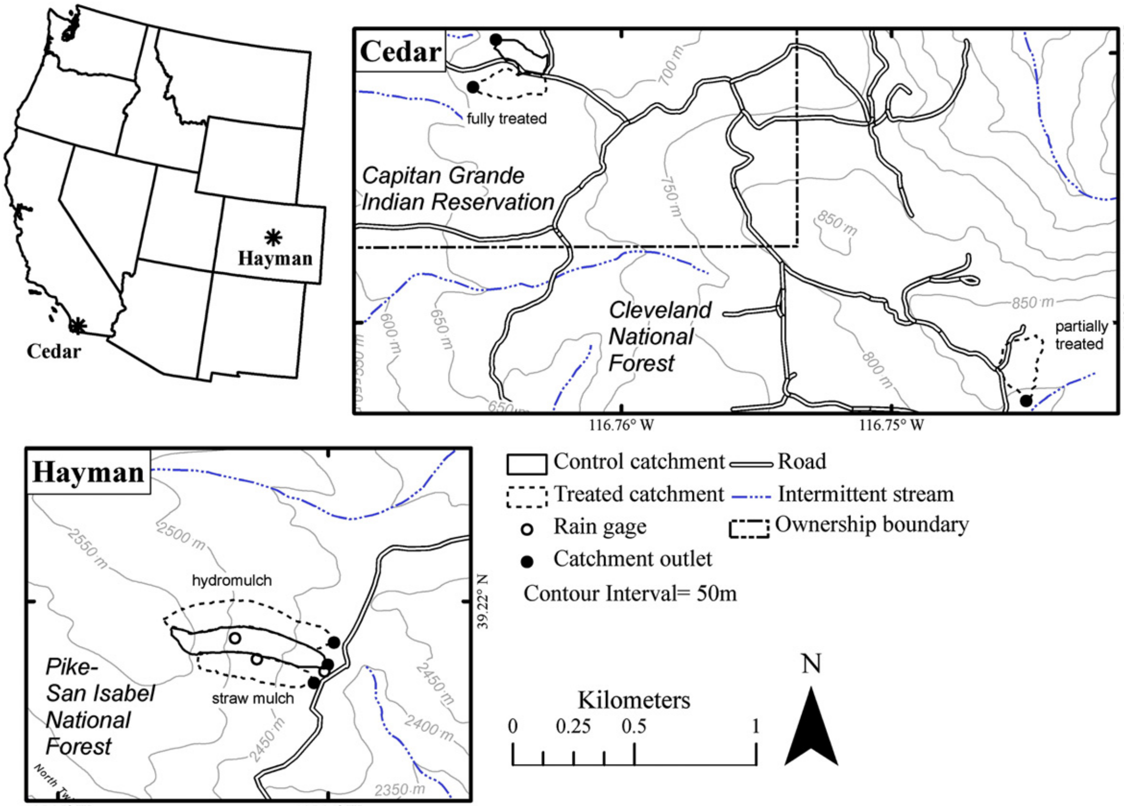

Fig. 1. Topographic maps of the post-fire matched catchment mulch treatment effectiveness study sites at the Hayman and Cedar fires, which are located in Colorado and southern California in the western US.

Table 1
General characteristics of the fire areas. Fire name, mean catchment outlet elevation (Elev); nearby long-term weather station name, elevation (Elev), distance from the study sites, record length, and mean annual precipitation; soil series, taxonomic class, and texture (as delineated by the USDA-NRCS soil classification system), mean soil bulk density (0–5 cm depth) and soil particle size distribution (0–1 cm depth) as determined from our laboratory analysis; and the dominant pre-fire overstory and understory vegetation for both fires.

Fire Elev (m)	Weather station			Soil characteristics				Pre-fire vegetation	
	Name Elev (m)	Distance to site (km) [record length (yr)]	Annual precip[a] (mm yr^{-1})	Soil series [taxonomic class]	Clay/silt/sand fractions (%)	Texture	Bulk density (g cm^{-3})	Dominant overstory species	Dominant understory species
Hayman 2430	Manitou Exp. Forest 2390	27 [64]	400	Sphinx [*sandy-skeletal, mixed, frigid, shallow Typic Ustorthents*] Legault [*sandy-skeletal, micaceous, shallow Typic Cryorthents*]	1/11/88	gravelly coarse sand	1.39	Ponderosa pine (*Pinus ponderosa*) Douglas fir (*Pseudotsuga menziesii*)	Common juniper (*Juniperus communis*) Kinnikinnick (*Arctosaphylos uva-ursi*) Pine dropseed (*Blepharoneuron tricholepis*)
Cedar 865	Alpine City 529	5 [36[b]]	398	Cieneba [*loamy, mixed, superactive, nonacid, thermic, shallow Typic Xerorthents*]	2/15/83	coarse loamy sand	0.99	Chamise (*Adenostoma fasiculatum*) Cupleaf ceanothus (*Ceanothus greggii*)	Cleveland sage (*Salvia clevelandii*) Chaparral yucca (*Hesperoyucca whipplei*) Flat-topped buckwheat (*Eriogonum fasciculatum*)

[a] The historic average annual precipitation is reported by water year for both sites.

[b] The historic average annual precipitation was calculated for water years with 5 or fewer days of missing data; 36 years of the 58-year record were used.

Treatments were aerially applied at both fires. Straw mulch was applied at a nominal rate of 2.2 Mg ha^{-1} to one Hayman catchment only. Hydromulch, a mixture of wood fiber, guar tackifier, and water was applied to the other treated Hayman catchment at a rate of 2.0 Mg ha^{-1} (dry mulch weight). Both treated catchments at the Cedar fire were hydromulched with a commercial hydromulch that included wood and paper fiber, a non-water soluble tackifier, and water. The hydromulch application was intended to cover the total area of the fully treated catchment and about half the area of the partially treated catchment by applying 30 m wide contour strips of hydromulch separated by 30 m wide strips of no treatment.

2.2.1. Instrumentation

A sediment trap and a 90° V-notch weir were constructed at the outlet of each catchment (Fig. 2) and surveyed to determine a depth–volume storage relationship and maximum storage volume of the sediment trap. A trash rack was constructed upstream of each weir to protect the control section from debris (Fig. 2).

Water level in each weir was measured using a magnetostrictive linear displacement transducer, a magnetic float along a stainless steel rod (MTS Systems Inc., Cary, North Carolina, USA). The depth of accumulated sediment, snow, and/or runoff in each sediment trap was measured using an ultrasonic depth sensor (Judd Communications Inc., Salt Lake City, Utah, USA) (Fig. 2).

Sediment accumulated in the sediment traps was periodically measured, sampled, and removed. Small quantities of accumulated sediment were weighed, sampled for soil moisture analysis, and removed with buckets. Larger quantities of accumulated sediment were removed with mechanical equipment after either surveying to calculate the sediment volume and sampling for bulk density calculation, or measuring the weight of material contained in a filled bucket on the excavating equipment, sampling for soil moisture, and counting the number of full buckets removed during the clean out. Field-measured sediment weights or volumes were converted to dry sediment mass using water content or bulk density of the samples.

Precipitation within the catchments was recorded using recording tipping bucket rain gages at the outlet of each catchment as well as within the boundary of each catchment, except at the Hayman fire where close proximity of the catchments allowed sharing of a single tipping bucket rain gage at the outlet of the center (control) catchment and two upslope gages (Fig. 1).

A data logger was used to control instruments, store data, and transmit data via modem to a common server. Rainfall was continuously measured and the cumulative rainfall was recorded at 1 min intervals. All other measurements were recorded every 1, 5, or 10 min.

2.3. Catchment characteristics

Ground cover in each catchment was assessed along 25-m transects—4 transects per catchment at Hayman (e.g., Fig. 3) and 5 transects per catchment at Cedar. Five 1-m^2 square quadrat samples equally spaced along each transect were used to sample and categorize ground cover. At the Hayman fire, the quadrat was divided into a 10-cm grid and the cover was classified at 100 points. At the Cedar fire, the fraction of each cover class within the quadrat was visually estimated. Cover classes were mineral soil (including gravel up to 25 mm), rock (>25 mm), wood (including all sizes of woody debris and burned trees or tree roots), litter (including needles, leaves, or other organic debris), vegetation (including moss, grass, forbs, and shrubs), and mulch treatment (hydromulch or straw). The locations of the quadrats and transects were marked during the first measurement in the year of the fire (late September 2002 at Hayman, 1 week after treatments were applied; and early March 2004 at Cedar, 2–3 months after treatments were applied) and subsequent measurements were conducted each year in late summer or autumn, except at the Cedar sites which were measured in June

Table 2
Wildfire start date, treatment types, and nominal treatment application rates of the dry mulch components are listed by fire and site. Catchment characteristics including area, outlet elevation, aspect, mean slope, and proportion of catchment with slopes greater than 30% describe each treatment site for both fires.

Fire	Fire start date	Treatment	Nominal dry mulch application rate ($Mg\ ha^{-1}$)	Catchment				
				Area (ha)	Outlet elevation (m)	Aspect (degrees)	Slope (%)	Area with >30% slope (%)
Hayman	8 Jun 2002	Straw mulch[a]	2.2	3.3	2430	100	35	68
		Hydromulch[b]	2.0	5.2	2430	81	28	39
		Control		4.6	2430	105	31	45
Cedar	26 Oct 2003	Fully treated[c]	2.2	2.1	785	270	20	7
		Partially treated[d]	1.1	2.6	1015	185	18	7
		Control		1.5	795	300	18	2

[a] Agricultural wheat straw.

[b] Wood fiber and guar tackifier; seed was added to the hydromulch for the general post-fire response but not to the hydromulch applied to the study watershed (D.Entwistle, USDA Forest Service, personal communication, 8 November 2006).

[c] Hydromulch of wood and paper fiber with non-water soluble binder (USDA Forest Service, 2003).

[d] Hydromulch of wood and paper fiber with non-water soluble binder applied in 30 m contour strips (USDA Forest Service, 2003).

of the year of the fire (second measurement that year) and in the first post-fire year.

2.4. Analysis

Individual storm events were separated by at least 6 h with no measured precipitation. The total rainfall (mm) and the 10-min and 30-min maximum rainfall intensities (I_{10} and I_{30}, respectively) were calculated for each rainfall event. Return periods for 10-min rainfall were calculated for each fire using a rainfall frequency atlas (Arkell and Richards, 1986; Frederick and Miller, 1979; Miller et al., 1973) and were used to categorize the observed rainfall events. The rainfall characteristics recorded at all rain gages at the Hayman fire were averaged for each event, whereas the rainfall characteristics were averaged across the two gages in each catchment at the Cedar fire.

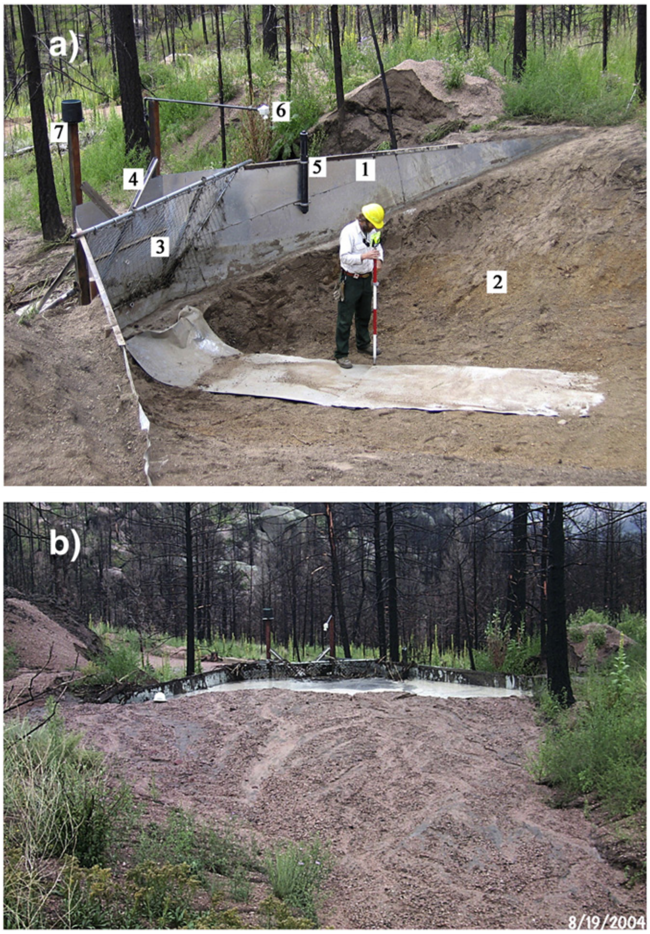

Fig. 2. A typical instrumented sediment trap and weir at the outlet of a catchment as exemplified by the Hayman control catchment. a) The empty catchment after sediment removal (Robichaud et al., 2008). b) The catchment with sediment from 19 Aug 04 event. Each of the study catchments had similar instrumentation as labeled in a): 1) steel headwall with concrete foundation; 2) runoff and sediment storage area; 3) trash rack; 4) 90° V-notch weir; 5) magnetostrictive stage gage; 6) ultrasonic depth sensor; and 7) tipping bucket rain gage.

Runoff consisted of water and transported sediment. The stage in each weir, h (mm), was converted to flow rate through the weir, Q ($m^3\ s^{-1}$), using the relationship:

$$Q = 4.89 \times 10^{-8} h^{2.48} \tag{1}$$

(USDA, 1979). The event runoff was the sum of residual volume of water and sediment in the sediment trap and the total flow through the weir during each event. The peak flow rate for each catchment and event was the maximum of either the peak flow rate through the weir or the maximum change in sediment trap volume per unit time.

Multiple runoff events occurred at the Hayman and Cedar fires between sediment measurements. The sediment values measured for these events (one event at Hayman and all but three events at Cedar) were prorated to determine per-event sediment yields. Given that sediment yields were more closely related to runoff rates at the Hayman site and to rainfall totals at the Cedar site, the cumulative sediment yields were prorated by the event runoff at the Hayman site and by the event rainfall at the Cedar site (19 accumulation periods). Each event sediment yield was then the cumulative sediment yield for the period of evaluation multiplied by the single event value (runoff or rainfall) divided by the total cumulative value (runoff or rainfall) of all events that produced runoff for the period of accumulation. The non-prorated cumulative sediment yields at the Cedar control catchment were used to compare to results from Hubbert et al. (2012).

The runoff, peak flow rates, and sediment yields (mm, $m^3\ s^{-1}\ km^{-2}$, and $Mg\ ha^{-1}$, respectively) were normalized by dividing by the catchment area. Events that occurred in a single wet season were grouped by post-fire years, and this differed slightly for the two fires. The year of fire occurrence was defined as beginning on the fire start date—8 Jun 2002 for the Hayman fire and 26 Oct 2003 for the Cedar fire. At the Hayman fire, the year of the fire continued through 31 Oct 2002. At the Cedar fire, the year of the fire continued through 30 Sep 2004. This allowed the wet season which immediately followed the fire to be considered the year of the fire at both fires. At the Hayman fire, subsequent post-fire years were defined as beginning on 1 Nov and ending on 31 Oct. The subsequent post-fire years at the Cedar fire were defined the same as the water year—beginning on 1 Oct and ending on 30 Sep.

We directly compared the runoff, peak flow, and sediment yield responses of the treated catchments to the responses in the controls

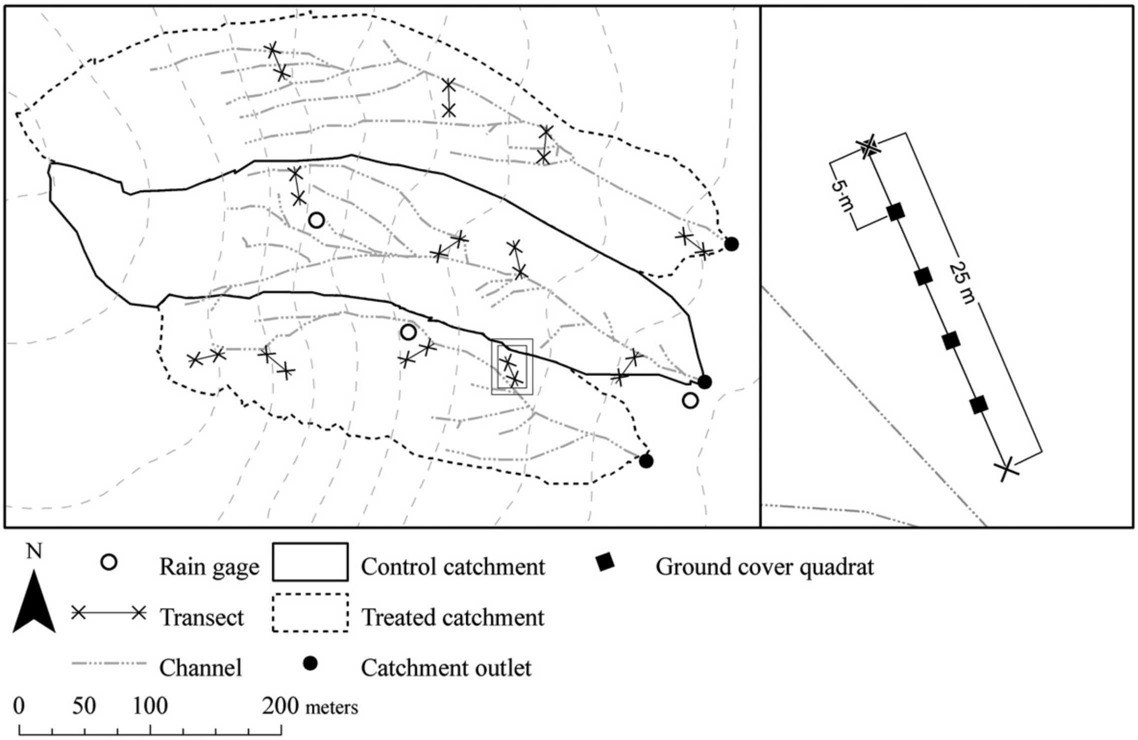

Fig. 3. A map of the layout of the three matched catchments at the Hayman fire. The 25-m ground cover transects are shown in each catchment. Transects were established by randomly selecting the distance from the weir to the start of a transect and an azimuth for the transect. The inset figure shows a typical transect with five ground cover quadrats spaced 5 m apart along its length.

in generalized linear models (Littell et al., 2006). The runoff, peak flow, and sediment yield data were square-root transformed to homogenize the variance of the residuals (Helsel and Hirsch, 2002). Repeated measures analyses were used to test for significant relationships in transformed runoff, peak flows, and sediment yields between the treated and control catchments for each event with complete data. When the statistical model's intercept was not significant, the model was re-computed without the intercept. A serial correlation among measurements was included in the repeated measures models by assuming a spatial power function of the number of days after burning for each event at each fire (Littell et al., 2006). The rainfall total, I_{10}, and I_{30} were also individually tested as covariates (Helsel and Hirsch, 2002). These statistical models took the form

$$Y^{0.5}{}_{ij} = b_0 + b_1 X^{0.5}{}_{ij} + b_2 Z_{ij} + b_3 T_{ij} + e_{ij} \tag{2}$$

where Y_{ij} was the runoff (mm), peak flow ($\mathrm{m^3\ s^{-1}\ km^{-2}}$), or sediment yield ($\mathrm{Mg\ ha^{-1}}$) in the ith treated catchment for the jth event; X_{ij} was the runoff, peak flow, or sediment yield in the ith control catchment for the jth event; β_0 was the model intercept, if it was significantly different from zero; β_1 was the modeled slope for the square root of X_{ij}; Z_{ij} were the rainfall parameters from the treated catchment (event rainfall in mm, I_{10} in mm $\mathrm{h^{-1}}$, or I_{30} in mm $\mathrm{h^{-1}}$) for the ith site and the jth event; β_2 was the modeled slope for Z_{ij} if it was significantly different from zero; T_{ij} was the number of years after burning for the ith site and the jth event; β_3 was the modeled slope for T_{ij} if it was significantly different from zero; and ε_{ij} was the residual error for the ith site and the jth event. Because of a lack of independence between rainfall characteristics, only the most significant Z term, if any, was retained in the model. Models for runoff, peak flow, and sediment yield were calculated by site and treatment.

These statistical models were first used to test whether each hydromulch catchment had similar responses to rainfall during a presumed untreated period as its respective control catchment. Given that no residual effects from the hydromulch were observed after the hydromulch was no longer visible on the soil, the untreated periods used to test for similarity were defined as the time at which the hydromulch ground cover proportion was less than 10% based on our measurements. These periods were: after the first post-fire year at the Hayman fire and the Cedar fully treated catchment, and all events after the first ground cover measurement at the Cedar partially treated catchment (3 March 2004). If the confidence intervals for the slope estimate of the control response variable (β_1 in Eq. (2)) included 1, similarity was assumed and the model was then used to test the treatment effect during the treated period. Conversely, if the confidence intervals for β_1 in the untreated period did not include 1, we concluded that the catchment in question during the presumed untreated period and its control were dissimilar, and no further statistical analysis was conducted. As there was no period unaffected by treatment in the straw catchment at Hayman—either straw mulch or grasses derived from seeds in the straw were always present—pre-treatment similarity was assumed for this catchment.

In the cases where our test in the untreated period resulted in an assumption of similarity, we assumed that prior to treatment application each of the treated catchments was equal to its respective control catchment with respect to per-unit-area runoff rates, peak flow rates, and sediment yields. This assumption allowed us to test whether the responses in the treated catchments, and hence the slopes in the statistical models, differed from one. When the values were significantly different from one, the difference in slope was attributed to a post-fire treatment effect.

Regression analyses were used to determine the relative strength of the relationship between event rainfall intensity (I_{10}) and rainfall amount on runoff, peak flow, and sediment yield on the control catchment at each fire. Data from all years were included in these analyses.

Changes in total ground cover and vegetation were evaluated using repeated-measures analyses on the ground cover values that were measured latest in each post-fire year. For each site and treatment, each quadrat (5 per transect) was treated as an independent observation of ground cover and live vegetation. Repeated-measures analyses of data from each site were conducted with quadrat as the subject and an autoregressive serial relationship (SAS Institute Inc., 2003). Least significant differences were used to compare differences in least-squares means between ground cover and live vegetation by fire, treatment, and year (Littell et al., 2006; SAS Institute Inc., 2003).

To compare erosion rates at the hillslope and catchment scales, data from both scales at both sites were used. The Hayman hillslope plots that were included in Part I of this two-part study were located about 4 km southwest of the Hayman catchments. Another untreated catchment established for separate studies (Robichaud et al., 2008; Wagenbrenner et al., in preparation) at the Hayman fire provided an additional sample of catchment-scale responses, and the outlet of this catchment was located only 200 m from the hillslope plots. Both control catchments and the hillslope plots at the Hayman fire were monitored during the same time period, and the data from the closer control catchment were used for the comparison across scales. The hillslope-scale measurements of sediment yields and rainfall that were reported in Hubbert et al. (2012) were compared to the Cedar catchment data reported in this study.

The sediment yield measurements from two scales were analyzed by relating the event sediment yield to the event I_{10} (Hayman fire) or rainfall (R) amount (Cedar fire) for both catchments and the hillslope plots. We fit a power function in the form

$$\text{Sediment yield} = a(I_{10})^b \qquad \text{[Hayman fire]} \tag{3a}$$

$$\text{Sediment yield} = a(R)^b \qquad \text{[Cedar fire]} \tag{3b}$$

where the coefficient, a, and exponent, b, were calculated for each set of data. Differences in rainfall–sediment yield relationships by time and by scale of measurement were examined for both fires.

3. Results

3.1. Precipitation

The Hayman fire had less precipitation than the long term annual average (400 mm) for all study years with the exception of the fifth post-fire year when 450 mm of precipitation was reported (Table 3). Generally, the rainfall events that resulted in measured runoff occurred in mid-summer to early autumn, and these were convective rain storms fed by monsoonal moisture which were often short duration, high intensity storms (the 2-yr I_{10} at Hayman was 53 mm h^{-1}). The median duration of all storms (>5 min duration, >1 mm rainfall) was 222 min as measured at the rain gage at the outlet of the control catchment. In the first post-fire year at the Hayman fire, 12% of the storms produced runoff and this declined to 2–3% for the third post-fire year and beyond (Table 3). The annual maxima I_{10} values of the events that produced runoff at the Hayman fire were 11 to 81 mm h^{-1}(mean of 54 mm h^{-1}), and the annual maxima event rainfall amounts that produced runoff were 11 to 40 mm (mean of 24 mm).

At the Cedar fire, wet winters provided the majority of the annual precipitation and there was little precipitation in the dry season between the late spring and mid-autumn. The rainfall at the Cedar fire was double the annual average in the first post-fire year and near or below average in all other years of the study (Table 3). The majority of the winter rain events that resulted in runoff at Cedar were generated by Pacific cyclonic storms, with long durations (median duration of 439 min) and moderate intensities (the 2-yr I_{10} at the Cedar fire was 39 mm h^{-1}). During the 5 years that the Cedar fire was monitored, at least 36% and up to 65% of the annual rainfall events produced measurable runoff in the control catchment (Table 3). The annual maxima I_{10} values of the events that produced runoff at the Cedar fire were 11 to 55 mm h^{-1} (mean of 36 mm h^{-1}) and the annual maximum event rainfall amounts that produced runoff were 47 to 151 mm (mean of 84 mm).

There were differences in rainfall among the three catchments at both the Hayman and the Cedar fires, but these differences were measured by separate rain gages at each catchment on the Cedar fire and the differential rainfall on the three Hayman catchments were observed (see Section 4.1). Of the 89 storms that resulted in runoff during the study at the Cedar fire, 65 had greater rainfall values for the partially treated catchment than for the control and the fully treated catchments. On average the rainfall values in the partially treated catchment were 18% greater than the control and 24% greater than the fully treated. Although the fully treated and control catchments were adjacent, the average rainfall that produced runoff was 12% greater in the control than in the fully treated.

Table 3

Long-term average annual precipitation and the annual precipitation totals for each water year of the study. The Hayman annual precipitation data are from the Manitou Experimental Forest gage (Table 1) while the Cedar annual precipitation data are from the Alpine RAWS. Unless otherwise noted, annual totals are based on daily records with five or fewer missing days. The annual number of storms and the proportion of runoff-producing storms were from the control watershed at each site. Precipitation events were separated by at least 6 h with no precipitation, and individual events had at least a 5 min duration and 1.0 mm of rain.

Fire [average annual precipitation (mm)]	Water year (1 Oct–30 Sep)	Annual precipitation (mm)	Post-fire year	Number of storms	Proportion of storms producing runoff (%)
Hayman [400]	2002	137	0	See note below table	
	2003	316	1	43	12
	2004	329	2	64	11
	2005	291	3	42	2.4
	2006	399	4	61	1.6
	2007	450	5	69	2.9
	2008	260	6	61	3.3
	2009	397	7	65	1.5
Cedar [398]	2004	258[a]	0[b]	17[b]	65
	2005	719[c]	1	48	54
	2006	341[d]	2	35	46
	2007	230	3	27	41
	2008	435	4	25	36
	2009	282[e]	5	25	44

[Note: The number of storms is not shown because of the short period between gage installation and end of the post-fire year (30 Oct). However, at least two runoff-producing storms occurred—one on 13 Sep 2002 before treatments were applied (no data recorded) and another on 1 Oct 2002 after treatments were applied. Data for this second storm are shown on Tables 6 and 7].

[a] Annual record has 22 missing days.

[b] Precipitation and storm data are for a partial year, 29 Jan 04, when rain gages were installed, through 30 Sep 04.

[c] Annual record has 24 missing days.

[d] Annual record has 8 missing days.

[e] Annual record has 10 missing days.

3.2. Ground cover

At the Hayman fire, the control catchment had only 5% ground cover the autumn after the fire occurred. During the first post-fire year ground cover increased to 16%, 1.5% of which was straw mulch that drifted into the control catchment from the adjacent straw mulch catchment. The ground cover in later years increased by 8–15% per year to a peak of 59% in the fifth post-fire year before declining in the sixth year and rebounding in the seventh post-fire year. The sixth post-fire year was an anomaly that was not corroborated by ground cover measurements in adjacent treated catchments. We suspect the measured value may have resulted from inconsistent observer interpretation of vegetation cover. Since no errors were detected in the data recording or calculations, we have retained the measured values.

Although the aerial application of straw mulch was somewhat uneven—we observed undisbursed straw clumps in some places within the catchment, the wheat straw mulch component of the ground cover provided 49% of the 80% total ground cover measured immediately after application. The straw mulch decreased to 10% of the total ground cover by the end of the first post-fire year, and further decreased to 5% by the end of the second post-fire year (Fig. 4). Despite the decrease in straw mulch and total cover, the straw mulch catchment had significantly greater total cover than the control catchment, except in the fifth post-fire year (Fig. 4). Initially, the wheat straw treatment provided the additional cover, but as the straw cover decreased the amount of litter and live vegetation cover increased more rapidly in the treated catchment than in the control catchment. The litter values from the fall ground cover counts included cheatgrass (*Bromus tectorum*), which generally died back before the fall cover measurement. This prolific invasive plant was inadvertently spread over parts of the Hayman fire burned area with the application of wheat straw mulch that contained cheatgrass seeds. The wheat straw used for treatments was certified as weed-free, but cheatgrass was not listed as a noxious weed in Colorado at the time of purchase. Before the contamination was identified and application halted, the straw containing the cheatgrass seeds had been spread in several areas, including our study catchment. Cheatgrass was observed growing throughout the straw treated catchment and spread into the adjacent control catchment during the course of this study. The total cover on the straw catchment increased by about 10% each year in post-fire years two and three, and maintained this level (75–80%) for the duration of the study.

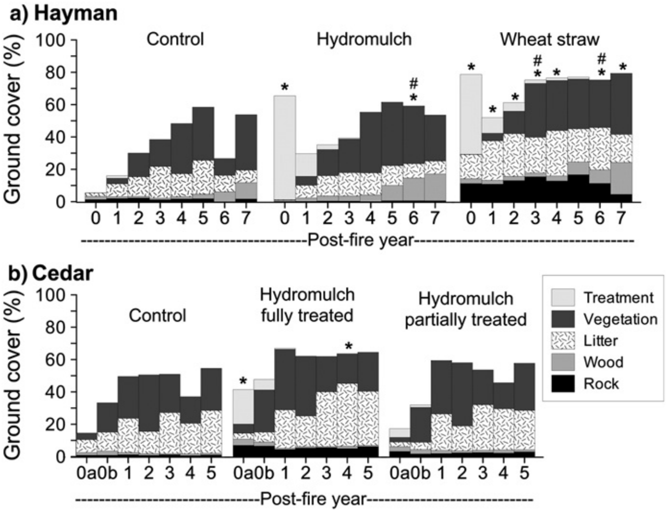

Fig. 4. Mean proportion of ground cover components (rock >25 mm, wood, litter, live vegetation, and treatment) by treatment and post-fire year for the Hayman and Cedar fires. Post-fire year 0 was the year the fire occurred. Data are from measurements taken in late summer or early autumn except for Cedar fire post-fire years 0a (measured 4 Mar 04, 4 months after burning) and 0b (measured 8 Jun 04, 7 months after burning). The years when the mean total ground cover on a treated site was significantly different ($\alpha = 0.05$) as compared to the control site are designated by "*" at the top of the bar in the treated plot. The years when the mean vegetation cover on a treated site was significantly different ($\alpha = 0.05$) as compared to the control site are designated by "#" at the top of the bar in the treated plot.

The Hayman hydromulch catchment had 65% total ground cover immediately after application, and 64% was hydromulch (Fig. 4a). By the end of the first post-fire year, the hydromulch component of the ground cover had declined to 14%. Unlike the straw catchment, the total ground cover in the hydromulch catchment (30%) was not significantly different from the control value (16%) in the first post-fire year. Even though the straw cover and hydromulch cover in the first post-fire year were nearly the same the straw catchment had more than three times as much litter as the hydromulch catchment (Fig. 4a). The total ground cover on the hydromulch catchment was only significantly different than on the control catchment in post-fire year six when the hydromulch catchment had more ground cover than was measured on the control catchment. However total ground cover was significantly lower on the hydromulch catchment as compared to the straw mulch catchment in post-fire years one, two, three, and seven (Fig. 4a).

Total ground cover values for each catchment at the Cedar fire in March 2004 were 15% in the control, 41% in the fully treated (21% was hydromulch), and 17% in the partially treated (5% was hydromulch). The cover in the fully treated catchment was significantly greater than the control catchment, but there was no difference in cover between the partially treated catchment and the control or the fully treated catchments. Three months later all three catchments had more vegetative cover, but not significantly different total cover (Fig. 4b). Nearly all of the hydromulch had degraded or was removed from the sites within five months after application. In post-fire years 1 through 5 the total ground cover ranged from 37–67% among the three catchments. The control catchment had smaller values than the two treated catchments but the only significant difference in total cover was between the control and the fully treated in the fourth post-fire year (Fig. 4b).

3.2.1. Vegetation cover

There was no live vegetation in any of the Hayman catchments in the year of the fire, and the vegetative cover gradually increased each year. In post-fire year three the vegetative cover in the Hayman control (24%) was significantly greater than in the year of the fire. The vegetative cover reached 31% in post-fire year four, and except for the questionably low vegetative cover value (10%) in the sixth post-fire year, the vegetation did not significantly change again through post-fire year seven (Fig. 4). The vegetation component of the ground cover on the treated catchments did not differ from the control catchment with two exceptions—in the third post-fire year when vegetation was greater in the straw mulched catchment than in the control and in the sixth post-fire year when the measured value of vegetative cover in the control was unusually low (Fig. 4a).

In the year of the fire, the vegetation measurement on the Cedar control catchment was 18%, and the maximum vegetation cover value of 35% was attained in post-fire year two (Fig. 4b). As observed by Hubbert et al. (2012), the decline in vegetation cover at all three Cedar sites in post-fire years 3 and 4 reflect typical successional dieback of post-fire herbaceous cover and recruitment of chaparral shrubs. The vegetation component of the ground cover on the Cedar fire treated catchments was not significantly different from the control catchment at any time during the study (Fig. 4b).

3.3. Hydromulch catchments' similarity to controls

Given the rapid loss of hydromulch at both the Hayman and Cedar fires, the hydromulch treated catchments were essentially untreated for large portions of this multi-year study. When runoff, peak flow, and sediment yield were modeled in the untreated period on the hydromulch treatment at the Hayman fire, the β_1 was significantly different from one only for the peak flow rates (Table 4), indicating the peak flow rates during the untreated period in the hydromulch catchment were different from the peak flows in the control. Similarity was assumed for both runoff and sediment yield in the Hayman hydromulch catchment (Table 4) (and for all three response variables in the straw mulch catchment as discussed in Section 2.4) and these variables were then tested for treatment effects (Sections 3.4–3.6; Table 5). In contrast, the modeling of the untreated period at the Cedar fire resulted in a significant difference in each response—runoff, peak flow, and sediment yield—in each of the treated catchments as compared to the control (Table 4). Thus, no further statistical modeling was done on the data from the Cedar fire.

3.4. Runoff

The first large storm that occurred at the Hayman fire (29 July 03) filled the control and hydromulch sediment traps to capacity with coarse-grained sediment. Lightning during this storm damaged our data logger, so our estimates of runoff and peak flow rate (Tables 6 and 7) were based on the total volume stored in the sediment traps. From our observations of scour in the road below the sediment traps these values greatly understated the actual event values. The storage capacity of each of the sediment traps at the Hayman fire was increased after this event.

Only 17 of the 405 (4%) rainfall events that occurred in the first seven post-fire years produced runoff in the control catchment at the Hayman fire. For the ranges of observed I_{10} and rainfall at the Hayman fire, the runoff rates were more strongly related to I_{10} than to rainfall amount (Fig. 5). The 19 Aug 04 (post-fire year two) storm, which had the second largest I_{10} value measured during the study (65 mm h^{-1}) and 18.1 mm of rainfall resulted in the largest measured runoff values on all three catchments—5.4, 4.3, and 3.3 mm for the control, straw mulch, and hydromulch catchments, respectively (Tables 6 and 7). A nearly identical storm (19.6 mm of rain with an I_{10} of 64 mm h^{-1}) occurred in the fifth post-fire year and resulted in notably lower runoff values of 0.9, 0.0, and 1.7 mm on the control, straw mulch, and hydromulch catchments, respectively. The greatest I_{10} value, 81 mm h^{-1}, was recorded for a storm that occurred in post-fire year seven and resulted in runoff and sediment production only in the hydromulch catchment (Tables 6 and 7). Although snowmelt generally caused large peak flow measurement at stream gages during April–June (e.g., USGS water data website for gage #06701620), no measurable overland flow occurred in the study catchments during the snow melt period in any year of the study.

Table 4
Estimates and 95% confidence intervals for the statistical model coefficients (Eq. (2)) for the untreated periods. If the confidence intervals for the slope estimate (β_1) included 1, similarity was assumed and the model was used to test the treatment effect during the treated period. Otherwise dissimilarity was assumed and no further statistical analysis was conducted. The intercept (β_0) was not significant in any model and was not included. If covariate slopes (β_2 and β_3) were significant ($p<0.05$) in the untreated period the covariate was included in the model for the treated period. Statistically significant effects are shown in bold type.

Hayman fire	Untreated period Hydromulch: post-fire years 2–7 (n = 14)		
Modeled variable	Catchment	β_1 (H_0: similar response between control and treated)	β_2 (post-fire year)
Runoff	Hydromulch	0.86 (0.63–1.09)	**0.12**
Peak flow	Hydromulch	**0.77 (0.59–0.96)**	0.20
Sediment	Hydromulch	0.82 (0.62–1.03)	**0.31**

Cedar fire	Untreated periods Partially treated: after 3 March 2004 (post-fire year 0)–post-fire year 5 (n = 72) Fully treated: post-fire years 1–5 (n = 70)	
Modeled variable	Catchment	β_1 (H_0: similar response between control and treated)
Runoff	Partially treated	**0.64 (0.45–0.83)**
	Fully treated	**0.70 (0.56–0.84)**
Peak flow	Partially treated	**0.46 (0.33–0.60)**
	Fully treated	**0.64 (0.49–0.80)**
Sediment	Partially treated	**0.58 (0.45–0.72)**
	Fully treated	**0.69 (0.58–0.80)**

Table 5
Estimates and 95% confidence intervals for the statistical model coefficients (Eq. (2)). Runoff, peak flow, and sediment yield were modeled for the Hayman straw mulch catchment, and runoff and sediment yield were modeled for the treated period on the Hayman hydromulch catchment. If the intercept (β_0) and other covariates (β_2 and β_3) were significant ($p<0.05$) in the untreated period the covariate was included in the model for the treated period and otherwise was denoted by "ns". Statistically significant effects are shown in bold type.

Hayman fire	Treated periods Straw: all years (n = 17) Hydromulch: post-fire years 0-1 (n = 6)			
Modeled variable	Catchment	β_1 (H_0: no treatment effect)	β_2 (post-fire year)	β_3 (event I_{10})
Runoff	Straw	0.88 (0.68–1.09)	**−0.14**	ns
	Hydromulch	1.08 (0.34–1.82)	−0.13	ns
Peak flow	Straw	**0.36 (−0.05–0.77)**	**−0.35**	**0.025**
	Hydromulch	dissimilarity assumed		
Sediment	Straw	**0.68 (0.58–0.78)**	**−0.25**	ns
	Hydromulch	0.82 (0.005–1.64)	0.13	ns

Despite differences in measured runoff among the catchments, no treatment effect was detected in the runoff models for either the straw mulch or the hydromulch catchments at the Hayman fire. The post-fire year was a significant covariate in the model for runoff on the straw mulch catchment (Table 4) and this significance reflects the lack of runoff after post-fire year two in the straw catchment.

The Cedar fire had a total of 151 rainfall events, fewer than the Hayman fire, but on average they were longer duration with more total rainfall (Fig. 5) and a greater number of these rainfall events produced runoff in the control catchment (Table 3). The Cedar fire was instrumented for nine months in the year of the fire, and during this time 65% of the rainfall events resulted in measurable runoff. Although this value decreased with time, it did not drop below 36% during the study.

An 80 h rain event at the Cedar fire produced the largest rainfall totals (141.7 mm in the control, 125.2 mm in the fully treated, and 150.9 mm in the partially treated catchments) during the first post-fire year (18–21 Oct 04). Runoff data for this storm were unavailable for the control and partially treated catchments due to equipment malfunction, but the runoff was 6.1 mm in the fully treated catchment. From the available data, the maximum event runoff in the control catchment at the Cedar fire (13.8 mm) was caused by an 85.1 mm rainfall event (28–30 Dec 04). During this same event, 70.9 mm of rainfall produced 12.6 mm of runoff in the fully treated catchment and 86.9 mm of rainfall produced 11.9 mm of runoff in the partially treated catchment (Tables 8 and 9). The largest runoff events on the two treated catchments occurred on 16–17 Dec 08 (fifth post-fire year) when 76.8 mm of rain produced 17.0 mm of runoff on the fully treated catchment and 81.0 mm of rain produced 19.3 mm of runoff in the partially treated catchment. This same event resulted in the second largest runoff (13.4 mm from 72.9 mm of rain) on the control catchment (Tables 8 and 9).

3.5. Peak flow rates

The peak flow rates at the Hayman fire were more strongly related to I_{10} than to rainfall amount (Fig. 5). The largest peak flow rate at the Hayman fire (7.1 m^3 s^{-1} km^{-2}) was measured on the control catchment on 28 Jun 04 (second post-fire year) in response to a rain event with an I_{10} of 43 mm h^{-1}. The largest peak flow on the straw mulch catchment was the estimated value of 4.5 m^3 s^{-1} km^{-2} on 29 Jul 03,

Table 6

Hayman straw and control catchment responses. Event date, post-fire year, rainfall amount, 10-min maximum rainfall intensity (I_{10}), and values for total runoff, peak flow rate, and total sediment yield for each event that produced a response in the Hayman straw and control catchments. Total sediment yields by post-fire year (1 Nov–30 Oct) are listed in bold type. Table symbols include "C" for control and "T" for treated. All listed events occurred after installation of treatments. Other events occurred after the fire but prior to installation of instruments and/or treatments. Rainfall amount and intensity values are means of all available gages at the Hayman site. When multiple storms occurred before sediment could be measured, sediment yields were prorated based on event runoff. Rain events occurring after the fifth post-fire year did not produce measurable responses in either of these watersheds.

Date	Post-fire year	Rainfall (mm)	I_{10} (mm h^{-1})	Runoff (mm)		Peak flow rate (m^3 s^{-1} km^{-2})		Sediment yield (Mg ha^{-1})	
				C	T	C	T	C	T
1 Oct 02	0	14.0	11	0.6	0.2	1.5	0.8	0.3	<0.05
19 Jul 03	1	8.4	18	0.0	0.0	0.0	0.0	<0.05	0.0
29 Jul 03	1	11.9	52	1.3[a]	1.4[a]	4.3[a]	4.5a	18.6[a]	7.2
9 Aug 03	1	13.3	34	0.2	0.1	0.6	0.5	0.9	0.4
30 Aug 03 00:30	1	19.3	21	0.8	0.2	1.1	0.3	1.2	0.3
30 Aug 03 20:45	1	11.4	24	0.9	0.2	2.4	<0.05	1.4	0.3
					First post-fire year total			**22.2**	**8.1**
21 Jun 04	2	17.3	24	0.2	0.0	0.4	0.0	0.6	<0.05
25 Jun 04	2	12.4	18	<0.05	0.0	0.0	0.0	0.1	0.0
27 Jun 04	2	20.2	27	0.4	0.4	0.6	0.2	1.3	0.0
28 Jul 04	2	11.4	43	2.2	0.5	7.1	1.6	5.4	0.8
7 Aug 04	2	6.6	32	0.7	0.2	1.8	0.4	3.4	0.3
19 Aug 04	2	18.1	65	5.4	3.3	5.6	3.9	24.4	10.2
27 Sep 04	2	23.2	28	1.1	1.1	2.2	0.9	3.4	1.0
					Second post-fire year total			**38.6**	**12.3**
5 Aug 05	3	11.2	51	0.8	0.0	2.8	0.0	5.1	0.0
					Third post-fire year total			**5.1**	**0.0**
2 Aug 06	4	23.5	46	0.6	0.0	0.9	0.0	2.1	0.0
					Fourth post-fire year total			**2.1**	**0.0**
19 Jul 07	5	19.6	64	0.9	0.0	1.9	0.0	3.3	0.0
29 Aug 07	5	25.0	44	0.6	0.0	0.9	0.0	3.5	0.0
					Fifth post-fire year total			**6.8**	**0.0**

[a] The sediment trap in the control catchment was completely filled with coarse sediment in this event, and we believe the actual sediment yield was much greater. Also, the data logger was struck by lightning, so the runoff and peak flow values are estimated from the volume of material stored in the sediment traps. These measured values also are understated.

Table 7

Hayman hydromulch and control catchment responses. Please refer to Table 6 for explanation of column headings. Rainfall amount and intensity values are means of all available gages at the Hayman site. When multiple storms occurred before sediment could be measured, sediment yields were prorated based on event runoff. Total sediment yields by post-fire year (1 Nov–30 Oct) are listed in bold type. The "untreated" period for this catchment was post-fire years 2–7. ND = no data.

Date	Post-fire year	Rainfall (mm)	I_{10} (mm h^{-1})	Runoff (mm)		Peak flow rate (m^3 s^{-1} km^{-2})		Sediment yield (Mg ha^{-1})	
				C	T	C	T	C	T
1 Oct 02	0	14.0	11	0.6	1.0	1.5	1.6	0.3	0.2
19 Jul 03	1	8.4	18	0.0	0.0	0.0	0.0	<0.05	0.0
29 Jul 03	1	11.9	52	1.3[a]	0.8[a]	4.3[a]	2.7[a]	18.6[a]	10.1[a]
9 Aug 03	1	13.3	34	0.2	0.0	0.6	0.0	0.9	0.0
30 Aug 03 00:30	1	19.3	21	0.8	0.9	1.1	0.3	1.2	3.5
30 Aug 03 20:45	1	11.4	24	0.9	1.1	2.4	1.9	1.4	4.4
					First post-fire year total			**22.2**	**18.1**
21 Jun 04	2	17.3	24	0.2	0.1	0.4	0.2	0.6	0.5
25 June 04	2	12.4	18	<0.05	0.0	0.0	0.0	0.1	0.1
27 Jun 04	2	20.2	27	0.4	0.2	0.6	0.2	1.3	1.4
28 Jun 04	2	11.4	43	2.2	0.8	7.1	3.5	5.4	2.6
7 Aug 04	2	6.6	32	0.7	0.5	1.8	1.1	3.4	2.9
19 Aug 04	2	18.1	65	5.4	4.3	5.6	4.5	24.4	17.3
27 Sep 04	2	23.2	28	1.1	0.5	2.2	ND	3.4	3.3
					Second post-fire year total			**38.6**	**28.1**
5 Aug 05	3	11.2	51	0.8	1.9	2.8	4.8	5.1	9.3
					Third post-fire year total			**5.1**	**9.3**
2 Aug 06	4	23.5	46	0.6	2.5	0.9	3.3	2.1	8.4
					Fourth post-fire year total			**2.1**	**8.4**
19 Jul 07	5	19.6	64	0.9	1.7	1.9	3.3	3.3	7.8
29 Aug 07	5	25.0	44	0.6	2.2	0.9	3.3	3.5	13.0
					Fifth post-fire year total			**6.8**	**20.8**
5 Aug 08	6	24.0	62	0.0	0.2	0.0	0.3	0.0	1.9
11 Sep 08	6	40.2	37	0.0	0.3	0.0	0.7	0.0	1.7
					Sixth post-fire year total			**0.0**	**3.6**
21 Jul 09	7	38.2	81	0.0	0.8	0.0	3.3	0.0	6.5
					Seventh post-fire year total			**0.0**	**6.5**

[a] The sediment traps in the control and hydromulch catchments were completely filled with coarse sediment in this event, and we believe the actual sediment yields were much greater. Also, the data logger was struck by lightning, so the runoff and peak flow values are estimated from the volume of material stored in the sediment traps.

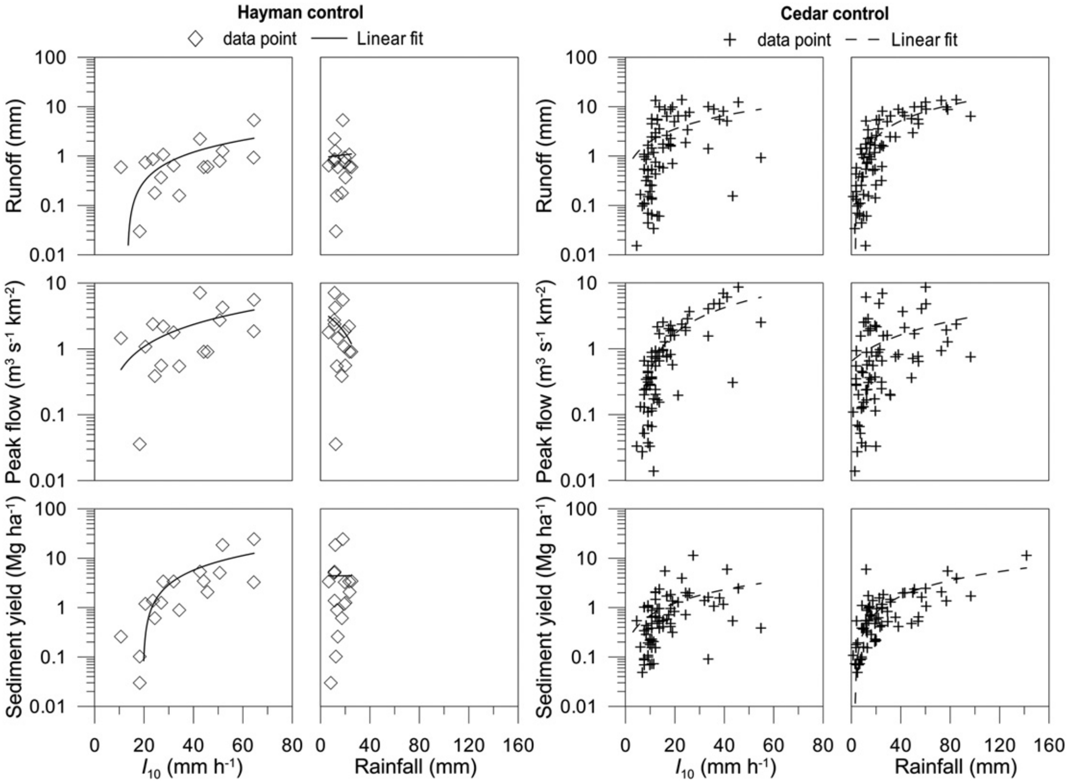

Fig. 5. Regressions of runoff, peak flow rate, and sediment yield for all events in the control catchments versus the event I_{10} and rainfall amount for the Hayman (left) and Cedar (right) fires. The responding variable is plotted on a logarithmic scale and the best linear fit is included in each plot.

which occurred in response to an I_{10} of 52 mm h^{-1} in post-fire year one (Table 6). On the hydromulch catchment, the maximum flow during the treated period was the estimated value of 2.7 m^3 $s^{-1}km^{-2}$ from the 29 Jul 03 storm, while the maximum flow during the untreated period was 4.8 m^3 s^{-1} km^{-2} from an I_{10} of 51 mm h^{-1} on 5 Aug 05 (third post-fire year) (Table 7). The largest I_{10} (81 mm h^{-1}) measured at the Hayman fire occurred in the seventh post-fire year and only the hydromulch catchment responded to this storm; a peak flow rate of 3.3 m^3 s^{-1} km^{-2} was recorded (Table 7).

The Hayman straw mulch catchment generally had smaller peak flows than the control, especially during post-fire years three through five when the straw mulch catchment produced no runoff (Table 6). The smaller peak flow rates produced a significant straw mulch treatment effect in reducing peak flow rates (Table 5). In the peak flow statistical model, both the post-fire year and the I_{10} were significant covariates (Table 4), indicating the importance of the lack of runoff in the straw catchment during the third through fifth post-fire years and the dependence of the peak flow rates on I_{10}.

During the “untreated” period on the Hayman hydromulch catchment (after the first post-fire year), the peak flow rates from the hydromulch catchment were larger than the peak flows in the control catchment, especially after the fifth post-fire year when the control catchment produced no runoff. This result led to our conclusion that the hydromulch and control catchments were not similar enough to test for the hydromulch treatment effect on peak flow rates (Table 4). With this caveat the peak flow rates on the hydromulch catchment during the “treated” period generally were similar to or slightly less than those on the control catchment (Table 7).

At the Cedar fire, the peak flow rate was the only responding variable that was more strongly related to I_{10} than to rainfall amount (Fig. 5). The maximum peak flow rates for each of the three catchments were measured on different storms. A maximum peak flow of 8.7 m^3 s^{-1} km^{-2} occurred on 21 Feb 05 (23:04 event) in the control catchment. The maximum peak flow rate in the fully treated catchment during the “treated” period was 3.2 m^3 s^{-1} km^{-2} in response to a rain event with an I_{10} of 24 mm h^{-1} on 1 Apr 04 (year of the fire) and during the “untreated” period was 9.0 m^3 s^{-1} km^{-2} (I_{10} of 38 mm h^{-1}) on 21 Nov 04 (Table 8). On the partially treated catchment the maximum peak flow rate during the “treated” period was 1.5 m^3 s^{-1} km^{-2} in response to a rain event with an I_{10} of 15 mm h^{-1} on 21 Feb 04 and during the “untreated” period was 4.8 m^3 s^{-1} km^{-2} (I_{10} of 41 mm h^{-1}) on 28 Jan 05 (Table 9). While the overall maxima flows at the Cedar fire occurred from three different events in the second post-fire year, each of catchments produced relatively large flows in each of the other post-fire years in the study (Tables 8 and 9). Even in the fifth post-fire year the maxima flows ranged from 1.9 m^3 s^{-1} km^{-2} (fully treated catchment) to 4.1 m^3 s^{-1} km^{-2} (control catchment) (Tables 8 and 9).

3.6. Sediment yields

At the Hayman fire, event sediment yield was more closely related to rainfall intensity than rainfall amount (Fig. 5). We estimated that the 29 Jul 03 (first post-fire year) storm with an I_{10} of 52 mm h^{-1} produced more sediment in the control catchment than any other during the study period; however, we do not have exact measurements (Table 6). The sediment trap was filled with coarse sediments rather than multiple layers of sediment that included layers of finer particles on top of the coarse particle layers normally collected. This suggested that much of the sediment yield was not trapped but remained entrained in the overflow that passed over the weir and headwall. The tabulated values for this event reflect only the material that was retained and measured. The largest measured event sediment yield, 24 Mg ha^{-1}, occurred in the second post-fire year

Table 8
Cedar fully treated and control catchment responses. Please refer to Table 6 for explanation of column headings. Rainfall amount and intensity values are means of all available gages in each catchment. When multiple storms occurred before sediment could be measured, sediment yields were prorated based on event rainfall. Total sediment yields by post-fire year (1 Oct–30 Sep) are listed in bold type. The "untreated" period for this catchment was post-fire years 1–5. ND = no data.

Date	Post-fire year	Control gages		Treated gages		Runoff (mm)		Peak flow rate ($m^3 s^{-1} km^{-2}$)		Sediment yield ($Mg ha^{-1}$)	
		Rainfall (mm)	I_{10} ($mm h^{-1}$)	Rainfall (mm)	I_{10} ($mm h^{-1}$)	C	T	C	T	C	T
2 Feb 04	0	25.9	18	24.4	17	1.6	1.1	1.6	1.2	1.8	0.8
18 Feb 04	0	12.4	11	11.2	9	1.5	0.6	0.9	0.5	0.9	0.4
21 Feb 04	0	78.0	16	77.0	15	8.8	3.7	1.2	1.5	5.5	2.5
26 Feb 04 01:27	0	14.9	9	15.2	8	1.1	0.6	0.4	0.3	1.1	0.5
26 Feb 04 21:19	0	13.6	18	13.2	17	2.3	1.2	1.9	1.4	1.0	0.4
28 Feb 04	0	1.5	9	1.5	8	0.2	0.0	0.1	0.0	0.1	0.0
2 Mar 04	0	14.5	8	14.0	8	1.0	0.2	0.7	0.7	1.0	0.5
1 Apr 04	0	13.6	25	12.7	24	3.4	2.2	2.9	3.2	1.7	0.9
2 Apr 04	0	8.6	9	8.3	12	0.4	0.4	0.5	0.4	1.1	0.6
4 Apr 04	0	4.2	15	3.8	14	0.6	0.4	0.9	0.7	0.5	0.3
17 Apr 04	0	9.9	6	9.0	6	0.2	<0.05	0.1	0.1	0.2	0.1
							Partial year of the fire			**15.0**	**7.0**
17 Oct 04	1	17.3	32	15.2	27	ND	1.7	ND	3.8	1.4	0.8
18 Oct 04	1	141.7	27	125.2	23	ND	6.1	ND	3.2	11.5	6.5
27 Oct 04	1	41.7	26	38.1	20	7.7	6.7	3.7	4.2	2.0	1.3
28 Oct 04	1	15.2	24	14.0	18	1.9	2.5	1.9	0.3	0.7	0.5
21 Nov 04	1	11.9	41	10.9	38	5.2	6.7	6.1	9.0	6.0	6.0
5 Dec 04	1	11.7	5	10.7	5	<0.05	0.2	<0.05	0.1	0.6	0.2
28 Dec 04	1	85.1	23	70.9	18	13.8	12.6	2.4	1.7	4.0	1.5
3 Jan 05	1	43.2	24	36.3	18	6.6	8.3	2.1	1.7	2.0	0.8
7 Jan 05	1	31.5	12	26.4	11	2.5	2.2	0.2	0.4	1.5	0.6
9 Jan 05	1	25.1	40	22.4	37	8.1	8.6	7.0	2.2	1.2	0.5
10 Jan 05	1	51.1	14	40.9	12	10.0	14.0	1.7	0.7	2.4	0.9
28 Jan 05	1	22.6	38	18.5	34	5.5	5.9	4.9	5.1	1.6	1.0
11 Feb 05	1	49.8	12	43.4	11	3.0	3.5	0.7	0.6	2.0	0.8
18 Feb 05 04:05	1	16.5	12	15.0	11	2.4	2.3	0.9	0.8	0.7	0.3
19 Feb 05	1	3.8	11	3.6	9	0.1	0.2	0.4	0.2	0.2	0.1
21 Feb 05 04:16	1	31.8	21	29.0	20	6.5	6.7	0.2	1.5	1.3	0.6
21 Feb 05 23:04	1	60.2	46	54.6	40	12.4	16.8	8.7	5.7	2.5	1.0
24 Feb 05	1	3.8	12	4.1	14	0.4	1.9	0.5	0.5	0.2	0.1
4 Mar 05	1	24.6	9	21.6	8	1.7	1.9	0.3	0.3	1.0	0.4
19 Mar 05	1	8.3	11	8.6	11	0.3	0.5	0.1	0.3	0.4	0.2
22 Mar 05	1	15.4	18	14.9	15	1.8	1.7	2.0	1.8	0.7	0.3
28 Apr 05 06:37	1	20.4	13	19.1	14	5.4	4.9	2.2	1.5	1.0	0.4
28 Apr 05 22:36	1	3.8	10	3.6	12	0.3	0.2	0.3	0.3	0.2	0.1
5 May 05	1	11.8	15	11.4	15	1.7	1.8	2.6	1.9	0.6	0.2
23 Jul 05 02:15	1	10.2	55	11.7	61	0.9	1.2	2.5	2.6	0.4	0.5
23 Jul 05 16:19	1	5.1	9	4.8	9	0.1	0.0	0.1	0.0	0.2	0.0
							First post-fire year total			**46.3**	**25.4**
16 Oct 05	2	12.7	19	12.7	18	0.7	0.5	0.6	0.4	0.3	0.0
17 Oct 05 13:19	2	2.9	11	3.0	14	0.0	0.0	<0.05	0.0	0.1	0.0
17 Oct 05 21:59	2	19.2	18	17.3	14	1.7	1.2	2.3	1.2	0.5	0.0
1 Jan 06	2	17.5	9	15.2	8	0.5	0.6	0.6	0.2	0.0	0.1
19 Feb 06[a]	2	8.3	5	8.3	5	0.0	0.1	0.0	0.0	0.0	0.0
27 Feb 06	2	54.1	13	47.0	18	5.5	3.2	0.8	0.5	0.5	<0.05
10 Mar 06	2	48.8	11	39.9	3	5.7	3.5	0.4	0.5	0.5	<0.05
12 Mar 06	2	5.0	7	ND	ND	0.1	0.0	<0.05	0.0	0.1	0.0
17 Mar 06[a]	2	20.1	10	20.1	10	0.3	0.6	<0.05	0.2	0.2	<0.05
20 Mar 06[a]	2	8.5	8	8.5	8	1.1	0.5	0.1	0.2	0.1	<0.05
28 Mar 06[a]	2	18.9	11	18.9	11	1.2	0.9	0.2	0.4	0.2	<0.05
4 Apr 06[a]	2	38.1	18	38.1	18	8.9	2.9	0.8	0.4	0.4	0.1
14 Apr 06[a]	2	19.6	11	19.6	11	0.1	0.6	0.1	0.2	0.2	<0.05
22 Apr 06[a]	2	6.7	11	6.7	11	0.1	0.1	0.1	0.1	0.1	<0.05
22 May 06[a]	2	10.2	11	10.2	11	0.0	0.3	0.0	0.2	<0.05	<0.05
3 Sep 06	2	14.0	43	15.2	47	0.2	1.1	0.3	1.2	0.5	0.1
							Second post-fire year total			**3.7**	**0.4**
9 Dec 06	3	9.9	14	8.1	3	0.1	0.5	0.2	0.5	0.4	<0.05
16 Dec 06[b]	3	12.4	13	10.2	13	0.1	0.5	0.2	0.7	0.5	<0.05
4 Jan 07[b]	3	9.5	9	7.9	9	0.4	0.1	0.4	0.1	0.4	<0.05
29 Jan 07	3	24.9	14	22.4	11	0.6	0.6	0.7	0.5	1.0	0.1
12 Feb 07	3	5.8	8	6.2	6	0.1	0.0	0.2	0.0	0.1	0.0
19 Feb 07	3	54.4	11	49.3	8	4.5	3.4	0.6	0.4	0.7	0.4
22 Feb 07	3	7.4	8	5.0	4	0.1	0.0	0.1	0.0	0.1	0.0
27 Feb 07	3	19.3	11	16.0	8	0.5	0.6	0.4	0.2	0.2	0.1
20 Mar 07	3	8.4	9	5.8	4	<0.05	0.0	<0.05	0.0	0.1	0.0
22 Mar 07	3	7.6	34	7.2	32	1.4	0.8	1.6	1.3	0.1	0.1
20 Apr 07[b]	3	13.0	12	8.1	12	0.8	0.5	0.2	1.9	0.2	0.1
							Third post-fire year total			**3.6**	**0.8**
30 Nov 07	4	60.6	36	40.0	34	8.9	5.2	4.8	3.0	1.1	0.4
7 Dec 07	4	24.6	8	22.1	6	0.3	0.5	0.2	0.2	0.4	0.2
20 Dec 07[a]	4	3.9	10	3.9	10	0.2	0.0	0.3	0.0	0.1	0.0

Table 8 (*continued*)

Date	Post-fire year	Control gages		Treated gages		Runoff (mm)		Peak flow rate ($m^3\ s^{-1}\ km^{-2}$)		Sediment yield ($Mg\ ha^{-1}$)	
		Rainfall (mm)	I_{10} ($mm\ h^{-1}$)	Rainfall (mm)	I_{10} ($mm\ h^{-1}$)	C	T	C	T	C	T
5 Jan 08[a]	4	96.6	17	96.6	17	6.4	9.0	0.8	0.5	1.7	0.9
23 Jan 08[a]	4	16.1	8	16.1	8	0.9	0.8	0.3	0.0	0.3	0.1
26 Jan 08[a]	4	77.0	19	77.0	19	9.8	14.1	1.9	1.3	1.4	0.7
3 Feb 08[a]	4	35.8	11	35.8	11	2.4	5.2	0.8	0.4	0.6	0.3
14 Feb 08[b]	4	23.2	15	43.7	15	1.5	2.3	1.0	1.1	0.4	0.4
22 Feb 08[b]	4	29.5	14	25.7	14	ND	5.8	ND	0.4	0.5	0.2
							Fourth post-fire year total			**6.5**	**3.2**
26 Nov 08 01:32	5	20.3	17	20.3	15	2.6	1.3	0.8	0.6	0.4	0.2
26 Nov 08 16:18	5	29.2	20	29.2	18	5.0	2.4	1.6	1.0	0.5	0.2
15 Dec 08	5	56.9	34	52.1	25	10.0	7.9	4.1	2.4	1.0	0.4
17 Dec 08	5	72.9	12	76.8	13	13.4	17.0	0.9	0.8	1.3	0.6
22 Dec 08	5	21.8	14	20.7	13	3.6	3.6	0.9	0.7	0.4	0.2
25 Dec 08	5	11.9	8	10.8	8	0.5	1.3	0.2	0.2	0.2	0.1
5 Feb 09	5	16.0	9	15.0	8	0.7	0.3	0.4	0.2	0.3	0.1
7 Feb 09	5	29.7	15	30.9	19	5.2	4.1	2.1	1.6	0.5	0.2
8 Feb 09	5	36.3	14	31.6	11	6.2	7.4	1.1	0.5	0.7	0.2
13 Feb 09	5	5.1	6	4.6	6	0.1	0	0.1	0	0.1	0
16 Feb 09	5	39.3	18	35.2	16	7.2	8.5	1.5	0.9	0.7	0.3
10 Apr 09	5	7.4	19	6.9	18	0.7	0.3	1.0	0.3	0.1	0.1
2 Sep 09	5	7.2	35	5.3	26	1.0	0	2.2	0	0.1	0
							Fifth post-fire year total			**6.3**	**2.6**

[a] No data from either treated rain gage. Used data from control rain gage.

[b] No I_{10} data from either treated rain gage. Used data from control rain gage.

(19 Aug 04) in the control catchment following a storm with an I_{10} of 65 mm h^{-1} (Table 6). This same storm produced the maxima measured sediment yields in the straw and the hydromulch catchments, 10 and 17 Mg ha^{-1}, respectively (Tables 6 and 7).

On the Hayman straw mulch catchment, the annual sediment yields in post-fire years one (8.1 Mg ha^{-1}) and two (12 Mg ha^{-1}) were about one third the magnitude of those on the control catchment (22 and 39 Mg ha^{-1}, respectively) (Table 6). The lack of runoff in the straw catchment after post-fire year two resulted in no sediment yields for this latter part of the study. Because of these results, the statistical models indicated the straw mulch significantly reduced the sediment yield as compared to the control catchment at the Hayman fire (Table 5).

Event sediment yields from the Hayman hydromulch catchment were not significantly different than the control during the first post-fire year—the "treated" period for the hydromulch catchment (Table 5). The annual sediment yield (18 Mg ha^{-1}) from the hydromulch catchment in post-fire year one ("treated" period) was 82% of the amount measured in the control catchment (Table 7). In the second post-fire year the "untreated" hydromulch catchment had an annual sediment yield of 28 Mg ha^{-1} which was 73% of the amount measured in the control catchment (Table 7). From that point on, the event and annual sediment yields in the "untreated" hydromulch catchment were larger than those measured in the control, especially in post-fire years six and seven when no sediment yields were measured in the control catchment (Table 7).

Regardless of treatment, measured annual sediment yields at the Hayman fire were largest in the second post-fire year when 7 events produced sediment and one storm was larger than the 2-yr, 10-min storm. Sediment yields decreased by 67–87% in the control and hydromulch catchments—and to zero in the straw mulch catchment—in the third post-fire year when only one rain event produced a response (Table 7). The sediment yields declined again in the fourth post-fire year when only one event produced a response (Table 7), but there was a large increase in sediment yield in the fifth post-fire year when two high-intensity events produced large sediment yields in the control and hydromulch catchments (Table 7). The sediment yields in the hydromulch catchment declined again in the sixth post-fire year, but the storm with the largest I_{10} (81 mm h^{-1}) occurred in the seventh post-fire year and this produced a sediment yield of 6.5 Mg ha^{-1} in the hydromulch catchment—nearly 25% of the value produced in the second post-fire year from seven rain events.

At the Cedar fire, event sediment yields were more closely related to rainfall amount than to I_{10} (Fig. 5). The largest prorated event sediment yields for the control, fully treated, and partially treated catchments were 11.5, 6.5, and 10.1 Mg ha^{-1}, respectively, and these occurred during the 18 Oct 04 event in the first post-fire year (Tables 8 and 9). These maxima sediment yields were produced by the maximum rainfall event on each of the catchments (141.7 mm, 125.2 mm, and 150.9 mm on the control, fully treated, and partially treated catchments, respectively) (Tables 8 and 9).

The Cedar fire had over 70 rain events that resulted in sediment yields during the 5.5 years it was observed. The annual sediment yields in the year of the fire on the Cedar partially treated (22 Mg ha^{-1}) and control catchments (15 Mg ha^{-1}) were similar, but the annual sediment yield on the fully treated catchment (7.0 Mg ha^{-1}) was only one-third to half as large (Tables 8 and 9). In the first post-fire year, during the "untreated" period when little hydromulch was detected in the ground cover, and rainfall was nearly double the average amount (Table 3), the annual sediment yield in the control catchment (46 Mg ha^{-1}) was nearly twice as much as the annual sediment yield values for the fully and partially treated catchments (25 and 27 Mg ha^{-1}, respectively) (Tables 8 and 9). Beginning in post-fire year two, the two treated catchments had similar annual sediment yields while the control catchment annual sediment yields were at least twice as large (Tables 8 and 9).

3.7. Sediment yields from hillslope plots and small catchments

At the Hayman fire the sediment yield measurements from the burned and untreated control hillslope plots and two catchments were analyzed by relating the event sediment yields to the event I_{10}s. The data were fit by site to a power function (Eq. (3a)). The Hayman fire data fits for the hillslope sediment yields had relatively low coefficients of determination until the data were split by post-fire year into two sets—post-fire years 0–2 and 3–7, respectively (Fig. 6). The exponents for the hillslope plots during both periods closely resembled those for both catchments (exponents ranged from 1.9 to 2.7), but the coefficient for the later period (3.9×10^{-5}) was much smaller than for either catchment or the hillslopes in post-fire years 0–2 (1.3×10^{-4} to 1.6×10^{-3}).

Table 9
Cedar partially treated and control catchment responses. Please refer to Table 6 for explanation of column headings. Rainfall amount and intensity values are means of all available gages in each catchment. When multiple storms occurred before sediment could be measured, sediment yields were prorated based on event rainfall. Total sediment yields by post-fire year (1 Oct–30 Sep) are listed in bold type. The "untreated" period for this catchment was after 3 March 2004. ND = no data.

Date	Post-fire year	Control gages		Treated gages		Runoff (mm)		Peak flow rate ($m^3 s^{-1} km^{-2}$)		Sediment yield ($Mg ha^{-1}$)	
		Rainfall (mm)	I_{10} ($mm h^{-1}$)	Rainfall (mm)	I_{10} ($mm h^{-1}$)	C	T	C	T	C	T
2 Feb 04	0	25.9	18	34.9	21	1.6	1.0	1.6	0.5	1.8	2.3
18 Feb 04	0	12.4	11	14.0	14	1.5	0.8	0.9	0.5	0.9	0.9
20 Feb 04	0	3.2	6	5.6	18	0.0	0.4	0.0	0.9	0.0	0.4
21 Feb 04	0	78.0	16	72.3	18	8.8	8.8	1.2	1.9	5.5	4.8
26 Feb 04 01:33	0	14.9	9	14.2	9	1.1	1.4	0.4	0.8	1.1	0.9
26 Feb 04 21:25	0	13.6	18	11.3	9	2.3	0.7	1.9	0.3	1.0	0.8
28 Feb 04	0	1.5	9	2.5	13	0.2	0.2	0.1	0.6	0.1	0.2
2 Mar 04	0	14.5	8	15.7	11	1.0	0.2	0.6	0.1	1.0	1.0
1 Apr 04	0	13.6	25	16.4	22	3.4	4.1	2.8	1.6	1.7	3.3
2 Apr 04	0	8.6	9	35.1	53	0.4	10.8	0.4	2.6	1.1	7.0
4 Apr 04	0	4.2	15	4.2	8	0.6	0.2	0.9	0.1	0.5	0.8
17 Apr 04	0	9.9	6	15.1	23	0.2	0.1	0.1	0.1	0.2	0.3
							Partial year of the fire			**15.0**	**22.3**
17 Oct 04	1	17.3	32	20.8	28	ND	ND	ND	ND	1.4	1.4
18 Oct 04	1	141.7	27	150.9	31	ND	ND	ND	ND	11.5	10.1
27 Oct 04 05:23	1	41.7	26	40.4	20	7.7	ND	3.7	ND	2.0	1.1
27 Oct 04 22:52	1	15.2	24	20.3	26	1.9	ND	1.9	ND	0.7	0.6
21 Nov 04	1	11.9	41	10.4	27	5.2	3.6	6.1	3.0	6.0	3.1
5 Dec 04	1	11.7	5	12.4	6	<0.05	0.0	<0.05	0.0	0.6	0.0
28 Dec 04	1	85.1	23	86.9	27	13.8	11.9	2.4	3.7	4.0	2.3
3 Jan 05	1	43.2	24	52.1	29	6.6	10.1	2.1	2.9	2.0	1.4
7 Jan 05	1	31.5	12	29.5	8	2.5	0.6	0.2	0.1	1.5	0.8
9 Jan 05	1	25.1	40	26.7	38	8.1	8.1	7.0	4.0	1.2	0.7
11 Jan 05	1	51.1	14	62.0	17	10.0	17.9	1.7	1.6	2.4	1.7
28 Jan 05	1	22.6	38	21.6	41	5.5	4.6	4.9	4.8	1.6	1.2
11 Feb 05	1	49.8	12	57.2	14	3.0	2.4	0.7	0.8	2.0	0.5
18 Feb 05 04:05	1	16.5	12	17.0	12	2.4	1.5	0.9	0.6	0.7	0.1
18 Feb 05 17:55	1	1.8	3	3.0	12	0.0	0.2	0.0	0.3	0.0	<0.05
19 Feb 05	1	3.8	11	8.6	9	0.1	0.4	0.4	0.3	0.2	0.1
20 Feb 05	1	1.0	5	3.6	9	0.0	0.1	0.0	0.1	0.0	<0.05
21 Feb 05 04:16	1	31.8	21	31.5	26	6.5	5.8	0.2	1.5	1.3	0.3
21 Feb 05 23:04	1	60.2	46	54.9	15	12.4	9.7	8.7	0.9	2.5	0.5
24 Feb 05	1	3.8	12	4.3	9	0.4	0.6	0.5	0.1	0.2	0.0
4 Mar 05	1	24.6	9	26.4	12	1.7	1.2	0.3	0.2	1.0	0.2
19 Mar 05	1	8.3	11	5.1	5	0.3	0.0	0.1	0.0	0.4	0.0
22 Mar 05	1	15.4	18	15.4	16	1.8	1.6	2.0	0.8	0.7	0.2
28 Apr 05 06:31	1	20.4	13	24.9	16	5.4	5.4	2.2	1.7	1.0	0.3
28 Apr 05 22:36	1	3.8	10	ND	ND	0.3	0.0	0.3	0.2	0.2	0.0
5 May 05	1	11.8	15	10.0	14	1.7	0.2	2.6	0.2	0.6	0.1
23 Jul 05 02:12	1	10.2	55	10.8	52	0.9	1.5	2.5	3.1	0.4	0.2
23 Jul 05 16:19	1	5.1	9	7.1	32	0.1	0.0	0.1	0.0	0.2	0.0
							First post-fire year total			**46.3**	**26.9**
16 Oct 05	2	12.7	19	13.3	21	0.7	0.4	0.6	0.3	0.3	0.1
17 Oct 05 13:29	2	2.9	11	2.8	11	<0.05	0.0	<0.05	0.0	0.1	0.0
17 Oct 05 21:44	2	19.2	18	19.1	14	1.7	1.5	2.3	1.4	0.5	0.1
1 Jan 06	2	17.5	9	29.2	23	0.5	0.8	0.6	0.8	0.0	<0.05
27 Feb 06	2	54.1	13	56.9	15	5.5	3.5	0.8	0.4	0.5	<0.05
9 Mar 06	2	48.8	11	46.5	7	5.7	3.3	0.4	0.2	0.5	<0.05
12 Mar 06	2	5.0	7	5.6	6	0.1	0.1	<0.05	0.2	0.1	0.0
17 Mar 06	2	20.1	10	20.6	8	0.3	0.4	<0.05	0.2	0.2	0.1
20 Mar 06	2	8.5	8	10.7	11	1.1	1.0	0.1	0.8	0.1	<0.05
28 Mar 06	2	18.9	11	19.1	8	1.2	0.8	0.2	0.7	0.2	0.1
4 Apr 06	2	38.1	18	43.4	14	8.9	5.1	0.8	2.0	0.4	0.1
14 Apr 06	2	19.6	11	21.6	9	0.1	0.2	0.1	0.8	0.2	0.1
22 Apr 06	2	6.7	11	8.0	8	0.1	0.1	0.1	0.4	0.1	<0.05
3 Sep 06	2	14.0	43	11.4	26	0.2	0.2	0.3	1.7	0.5	0.0
							Second post-fire year total			**3.7**	**0.6**
9 Dec 06	3	9.9	14	9.4	20	0.1	0.0	0.2	0.0	0.4	0.0
16 Dec 06	3	12.4	13	9.4	12	0.1	<0.05	0.2	0.2	0.5	0.0
4 Jan 07[b]	3	9.5	9	5.8	3	0.4	0.0	0.4	0.0	0.4	0.0
30 Jan 07	3	24.9	14	25.9	5	0.6	<0.05	0.7	0.0	1.0	0.0
12 Feb 07	3	5.8	8	9.9	3	0.1	0.0	0.2	0.0	0.1	0.0
19 Feb 07	3	54.4	11	61.2	5	4.5	1.9	0.6	0.3	0.7	<0.05
22 Feb 07	3	7.4	8	7.6	2	0.1	0.1	0.1	0.0	0.1	0.0
27 Feb 07	3	19.3	11	20.3	11	0.5	0.4	0.4	0.1	0.2	<0.05
20 Mar 07	3	8.4	9	9.4	3	<0.05	0.0	<0.05	0.0	0.1	0.0
22 Mar 07	3	7.6	34	5.8	3	1.4	0.1	1.6	0.2	0.1	0.0
20 Apr 07	3	13.0	12	12.4	5	0.8	0.0	0.2	0.0	0.2	0.0
							Third post-fire year total			**3.6**	**0.06**
30 Nov 07	4	60.6	36	11.4	2	8.9	8.1	4.8	4.4	1.1	0.1
7 Dec 07[a]	4	24.6	8	24.6	8	0.3	0.3	0.2	0.2	0.4	0.2

Table 9 (*continued*)

Date	Post-fire year	Control gages		Treated gages		Runoff (mm)		Peak flow rate ($m^3\ s^{-1}\ km^{-2}$)		Sediment yield (Mg ha^{-1})	
		Rainfall (mm)	I_{10} (mm h^{-1})	Rainfall (mm)	I_{10} (mm h^{-1})	C	T	C	T	C	T
20 Dec 07[a]	4	3.9	10	3.9	10	0.2	0.0	0.3	0.0	0.1	0.0
5 Jan 08	4	96.6	17	106.7	9	6.4	15.1	0.8	1.0	1.7	1.0
23 Jan 08	4	16.1	8	13.0	6	0.9	0.0	0.3	0.0	0.3	0.0
26 Jan 08	4	77.0	19	57.9	6	9.8	15.3	1.9	1.9	1.4	0.5
3 Feb 08[a]	4	35.8	11	35.8	11	2.4	5.8	0.8	0.3	0.6	0.3
14 Feb 08	4	23.2	15	25.1	6	1.5	1.1	1.0	0.5	0.4	0.2
22 Feb 08	4	29.5	14	33.3	5	ND	8.3	ND	0.4	0.5	0.3
							Fourth post-fire year total			**6.5**	**2.7**
26 Nov 08 01:32	5	20.3	17	21.3	18	2.63	0.0	0.8	0.0	0.4	0.1
26 Nov 08 16:18	5	29.2	20	36.1	27	5.0	3.7	1.6	0.8	0.5	0.2
15 Dec 08	5	56.9	34	63.2	30	10.0	9.2	4.1	2.8	1.0	0.3
16 Dec 08	5	72.9	12	81.0	12	13.4	19.3	0.9	1.0	1.3	0.4
22 Dec 08	5	21.8	14	19.6	12	3.6	1.8	0.9	0.4	0.4	0.1
25 Dec 08	5	11.9	8	17.3	11	0.5	1.7	0.2	0.3	0.2	0.1
5 Feb 09	5	16.0	9	19.8	11	0.7	0.0	0.4	0.0	0.3	0.0
7 Feb 09	5	29.7	15	28.7	20	5.2	1.2	2.1	1.4	0.5	0.2
8 Feb 09	5	36.3	14	37.3	12	6.2	2.8	1.1	0.4	0.7	0.2
13 Feb 09	5	5.1	6	8.9	9	0.1	0.1	0.1	0.1	0.1	0.0
16 Feb 09	5	39.3	18	40.9	17	7.2	4.7	1.5	0.8	0.7	0.2
10 Apr 09	5	7.4	19	7.6	15	0.7	0.0	1.0	0.0	0.1	0.0
2 Sep 09	5	7.2	35	2.5	11	1.0	0.0	2.2	0.0	0.1	0.0
							Fifth post-fire year total			**6.1**	**1.8**

[a] No data from either treated rain gage. Used data from control rain gage.

[b] No I_{10} data from either treated rain gage. Used data from control rain gage.

The power function fits for the hillslopes in post-fire years 0–2 and the catchment from Wagenbrenner et al. (in preparation) were nearly identical with exponents of 2.0 and 1.9 and coefficients of 1.0×10^{-3} and 1.6×10^{-3}, respectively. These results suggest that for the range of I_{10} and sediment yields observed: 1) the per-unit-area sediment production for a given I_{10} was nearly the same in the hillslope plots as in the catchments and the similarity increased when compared to the catchment located closer to the hillslope plots; 2) the per-unit-area sediment production as a function of I_{10} in the hillslope plots decreased after the first two years, whereas there was no observed decrease in sediment production in the catchments; and 3) for a given I_{10}, the sediment yield produced in the hillslope plots in post-fire years 3–7 was about an order of magnitude smaller than the yield in either catchment during the same period and was an order of magnitude smaller than the hillslope plot yields in post-fire years 0–2 (Fig. 6).

We conducted a similar comparison across scales by using our data from the Cedar control catchment and data from the "granitic soil" control hillslope plots (140 m^2) reported in the Hubbert et al. (2012) study, which was conducted simultaneously with the first 2.5 years of the current study. The cumulative sediment yield in the control catchment as a function of rainfall for 19 accumulation periods was compared to the mean cumulative sediment yield from 10 plots as a function of rainfall (Eq. (3b)) for five accumulation periods as reported in Hubbert et al. (2012) (Fig. 4). In this analysis, the catchment and the hillslope plot data were both divided into two time periods—February 2004–June 2005 and July 2005–April 2006 for the hillslope plots or July 2005–February 2009 for the catchments (Fig. 7).

As there were only 5 observed sediment yields in the hillslope plots, the between-scales analysis at the Cedar fire was more limited than at the Hayman fire. Still, the three sediment yield and rainfall observations for the hillslope plots in the early period fall near the power function derived for the same period for the catchment (Fig. 7). The catchment response to rainfall in the later periods was smaller than the response in the early period, and for a given rainfall, the sediment yield in the later period was about one-third that in the early period. This was quantified in the coefficients in the power functions, which were 0.11 for the early and 0.065 for the later period (the exponents were similar for each period: 0.88 for early, 0.73 for later). For the hillslope plots, the two observations of sediment yield response to rainfall in the later period were much smaller than either the values or the power function fit for the catchment for this period (Fig. 7). The responses in the hillslope plots were about an order of magnitude smaller the estimated responses from the catchment for the same rainfall.

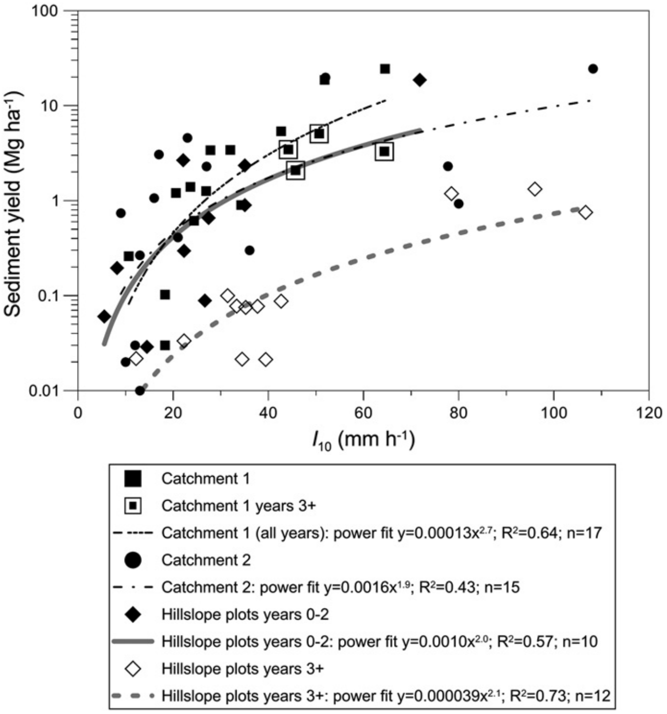

Fig. 6. Event sediment yields versus 10-min maximum intensity (I_{10}) for the Hayman fire control sites. Catchment 1 is from the current study. Catchment 2 is another control catchment in the Hayman fire located closer to the hillslope plots; the same methods were used as in the current study (Wagenbrenner et al., in preparation). The catchment fit lines are based on all data at each catchment; the open symbols indicate the data collected after post-fire year 2 for comparison to the hillslope plot data for the same period. The plot data are the mean sediment yields from the control hillslope plots in part I of the current study (Robichaud et al., 2013). The plot data are shown in two groups: post-fire years 0–2 and post-fire years 3–7; the fit lines were modeled separately for each group.

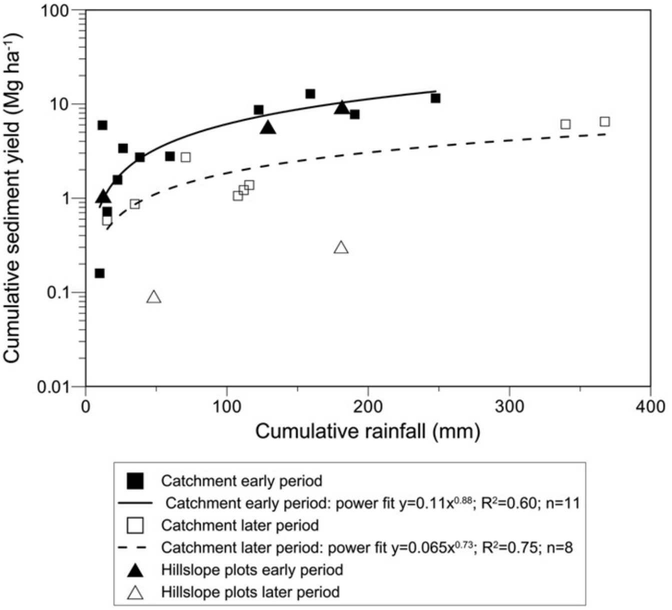

Fig. 7. Cumulative sediment yield versus cumulative rainfall for each accumulation period at the control catchment and hillslope plots at the Cedar fire. The sediment yield accumulation periods are shown in two separate periods: the early period extended from January 2004 through June 2005; and the later period was July 2005 through the end of the study (February 2009 for the catchment and April 2006 for the hillslope plots). The hillslope plot data are means of 10 plots as reported in Hubbert et al. (2012). The fit lines were modeled using all catchment data within each accumulation period.

4. Discussion

4.1. Comparisons within fires

Inputs and responses among the catchments at each fire varied, impacting our ability to discern significant treatment effects. At the Hayman fire, the control catchment had measurable event runoff and sediment yield associated with the 9 Aug 03 event, but no runoff or sediment was measured in the hydromulch catchment, and field observations indicated that the hydromulch catchment received substantially less rainfall than the straw mulch and control catchments. The relatively small spatial extent of the convective thunderstorms common along the Colorado Front Range made it likely that unequal rainfall among the three catchments occurred at other times during the study. Rainfall differences that were measured among the three catchments at the Cedar fire were unexpected given the close proximity of two of the three catchments and the relatively large spatial extent of the Pacific cyclonic frontal storms that produced most of the rainfall at Cedar. In addition, catchment differences beyond rainfall, such as differences in hillslope infiltration and subsurface flow rates, channel storage capacity, channel scouring, persistent rilling, etc., likely impacted sediment yields, but were not tested in this study. Kinoshita and Hogue (2011) described the significant influence of slope aspect on vegetative recovery and the subsequent influence on hydrologic responses in chaparral-dominated catchments. At the Cedar fire, the partially treated catchment faced south and the control catchment had a northwest aspect (Table 2), but there were no significant differences in vegetation or total ground cover (Fig. 4) between the two catchments.

4.2. Comparison between fires

The regions of the two study areas—central Colorado Front Range (Hayman) and the coastal mountains of southern California (Cedar)—had similar average annual rainfall amounts (~400 mm). Given that 30% of the annual precipitation at the Hayman fire falls as snow and the observed lack of erosion produced from snow melt periods, a smaller proportion of the total precipitation had the potential to drive erosion at the Hayman fire as compared to the Cedar fire. Also, the Hayman fire had relatively dry summers during the study, as reflected in the average annual rainfall during the seven study years (322 mm) (Table 3). At the Cedar fire, nearly all precipitation fell as rain in the winter wet season, and the average annual precipitation during the study (378 mm) (Table 3) was, on average, 56 mm per year greater than the Hayman fire. These two factors resulted in much less rainfall available to drive hillslope erosion at the Hayman fire as compared to the Cedar fire. In addition, the proportion of storms that produced runoff was much lower for the Hayman fire (1.5–12%) as compared to the Cedar fire (36–64%). Even the lowest proportion in the Cedar fire range (36%, fourth post-fire year) was more than three times the maximum value in the Hayman fire range (12%, first post-fire year) (Table 3). Consequently, there were 4.6 times more response-producing rainfall events (on a per year basis) at the Cedar fire as compared to the Hayman fire during this study (Table 3).

At the Hayman fire, a relatively few high intensity, short duration storms with small amounts of rain generated moderate amounts of runoff and transported large amounts of sediment to the catchment outlets. A single large-magnitude event sediment yield would produce most of the annual sediment yield. For example, the largest individual events in the first and second post-fire years produced 84% and 63% of the annual sediment yields, respectively, in the Hayman control catchment (Table 7). In contrast, at the Cedar fire, long-duration storms with lower rainfall intensities and large amounts of rain produced large event runoff amounts and large sediment yields. The largest individual sediment yields on the Cedar control catchment were 37%, 26%, and 14% (cumulative over 3 events) of the annual sediment yields in the year of the fire, and the first and second post-fire years, respectively (Table 8). The large number of rainfall events resulted in a fairly continuous input of runoff and sediment at the outlet of the Cedar catchments during the wet season.

The initial rate of vegetative increase in the Hayman control catchment was less than at the Cedar fire. On the Cedar control catchment, the maximum vegetation cover value of 35% was similar to the maximum value of 34% at Hayman control catchment, but this value occurred in post-fire year two at Cedar and not until post-fire year five at Hayman (Fig. 4). Debats et al. (2008) reported that a continuous, dense layer of hydromulch significantly lowered plant densities on both low and high burn intensity areas as compared to non-treated areas in the first growing season after a wildfire in a chaparral area in Los Angeles, CA. However, there were no discernible treatment effects on vegetative growth at either the Hayman or Cedar fire. This likely reflects the low density of the hydromulch applications, the short residence time of an intact hydromulch layer, and the lack of seed in both hydromulch mixes.

4.3. Treatment effectiveness

Despite the differences in climate, vegetation, and response to rainfall, both the Hayman and Cedar fires generally produced the largest runoff and sediment yields in the first two years after the fire with order-of-magnitude decreases by the third post-fire year. The untreated control catchments at both fires produced high sediment yields in the first two full wet seasons after the fire, but relatively high sediment yields continued to be produced in post-fire years 5–7. These data indicate that ideal post-fire emergency stabilization treatment(s) in these two areas would provide significant protection against erosion for at least 5–7 years and that treatment protection would decline slowly as the cover from vegetation and litter increased in the areas burned at high severity.

While large responses occurred in the Hayman wheat straw mulch catchment during the first two post-fire years, based on our definition of effectiveness (significantly smaller response than the control) wheat straw mulch did effectively reduce peak flow rates and sediment yields. Although the runoff rates were not significantly impacted, the reduction in peak flow rates suggests that the time to concentration was extended in the straw mulch catchment. The straw mulch likely increased hydraulic roughness on the hillslopes, thereby decreasing the runoff velocity and extending the time required for runoff to reach the catchment outlet. Similarly, the sediment yields were decreased because of 1) greater surface soil protection from rain splash erosion; 2) decreased overland flow velocity reducing sheet wash and rill erosion rates; and 3) reduction of the peak flow rate, which decreased shear stresses on the channel bed and banks, and thereby decreased channel erosion rates. Over time vegetation and litter replaced the straw cover, and these effects on cover resulted in no detectable outputs from the catchment after the second post-fire year. While the cheatgrass that was inadvertently seeded with the straw mulch treatment certainly increased the vegetation and litter components in the Hayman straw mulch catchment, other studies have shown that treatment benefits from weed-free straw may also extend 3–5 years (Wagenbrenner et al., 2006; Robichaud et al., 2013).

Hydromulch formulations differed between the Hayman and Cedar fires. The formulation used at Cedar had a non-water soluble tackifier that was expected to persist longer than the hydromulch at the Hayman fire that had a water soluble guar-based tackifier. However, the visible components of the hydromulch persisted longer at the Hayman fire than at the Cedar fire (Fig. 4). The hydromulch treatment at the Hayman fire did not significantly affect runoff or sediment yields (Table 5), and peak flow rates could not be directly compared (Table 4). Robichaud et al. (2013) also showed that the post-fire hydromulch treatment had no detectable effect on sediment yields measured at the hillslope scale in Washington and Idaho. However, immediately after the Hayman fire, Rough (2007) tested the effectiveness of a wood-based hydromulch containing seeds with and without polyacrylamide (PAM) in reducing erosion rates on paired or nearby swales (average area of 0.3 ha) burned at high severity. The hydromulch with PAM was applied aerially and reduced erosion rates by 95% in the first post-fire year and 50% the second post-fire year as compared to control swales that were 100–900 m away. The hydromulch without PAM contained half as much seed as the hydromulch with PAM, and was applied using truck-based sprayers. It did not reduce erosion rates in either year as compared to the adjacent paired control swales (Rough, 2007). The differences in the results between the two hydromulch formulations in the Rough (2007) study as well as the contrast between formulations in this study suggests that differences in hydromulch components, application techniques, and application rates likely impact hydromulch effectiveness. Hydromulch formulations specifically designed to increase the longevity of the fibers and the integrity of the hydromulch mat on the soil may improve its effectiveness in reducing post-fire erosion.

The first measure of ground cover at the Cedar fire resulted in only a fraction of the target mulch cover (Fig. 4), despite the manufacturer's expectations that it would stay intact on the soil for 6–12 months and then break down gradually (USDA Forest Service, 2003). The Cedar Fire started 25 Oct 03 and it was mid-December—well into the normal wet season—when the fire was fully controlled and the post-fire treatment plan implemented. The rainfall that occurred between treatment installation (second and third weeks of December, 2003) and the first ground cover measurement (4 Mar 04) likely contributed to the low amounts of hydromulch observed in the ground cover at the Cedar fire. These rain events were not measured as part of this study; however, in another hydromulch effectiveness study done in close proximity to the Cedar catchments, Hubbert et al. (2012) reported that 121 mm of precipitation was measured between the installation of the hydromulch treatments and their first ground cover measurements made on 18 Feb 04. The hydromulch cover values from their first ground cover assessment were about half the nominal 100% and 50% coverage rates (56% and 24%, respectively) and Hubbert et al. (2012) speculated that the precipitation after treatment application but before the ground cover assessments had resulted in a rapid erosion of the hydromulch. During the two weeks between the Hubbert et al. (2012) ground cover measurement and our first ground cover measurement, an additional 132–136 mm of precipitation was measured in the treated catchments. The differences in the hydromulch cover between Hubbert et al. (2012) and in the current study (21% hydromulch in the fully treated catchment and 5% in the partially treated catchment) reflect the continued effects of the numerous winter rainfall events that occurred between these two ground cover assessments.

Hydromulch, as an alternative to straw mulches, is of particular interest for post-fire treatment in chaparral and coastal sage regions in southern California. These shrub lands are prone to frequent fires, have high post-fire erosion rates, experience high wind events (e.g., the Santa Ana winds), and have population centers and values at risk below the steep canyons that lead downstream from the coastal mountains (Keeley and Fotheringham, 2001). Thus, there is a societal need for highly effective post-fire treatments that reduce runoff and erosion and are not easily displaced by long duration rains and high winds.

Initial results from hydromulch effectiveness monitoring at the Cedar fire encouraged manufacturers to develop a hydromulch formulation that would be more resilient to weathering and runoff (Wohlgemuth et al., 2006). Hydromulch products using paper fibers with higher concentrations of tackifiers and binding agents are currently being tested at three recent fires in southern California. Initial observations indicate that these hydromulch formulations and applications have been longer lived and are potentially more effective than those used at the Cedar fire (P. Robichaud, unpublished data).

4.4. Comparison of sediment yields from hillslope plots and small catchments

This study, the accompanying study (Robichaud et al., 2013), and Hubbert et al. (2012) all measured decreases in sediment yields over time in the control plots, but the magnitude of the decrease was greater at the hillslope scale than at the catchment scale (Figs. 6 and 7). These results may reflect the relationships between spatial scale and unit-area sediment yields. These relationships have been studied but mostly on unburned landscapes. In general, unit-area sediment yields decrease with increasing contributing area (Lane et al., 1997), especially at larger spatial scales than our experimental catchments. One experiment in Arizona showed that the sediment yields from hillslope plots between 2 and 28 m long would increase with increasing plot length until the maximum occurred, which generally was at plot lengths between 4 and 14 m, and then the yields would decrease with greater length (Parsons et al., 2006). Other researchers developed a conceptualization for the unit-area sediment yields for a range of spatial scales (de Vente and Poesen, 2005; de Vente et al., 2007). They suggested area-specific sediment yields tend to increase with increasing area at the m^2–km^2 scale because more erosion processes come into play, and then decline with increasing area when additional processes (e.g., floodplain storage) became more significant at larger ($>km^2$) scales (de Vente et al., 2007). According to these conceptual models, our study catchments (0.06 km^2 or less) were at the lower range of the spatial scale that would tend to have increasing sediment yields with increasing contributing areas. However, de Vente and Poesen (2005) also suggest that local environmental conditions and their spatial distributions explain a large part of the variation in sediment delivery. Given the dramatic effects of wildfire on vegetative cover, erosion and transport processes, sediment storage, and level of connectivity, we might expect that spatial distributions of these post-fire environmental conditions may have greater influence on the variation of sediment yields by scale than the unit-area concept alone.

One possible explanation for the greater rate of reduction in sediment yields over time at the smaller scales was that increasing vegetation regrowth caused a reduction in raindrop splash erosion and an increase in the rainfall (intensity or amount) threshold that allowed overland flow to concentrate into rills. A decrease in total overland flow was observed in the catchments at both the Hayman and Cedar fires (Tables 7 and 8). It is therefore likely that lower rill flow and erosion rates occurred during the same period in the hillslope plots and that these rates also decreased over time with the reductions in runoff that were measured at the catchment scale. However, overland flow may have been sufficient to concentrate into rills due to the greater slope lengths and variability of terrain in the catchments as compared to the hillslope plots. The overland flow may have connected the hillslope to the channel network via rill development. This connection occurred regardless of the decreased overland flow compared to the early period in each study.

Perhaps the most significant difference in the hillslope plots as compared to the catchments was the absence of defined channels, and as a consequence, the lack of channel erosion and storage processes. Moody and Martin (2009) synthesized the post-fire erosion rates that had been measured within 2 years of fires in the western US. They found that the mean sediment yield from channels (240 t ha^{-1}) was significantly greater than from hillslopes (82 t ha^{-1}) and concluded that channels were the primary sources of available sediment for transport. Wildfire effects, such as greatly reduced soil cover, disaggregated surface soils, increased dry ravel (Lamb et al., 2011; Shakesby and Doerr, 2006), likely increased hillslope sediment (measured in the hillslope plots) delivery to channels and thereby increased the sediment available for transport in those channels. Rain events would cause increased flow depths and resultant sheer stress in the channels and some of the alluvium would be transported downslope (measured in the catchments). Occasional pulses of sediment from hillslope erosion processes, including dry ravel at the Cedar fire, provided additional sediment for subsequent transport over time.

Although it is conceivable that the supply of transportable sediment on bounded hillslope plots became depleted, we do not believe this is the case at the Hayman fire. Sediment yields on the Hayman hillslope plots continued to be greater than 1 Mg ha^{-1} yr^{-1} even in the seventh post-fire year, albeit with relatively high rainfall intensity in the later years (Robichaud et al., 2013). The relatively high erosion rates over several post-fire years at the Hayman fire may be a unique feature of the Hayman area, where the gravelly unconsolidated soils are highly erodible and the ground cover is sparse compared to other less arid forests in the western US. Nonetheless, sediment yields from areas burned at high severity and measured with hillslope plots decreased more rapidly over time than their corresponding catchments, and this suggests that caution should be used when describing post-fire erosion rates and erosion rate recovery based on data derived from planar hillslope plots alone.

5. Conclusions

Climate and rainfall characteristics varied considerably between the Hayman and Cedar fires where we measured post-fire runoff, peak flow, and sediment yields in mulched and untreated matched catchments. The erosive soils at the Hayman fire combined with the common occurrence of high intensity summer thunderstorms resulted in generally greater event erosion rates than at the Cedar fire. The Cedar fire had a Mediterranean climate, with nearly all precipitation falling during the winter wet season in long duration rain storms.

Immediately after application, the straw mulch in the Hayman catchment provided an additional 50% ground cover bringing the total ground cover to 80%. Total ground cover stayed high in the straw mulch catchment as the vegetation and litter components—including the contribution by the non-native cheatgrass that was inadvertently introduced as seed in the wheat straw mulch—increased and replaced the decreasing straw mulch cover. Because of the initial and continued increase in ground cover, the wheat straw mulch treatment significantly reduced peak flow rates and sediment yields as compared to the control catchment. The time since the fire was a significant covariate for all responding variables, and the impact of increasing time is reflected in the observed reduction in peak flow rates and sediment yields over time and the lack of runoff in the straw catchment after the second post-fire year.

The two formulations of hydromulch applied at the Hayman and Cedar fires had limited residence times on the ground—about one year at the Hayman fire, about 6 months at the Cedar fully treated catchment, and about 2.5 months on the Cedar partially treated catchment. Despite our efforts to match the catchments used in the study, the three catchments at the Cedar fire had sufficiently different hydrologic responses during the “untreated” periods (after the hydromulch contributed less than 10% ground cover) that we were unable to test treatment effectiveness. Similarly, we were not able to test for any treatment effect on peak flow responses on the Hayman hydromulch catchment; but the Hayman hydromulch treatment was not effective in reducing post-fire runoff or sediment yields during the treated period.

Sediment yields in the catchments measured soon after the fire were similar to those measured on hillslope plots at both the Hayman and Cedar fires; however, sediment yields from the catchments in later post-fire years were at least double the sediment yields measured on hillslope plots. The longer duration of elevated erosion rates in the catchments likely reflect the addition of channel erosion and transport processes and the hydrological connectivity of the larger landscape. These results suggest that post-fire recovery includes not only increased ground cover and reduction of hillslope erosion, but also mitigation of runoff generation and delivery to channels. In addition, an appropriate scale of measurement should be adopted when using sediment yield data for management or research needs.

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Appendix A. Supplementary video

Supplementary video related to this article can be found online at http://dx.doi.org/10.1016/j.catena.2012.11.016.

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