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Effectiveness of straw bale check dams at reducing post-fire sediment yields from steep ephemeral channels

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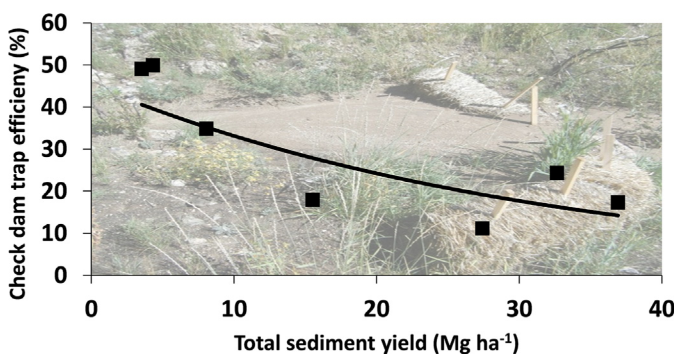
HIGHLIGHTS

- Rainfall intensities were often >2-yr return intervals.
- Straw bale check dams filled to capacity during initial rain events.
- Straw bale trap efficiency was low overall.
- Hillslope and catchment sediment yields were high.

GRAPHICAL ABSTRACT



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ABSTRACT

Post-fire flooding and elevated sediment loads in channels can pose hazards to people and structures within the wildland-urban interface. Mitigation of these hazards is essential to protect downstream resources. Straw bale check dams are one treatment designed to reduce sediment yields in small ephemeral catchments (<2 ha). This study investigated their effectiveness in five paired catchments burned at high severity during the 2010 Twitchell Canyon Fire in Utah. Rainfall, ground cover and hillslope erosion rates were also measured during the two-year study. Adjacent paired catchments were physically similar and ranged in size from 0.2 to 1.6 ha across pairs. Within pairs, one catchment was an untreated control and the other treated at a rate of four straw bale check dams ha^{-1}. High intensity rainfall, erodible soils and slow regrowth contributed to the observed high hillslope sediment yields (> 60 Mg ha^{-1}). 1- and 2-yr I_{30} return period rain events early in the study quickly filled the straw bale check dams indicating the treatment did not statistically reduce annual sediment yields. First year annual sediment yields across all catchments were 19.6 to 25.7 Mg ha^{-1}. Once the check dams were full, they had limited storage capacity during the second post-fire year, allowing 3.8 to 13.1 Mg ha^{-1} of sediment to pass over the check dams. The mean mass of sediment trapped by individual straw bale check dams was 1.3 Mg, which allowed them to trap a mean of 5.9 Mg ha^{-1} of sediment at the given treatment rate. Straw bale check dams trapped <50% of the total mass delivered from catchments with efficiency decreasing over time. Increasing straw bale check dam treatment rate in stable channels may improve trap efficiency. Application of this treatment in areas with lower expected rainfall intensities and less erodible soils may be justifiable.

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1. Introduction

Wildfires have increased in frequency and total area burned for the last three decades in the western United States (Westerling et al., 2006; Morgan et al., 2008; Moritz et al., 2014). Accelerated rates of runoff, hillslope erosion, and channel sediment yields are often associated with post-fire hydrologic events (Canfield et al., 2005; Smith and Dragovich, 2008; Shakesby and Doerr, 2006; Vieira et al., 2016). Such events have become increasingly hazardous to life, homes, and infrastructure with the expansion of the wildland-urban interface (Gallup, 1975). Therefore, it is critical for land managers tasked with mitigating these hazards to understand the benefits and drawbacks of a given erosion control treatment and determine if it is meeting their objectives.

Wildfire alters vegetation and soil characteristics changing landscape response to rainfall events (McMichael and Hope, 2007; Van Eck et al., 2016). Wildfires typically burn in an uneven patchwork mosaic of low, moderate, and high severities (Parsons et al., 2010; van Wagtendonk and Lutz, 2007), and the relationship of the patches of moderate and high severity influences runoff and sediment yields (Moody and Martin, 2009). High soil burn severity areas, with significant vegetation mortality, litter, duff, and soil organic matter consumption and high soil heating (Lentile et al., 2006), are the most susceptible to accelerated runoff and sediment yields, usually driven by high intensity rain events (Moody and Martin, 2001; Benavides-Solorio and MacDonald, 2005). Catchments burned at high severity from the upper most hydrologic divides to the outlets have increased drainage connectivity, shortened times of concentration, and greater peak flows relative to catchments with unburned or lower severity patches (Moody et al., 2013; Wagenbrenner and Robichaud, 2014).

Post-fire runoff events move sediment through detachment, transport, deposition and re-entrainment of ash, soil, cobbles, and wood. Rill networks detach and transport up to 80% of hillslope sediment erosion (Pierson et al., 2008). The eroded hillslope sediment can be redeposited on hillslopes (Wagenbrenner et al., 2010), deposited in channels (Moody and Martin, 2009), or transported to higher order streams or onto alluvial fans (Willgoose et al., 1992). Moody and Martin (2009) show ranges in post-fire channel bedload sediment yields of 14 to 300 Mg ha^{-1} with a mean of 240 Mg ha^{-1} in the first two years after a wildfire.

Post-fire channel treatments are implemented by land managers to trap sediment and stabilize channels (Tracy and Ruby, 1994; Napper, 2006). Ephemeral channels draining low-order catchments are often treated with erosion control check dams made of rock, wood, straw bales, rock gabions or a combination of these materials. Check dam storage capacity is related to crest height of the spillway and channel slope. Fox (2011) found gaps and holes within log debris check dams effectively reduced the spillway height by over 50%, significantly reducing potential storage capacities.

Straw bale check dams are a relatively quick and easy treatment to install in burned catchments. They are installed perpendicular to flow in the channel bed by keying in and tightly abutting straw bales together end to end (Napper, 2006) (Fig. 1). For added stability, the bales are placed with a small concave curve up-channel and have wooden stakes driven through them into channel bed. Weak points such as the joints between abutting straw bales are often strengthened by tightly wedging excess loose straw, sticks, or rocks into gaps. The straw bales extend up onto the channel banks on either side to form a "U" shaped structure. It is necessary to ensure the outside bottom corner of the end bales are higher (0.2 to 0.3 m) than the crest of the center spillway to prevent runoff from routing around the check dam. Large cobbles are often placed on the downstream side of the check dam at the below the spillway to reduce scour.

Studies to evaluate post-fire channel sediment yields with the use of straw bale check dams produced mixed findings and recommendations (Ruby, 1997; Miles et al., 1989). Ruby (1997) suggests the treatment is unsuccessful in primary watersheds or small catchments if fine sediments and ashes wash past the structures and are released into higher order channels. Following the 1991 Oakland Hills Fire, straw bale check dams had a 50% failure rate just three months after installation (Collins and Johnston, 1995). Primary failure mechanisms were undercutting, flow routing around structures, structure displacement, and erosion of previously deposited sediment. Sprague et al. (2014) also reported undermining of straw bale check dams as a common failure in a flume study.

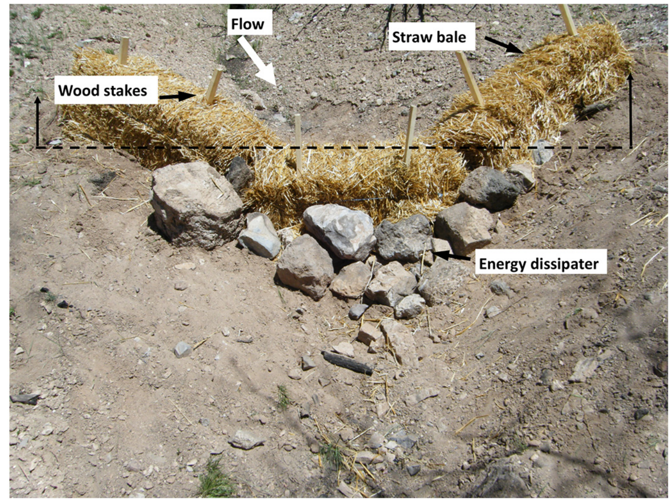

Fig. 1. A straw bale check dam. Straw bales are keyed into the bed and banks to create a U-shaped structure that spans the width of the channel. Ground surfaces at upslope ends of bookend straw bales (vertical arrows) are higher elevation than the top of the center spillway bale (dashed line). Energy dissipating rocks are positioned on the downstream side to reduce scour.

Minor successes of straw bale check dams have also been reported in the past. After the 2003 Grand Prix/Old Fire in California, straw bale check dams trapped sediment along steep channel gradients (6 to 20%) for the first series of small rainfall events (Wohlgemuth et al., 2007). Vegetation was observed growing in the trapped sediment, however after a series of rain events totaling 92 mm one year after the fire the majority of the check dams were displaced. The few remaining check dams were displaced two years later after record-setting 500 mm of rainfall occurred in one month. They noted that the straw bale check dams likely failed because of piping, dams being undermined by flow, and destabilization of channel banks due to localized flow. In contrast, straw bale check dams in Portugal retained sediment and the stabilized sediment revegetated with no check dam failures (Vieira et al., 2013). After the 1987 South Fork Trinity River Fire in California straw bale check dams trapped an average of 1.1 m^3 of sediment and had a failure rate of only 13% from piping underneath or between straw bales (Miles et al., 1989).

Napper (2006) recommends placing multiple check dams in a channel using the head-to-toe spacing approach, where the elevation of the spillway of a given check dam is the same as the channel elevation of the next upstream check dam. However, a per unit area treatment rate is notably absent from post-fire mitigation literature on straw bale check dams (Napper, 2006). At construction sites, straw bale check dams have been effective when the installation rate is 2 structures ha^{-1} or more. (Goldman et al., 1986) Under these conditions, regular maintenance is necessary to remove trapped sediment when the structure becomes more than half full to maintain efficacy (Goldman et al., 1986). Castillo et al. (2007) also suggests proper placement and maintenance as crucial factors in check dam effectiveness.

Ephemeral channels in burned areas have been treated with straw bale check dams for at least the past four decades (Robichaud et al., 2000), however, no studies definitively show if they significantly reduce sediment yields from burned catchments. Our objectives were to: 1) determine if post-fire sediment yields are significantly reduced in catchments treated with straw bale check dams as compared to a catchment with similar characteristics without treatment, 2) determine the trap efficiency of straw bale check dams in burned areas, and 3) to quantify hillslope sediment yield rates.

2. Methods

2.1. Site description

This study was conducted within the 18,000 ha 2010 Twitchell Canyon Fire in the Tushar Mountains of south-central Utah, USA (Fig. 2). Dominant pre-fire vegetation at the study site included pinyon pine (*Pinus edulis*), juniper (*Juniperus osteosperma*), and gamble oak shrub (*Quercus gambelii*) with perennial grasses and forbs and mountain big sagebrush (*Artemisia tridentata*) dominating the understory (USDA Forest Service, 2010). The silt loam soils are highly erodible *Aridic Argiustolls* and *Aridic/Typic Haplustolls* (USDA Forest Service, 2010) (34% sand, 65% silt, <1% clay) derived from the Sevier River Formation sandstone (Rowley et al., 2002).

The average annual rainfall at the study site is 525 mm with the majority of precipitation occurring as snow (Utah State University, Climate Center, https://climate.usu.edu/; accessed 23 Sep 2018). At the nearby Kimberly Mine Snow Telemetry site, 4 km south and 500 m higher in elevation (2783 m), 80% of precipitation occurred as snow during the study periods (USDA, NRCS, http://www.wcc.nrcs.usda.gov, Kimberly Mine; accessed 19 Sep 2018). The regional climate is influenced by the North American monsoon precipitation regime during the summer (Higgins et al., 1998). Winter precipitation is from frontal systems out of the Pacific Northwest. The onsite precipitation frequency estimates for the study site (Lat. 38.536°, Long. −112.411°) are a 2-year, 10-minute maximum rainfall intensity (I_{10}) return period is 48 mm h^{-1}, a 5-year I_{10} of 66 mm h^{-1}, a 2-year I_{30} of 26 mm h^{-1}, and a 5-year I_{30} of 37 mm h^{-1} (https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html; accessed 4 Nov 2018).

2.2. Paired catchments

Ten small ephemeral catchments were identified and paired within two neighboring canyons approximately 1.2 km apart; three pairs in Sevier Canyon and two pairs in Middle Canyon (Fig. 2). Catchments ranged in size from 0.2 to 1.6 ha (Fig. 2, Table 1). Each pair was similar in area, aspect, degree of channel incision, hillslope and channel gradients, and was burned at high soil burn severity (USDA Forest Service, 2010). One catchment within each pair was randomly selected for treatment with straw bale check dams, the other catchment was the control with no treatment. All above-ground organic matter, including fine fuels, leaf litter and duff, were consumed resulting in high vegetation mortality and reduced ground cover.

The study catchments are located between 2060 and 2250 m in elevation, with <80 m of relief across all catchments. Study catchments

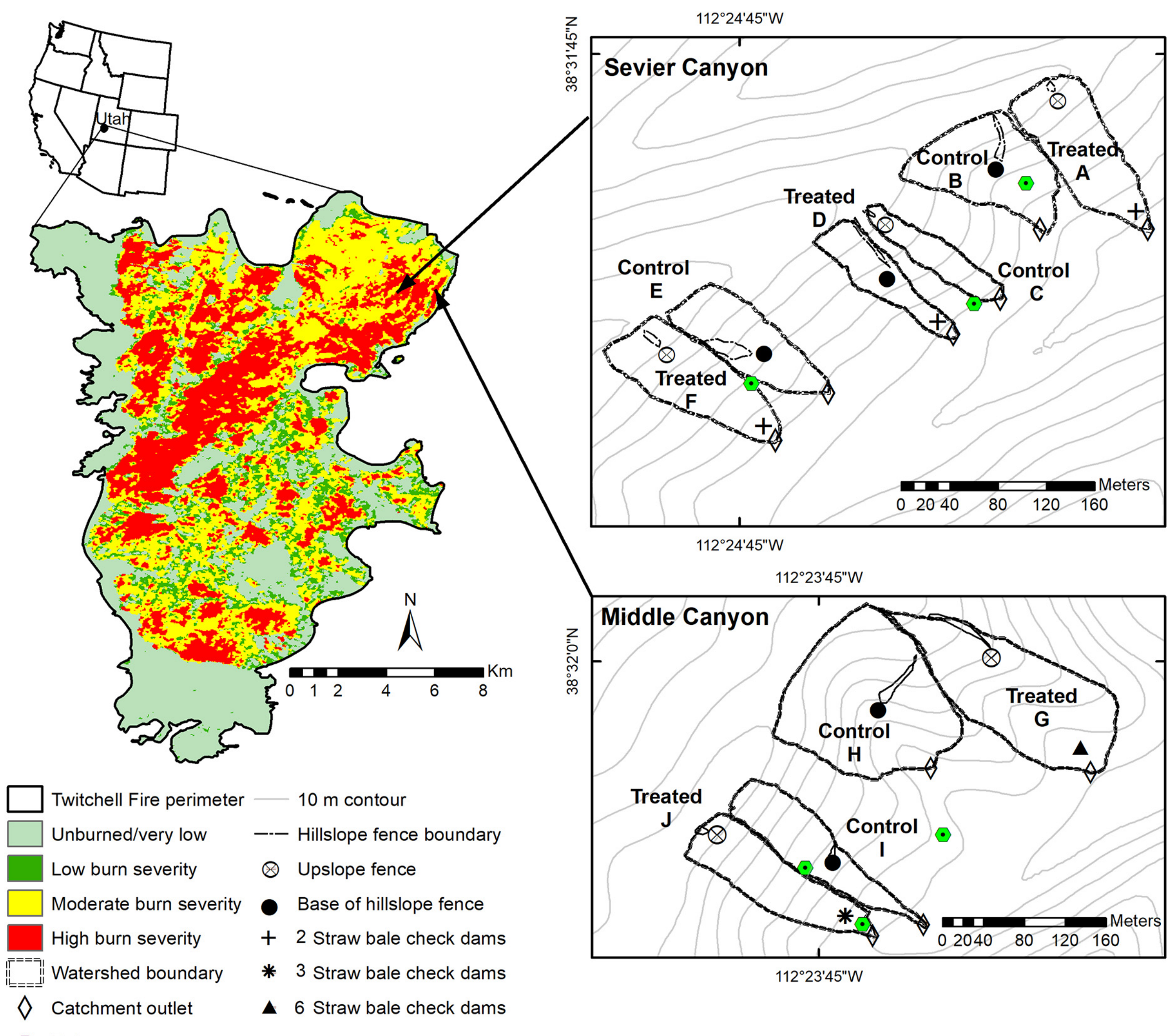

Fig. 2. The 2010 Twitchell Canyon Fire burn severity and catchment maps.

Table 1
Location, catchment label, treatment, # of straw bale check dams, catchment area (ha), vertical relief of catchment (m), mean channel gradient (%) and channel length (m) from the outlet to the channel head for each study catchment. Catchments pairs were A-B, C-D, E-F, G-H, and I-J.

Location	Catchment	Treatment	# of straw bale check dams	Catchment area (ha)	Vertical relief (m)	Mean channel gradient (%)	Channel length (m)
Sevier Canyon	A	Treated	2	0.5	56	23	85
	B	Control		0.6	59	27	48
	C	Control		0.2	53	47	52
	D	Treated	2	0.3	57	49	37
	E	Control		0.4	63	36	45
	F	Treated	2	0.6	69	32	50
Middle Canyon	G	Treated	6	1.4	76	20	90
	H	Control		1.6	21	30	125
	I	Control		0.6	66	26	118
	J	Treated	3	0.7	71	33	130

have steep headwalls and side slopes with a mean gradient of 58% that drain into bedrock channels with a mean gradient of 29% (Table 1). The bedrock channels begin high in the drainages and form from the topographic convergence of hillslopes and rills over a distance of 4 to 9 m before they are fully defined. Channel lengths range from 38 to 137 m and lead to alluvial fans or higher order channels.

Check dams were installed at a rate of 1 dam per 0.25 ha^{-1}, 4 dams per ha^{-1}, of contributing area. Each straw bale check dam was installed following Napper (2006), using three to five straw bales tightly abutted end to end and keyed or trenched 0.1 m in to the channel bed and banks creating a U-shaped structure perpendicular to flow (Fig. 1). Straw bales were 0.5 m by 0.4 m by 1 m in size, weighed ~18 kg, and were secured by two to three wooden stakes (2.5 cm × 5 cm × 0.6 m) driven through each bale into the ground (Napper, 2006) (Fig. 1). The straw bale check dam structures were installed 5 to 15 m upstream of catchment outlets and were spaced about 4.5 m apart. There were between 2 and 6 check dams in each treated catchment (Table 1).

2.3. Rainfall events

The paired catchments were identified and instrumented in spring 2011 after the first snow accumulation and melt period but before the first post-fire monsoon season. Five tipping bucket rain gauges (RainWise, Bar Harbor, ME; HOBO Event Logger, Onset Computer, Bourne, MA) monitored continuously during both post-fire monsoon seasons. They recorded rain event timing and amounts. The rain gauges were located between adjoining paired catchment ridges or on a nearby ridge to provide a spatial-distributed network of rain gauges (Fig. 2). Total precipitation (mm), duration (min), and 10-minute (I_{10}) and 30-minute (I_{30}) rainfall intensities were determined for each event separated by 6 h with no tips, and each event was categorized for recurrence intervals (Robichaud and Brown, 2002).

2.4. Ground cover

Ground cover was measured along transects in the spring and fall of 2011 and the fall of 2012 to quantify bare soil and vegetative re-growth in each catchment. Cover was classified at 0, 10, 20, 30, and 40 m using five 1 × 1 m plots were evenly spaced along three 40 m transects. One transect was along the length of the channel, and two transects were parallel to the channel on each side about 50 m above the channel. At each location, the ground cover falling at the intersections of a 10 × 10 cm grid was used to classify the material on the ground surface as mineral soil, vegetation, litter, wood, or rock, for a total 100 sample points per plot (Robichaud and Brown, 2002).

2.5. Hillslope sediment yields

Hillslope sediment yields were measured at two spatial scales to determine if the catchment sediment yields were different from hillslope sediment yields. The upslope plots were to determine if hillslope erosion occurred at the onset of rill convergence in the upper portions of the catchments and the base of slope plots were used to determine if larger contributing areas were needed to generate sediment. Hillslope sediment yields were measured with hillslope fences, following the design by Robichaud and Brown (2002), with one of two randomly assigned spatial scales within each paired catchment. The mean contributing area of upslope plots was 50 m^2, a mean slope length of 16 m and mean gradient of 50%. The mean contributing area of base of slope plots was 130 m^2 with a mean slope length of 46 m and gradient of 50% (Table 2). Sediment yields collected in hillslope fences were removed by hand with 20 l buckets, weighed and sub-sampled for sediment moisture content after each rainfall event. Sediment yields were the dry sediment weights divided by the contributing area.

2.6. Catchment sediment yields and straw bale check dam storage

Bedload sediment yields eroded from catchments were captured with sediment traps installed at the catchment outlets with reinforced

Table 2
Location, catchment label, fence topographic position, contributing area of hillslope (m^2), slope length (m) from the hydrologic divide to the hillslope fence, and mean gradient (%) above each hillslope fence.

Location	Catchment	Topographic position	Contributing area (m^2)	Slope length (m)	Gradient (%)
Sevier Canyon	A	upslope	29	11	53
	B	base of hillslope	116	43	62
	C	upslope	22	11	61
	D	base of hillslope	108	55	43
	E	base of hillslope	276	44	58
	F	upslope	64	21	43
Middle Canyon	G	upslope	227	66	25
	H	base of hillslope	224	64	46
	I	base of hillslope	27	12	39
	J	upslope	59	12	67

sediment retention structures modified from Robichaud and Brown (2002) (Fig. 3). The sediment retention structures were built with standard framing lumber (10 × 4 × 305 cm, wood stakes (5 × 5 × 120 cm), 5 × 10 cm welded mesh wire, 14-gauge wire, and high tensile strength woven geotextile fabric (US Fabrics, Cincinnati, OH). Lumber framed structures spanning the channel widths were secured to the channel bed and banks with side walls extending out from the center spillway wall and angled slightly up-channel. The structures' center spillway walls ranged in height from 90 to 150 cm tall depending on the channel's shape. Welded wire and geotextile fabric were secured to the up-channel face of the lumber frames and the fabric extended up the channel bed 1 to 3 m (details in Storrar, 2013). Two sediment retention structures were built in series in each channel to capture bedload sediment yields. However, sediment yields were greater than expected (Robichaud et al., 2013a); therefore in 2 catchments a third structure was added to increase the storage capacity. There were several events that sediment yields exceeded the storage capacity of the sediment retention structures and these sediment yields are noted as minimum values.

Trapped bedload sediment was measured and removed using one of two different techniques depending on the size of the deposit. Small sediment yields (<1 Mg) were removed and weighed with plastic buckets and sub-sampled to determine sediment water content, which was then used to convert the wet field mass to a dry sediment yield (dry mass of sediment divided by contributing area). This direct measurement of the sediment weight was preferred (Robichaud and Brown, 2002).

The volumes of large sediment yields (>1 Mg) were measured by differencing digital elevation models created from topographic surveys of the depositional areas upstream of retention structures. Surveys were conducted with a total station (Topcon GTS-2110, Livermore, CA) before any sediment accumulated and then after each large sediment accumulation and cleanout. Sediment was removed by shovel or with a mini-excavator. Surveyed volumes were converted to mass using bulk density core samples taken within the trapped sediment deposits. On two occasions sediment yields trapped in retention structures (>1 Mg) were measured using both techniques and the two approaches produced sediment yields within 4% of each other. Straw bale check dam storage volume capacities were measured at installation and after sediment producing events using differencing digital elevation models. Although foot traffic was necessary to conduct all aspects of this field experiment, our observations indicated negligible impact on any of our sediment yield measurements due to vegetation disturbance or soil compaction.

Fig. 3. Sediment captured by sediment retention structures in catchment I from a rain event on 8 July 2011 (12 mm total, $I_{30} = 14$ mm h^{-1}).

2.7. Straw bale check dam analysis

Trap efficiency of straw bale check dams (SCD trap efficiency) was determined by:

$$\textit{SCD Trap efficiency}\ (\%) = \frac{\Sigma\ \textit{SCD trapped mass}\ \left(\textit{Mg ha}^{-1}\right)}{\textit{SCD Trapped mass}\ \left(\textit{Mg ha}^{-1}\right) + \textit{Total catchment sediment yield}\ \left(\textit{Mg ha}^{-1}\right)} \times 100\% \quad (1)$$

where SCD trapped mass (Mg ha^{-1}) was the sum of sediment mass trapped by the straw bale check dams divided by the contributing area of the catchment; and catchment sediment yield was the sediment yield (Mg ha^{-1} yr^{-1}) of the catchment including hillslope fence sediment. Trap efficiencies were calculated for 2011 and for the cumulative period 2011 and 2012.

We assumed the sediment yield for each catchment was equal to the sediment yield of its paired catchment before treatments were installed. The paired catchment sediment yield ratio was determined by:

$$\textit{Paired catchment ratio} = \left(\frac{\textit{SCD Trapped Mass}\ \left(\textit{Mg ha}^{-1}\right) + \textit{Treated catchment sediment yield}\ \left(\textit{Mg ha}^{-1}\right)}{\textit{Control catchment sediment yield}\ \left(\textit{Mg ha}^{-1.}\right)}\right) \quad (2)$$

Some sediment retention structure failures including overtopping in 2011, did not allow for trap efficiency or paired catchment ratios to be calculated in Sevier Canyon. Some of the straw bale check dams were full at the start of 2012, thus the SCD trapped mass was zero in these cases.

2.8. Statistical analysis

Sediment yields were analyzed on an annual basis to determine significance of treatment effectiveness (Ramsey and Schafer, 2012). Paired catchment data from Sevier Canyon in 2011 were not analyzed for treatment effectiveness due to incomplete data sets for the three pairs when sediment retention structures were overtopped or failed during runoff events. Sediment yields were skewed right, therefore values were log-transformed for statistical analysis. In order to log transform zero values half the smallest recorded sediment yield (0.002 Mg ha^{-1}) was added to all sample values.

Generalized least squares and mixed effects models were used to analyze paired catchment sediment yield data. For both of these models, treatment type (control or treated) was used as explanatory variables, and covariates believed to potentially influence sediment yields were included: total event rainfall (mm), maximum 10-min rainfall intensity (I_{10}, mm h^{-1}), maximum 30-min rainfall intensity (I_{30}, mm h^{-1}), within catchment upslope or base of hillslope log-transformed sediment yield, channel and hillslope gradient (%), 10-day antecedent rainfall (mm), basin shape which is channel length squared/catchment area, post-fire year, mineral soil cover within the channel, mineral soil cover on the hillslopes, and the interactions between year and upslope plot, and year and base of slope plot log-transformed sediment yields. The area normalized sediment yields were nested within location (canyon name) as a random factor allowing for within group variance and were autocorrelated with a continuous time covariate, the number of days since fire containment that the event occurred (Pinheiro et al., 2013; Zuur, 2009). Similar model selection approach was applied to upslope and base of slope sediment yields.

A backward selection approach was used to test covariates for inclusion in the final model using maximum likelihood estimation. Each fixed effect covariate was independently tested for significance and the most non-significant factor was removed from the model. This iterative procedure continued progressively with the pared down full model until all factors were significant. Rainfall variables were included one at a time in the model due to a lack in independence. Mineral soil cover was transformed by the arcsine square root for a more normal distribution (Lloret, 1998). The final model was visually inspected for normality using quantile-quantile plots and the final model residuals were plotted against each explanatory variable to check for equal distribution.

Welch Two Sample *t*-tests were used to assess significance of differences between hillslope and channel cover. A paired t-test was used to test for significant differences among sampling intervals. Prior to statistical analysis of the five ground cover variables, they were square-root or arcsine square-root transformed (Lloret, 1998). Statistical significance occurred if $p \leq 0.05$. All analyses were done in the R v.2.15 software environment (R Core Team, 2012) using the nlme package (Pinheiro et al., 2013). Additional details of statistical methods are provided in Storrar (2013).

3. Results

3.1. Rainfall events

The area experienced near normal rainfall during the two-year study period. In 2011, 41 to 49 rain events produced 144 to 240 mm of rainfall across the rain gauges and in 2012, 32 to 45 events recorded 129 to 194 mm of rainfall (Table 3). Sevier Canyon received more high intensity rainfall events and precipitation compared to Middle Canyon. The highest intensity events included two 5-year return period I_{10}s, three 2-year I_{10}s, and two 1-year I_{10}s, with the overall maximum I_{10} of 59 mm h^{-1}, (Table 4). Middle Canyon had a similar number of rain events as Sevier Canyon, however, it had much lower intensity events with only one 1-year I_{10}.

Sevier and Middle Canyons received less precipitation and fewer events during 2012, when 32 to 45 events produced 129 to 194 mm of rainfall (Table 3). However, both canyons received a greater number of high intensity events equal to or greater than a 1-year I_{10} return period (Table 4). In 2012, Sevier Canyon experienced four events where at least one gauge measured at least a 2-year return period I_{10}, and two events where at least one gauge recorded a 1-year I_{10} return period events.

3.2. Ground cover

Hillslopes and channels had similar distributions of ground cover (Fig. 4). Several of the ground cover categories were similar from fall 2011 to fall 2012 (Fig. 4). The largest shifts in hillslope cover from fall 2011 to fall 2012 were a significant increase ($p = 0.001$) in the vegetation, mostly gamble oak shrub (*Quercus gambelii*) (18 to 30%), and a significant decrease in mineral soil (56 to 39%). Vegetation cover on the hillslopes (30%) was significantly less ($p = 0.001$) than in the channels (43%) in 2012. There was also a significant increase in vegetation cover in the channels between 2011 (26%) and 2012 (43%).

Table 3
Location, catchment pair, elevation (m), number of events and total precipitation (mm) for each rain gauge and year. The monitored periods were 10 Jun - 8 Oct 2011 and 7 May - 27 Sep 2012.

Location	Catchment pair	Elevation (m)	Year	No. of rain events	Total rainfall (mm)
Sevier Canyon	A-B	2190	2011	41	240
			2012	35	150
	C-D	2197	2011	42	199
			2012	36	144
	E-F	2236	2011	49	237
			2012	47	164
Middle Canyon	G-H	2104	2011	41	189
			2012	32	129
	I-J	2133	2011	45	194
			2012	32	134

Table 4
Rainfall event date, post-fire year, catchment pair, rainfall amount (mm), maximum 10-min rainfall intensity (I_{10}, mm h^{-1}), maximum 30-min rainfall intensity (I_{30}, mm h^{-1}) and return periods associated with I_{10} and I_{30} for all events that produced sediment.

Event date [post-fire year]	Pair	Rainfall (mm)	I_{10} (mm h^{-1}) [return period]*	I_{30} (mm h^{-1}) [return period]*
15 Jun 2011 [1]	A-B	14	43 [2]	28 [2]
8 Jul 2011 [1]	A-B	15	58 [5]	20 [1]
	C-D	14	55 [2]	20 [1]
	E-F	16	59 [5]	21 [1]
	G-H	11	27	13
	I-J	12	32 [1]	14
27 Jul 2011 [1]	A-B	8	18	10
	C-D	7	17	9
	E-F	8	18	10
	G-H	8	20	9
	I-J	8	18	9
3 Aug 2011 [1]	A-B	26	37 [1]	15
	C-D	22	32 [1]	13
	E-F	26	43 [2]	15
	G-H	17	17	12
	I-J	18	18	12
25 Aug 2011 [1]	A-B	10	32 [1]	19 [1]
	C-D	8	29	16
	E-F	9	27	17
	G-H	8	27	15
	I-J	8	27	15
6 Oct 2011 [1]	A-B	37	14	10
	C-D	21	11	10
	E-F	22	11	9
	G-H	10	15	12
	I-J	12	18	16
16 Jul 2012 [2]	A-B	15	47 [2]	23 [1]
	C-D	16	52 [2]	24 [2]
	E-F	15	52 [2]	24 [2]
	G-H	24	53 [2]	38 [5]
	I-J	26	61 [5]	41 [5]
31 Jul 2012 [2]	I-J	11	32 [1]	15
1 Aug 2012 [2]	A-B	6	37 [1]	13
	C-D	7	38 [1]	13
	E-F	7	40 [1]	14
	G-H	8	49 [2]	17
	I-J	8	44 [2]	16
14 Aug 2012 [2]	A-B	16	49 [2]	22 [1]
	C-D	13	40 [1]	19 [1]
	E-F	14	40 [1]	19 [1]
	G-H	6	23	10
	I-J	10	26	15
24 Aug 2012 [2]	A-B	7	37 [1]	13
	C-D	7	41 [1]	14
	E-F	8	44 [2]	15
10 Sep 2012 [2]	A-B	9	35 [1]	12
	C-D	9	35 [1]	12
	E-F	8	27	10
	G-H	11	35 [1]	13
	I-J	11	37 [1]	14

* I_{10} and I_{30} rainfall intensity for Lat. 38.526°, Long. -112.41° from: http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_maps_cont.html?bkmrk=ut; accessed 18 Sep 2018.

3.3. Hillslope sediment yields

Hillslope fences measured sediment yields during 2011 with the majority (92%) of annual sediment coming from the 8 Jul and 3 Aug events (Table 5). The fences at the base of hillslopes in catchments B and E were overtopped by sediment during the 8 Jul 2011 rain event, and hillslope fence E was overtopped during the 3 Aug 2011 event (Table 5). The sediment yields from these cleanouts are conservative values that reflect the maximum storage capacity of the hillslope fence rather than the true hillslope sediment yields. The 2011 mean annual

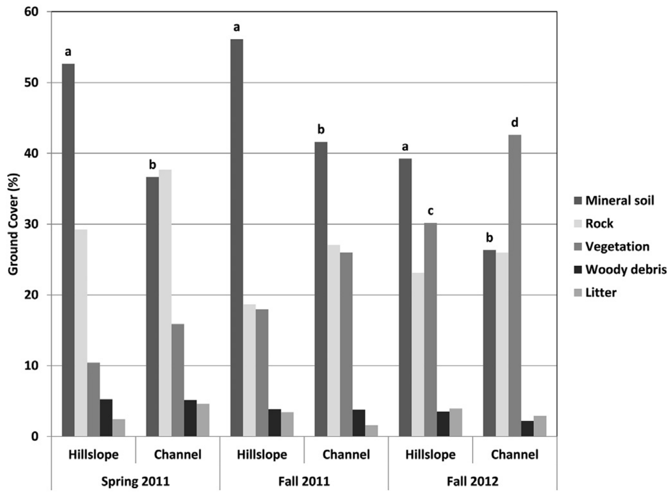

Fig. 4. Ground cover of the five cover classes: mineral soil, rock, vegetation, woody debris and litter, for spring and fall 2011 and fall 2012. Labels a and b indicate mineral soil exposure on hillslopes was significantly greater than in channels. Labels c and d indicate a significant difference in vegetation soil cover between hillslope and channels in 2012 at $p = 0.05$.

sediment yield from the upslope fences in Sevier Canyon was 62.3 Mg ha^{-1} and the mean for the fences at the bases of slopes was 59.0 Mg ha^{-1}. In Sevier Canyon, the 8 Jul 2011 and 3 Aug 2011 events accounted for 95% of the annual sediment yield for all the upslope and base of slope fences (Table 5).

In Middle Canyon the 2011 annual hillslope sediment yield were less than in Sevier Canyon and the yields varied widely for the two upslope fences with complete records (range 6.8 to 24.5 Mg ha^{-1}). The one base of slope fence with complete data produced 35.6 Mg ha^{-1}. The cleanout after the 8 Jul 2011 event accounted for 55% of annual season sediment yield in upslope fences and 65% of annual season sediment yield for base of slope fences. There was no significant difference in sediment yields between the upslope and base of hillslope fences. The mean 2011 hillslope sediment yield of the combined four upslope and base of slope fences was 16.7 Mg ha^{-1}.

Annual hillslope sediment yields in 2012 were significantly less than in 2011 ($p = 0.005$) (Table 5). However, the events on 1 Aug 2012 and 14 Aug 2012 in base of slope fence E accounted for 99% of the annual sediment yield in this fence, and 67 to 86% of annual sediment yields in the other five Sevier Canyon fences also occurred during the 14 Aug 2012 event. There was no significant difference ($p = 0.54$) between hillslope sediment yields for upslope and base of slope plots in 2012.

Ten-minute maximum rainfall intensity was a positive significant covariate ($p < 0.001$) in the model of hillslope sediment yields as was antecedent rainfall ($p < 0.001$). Event rainfall amount was not a significant covariate.

3.4. Paired catchment sediment yields

Sediment yields in the catchments varied greatly among events during the two-year study. The sediment retention structures were cleaned out five times during 2011 (Table 6). One cleanout in pair A-B was the combined sediment yield from a 2-year return period I_{10} on 15 Jun and a 5-year return period I_{10} on 8 Jul 2011. These same combined events caused sediment retention structures to fill to maximum capacity or fail in 5 of the 10 catchments in Sevier Canyon. Also, the sediment yield event on 3 Aug 2011 overtopped sediment retention structures in 3 of the 10 catchments. These large events accounted for over 90% of the sediment yields in Sevier Canyon. Control catchment B captured 25.5 Mg ha^{-1} in the first event and 33.5 Mg ha^{-1} for the first post-fire year without overtopping signifying the large amount of sediment transported (Table 6). As with some of the hillslope fences, sediment yields measured in the overtopped sediment retention structures were conservative values. Also, the partial failure of some of the sediment retention structures makes direct comparison of sediment yields from control and treated catchments difficult in Sevier Canyon.

The 2011 sediment yields in Middle Canyon's paired catchments G-H and I-J were much lower than those in Sevier Canyon, allowing the sediment retention structures to capture the total bedload sediment yields. In Middle Canyon the mean annual sediment yield from the control catchments was 16.1 Mg ha^{-1} and the value from treated catchments was 3.9 Mg ha^{-1}, equivalent to a 76% reduction in sediment yield although this difference was not significant ($p = 0.22$). Interestingly in catchment G, the sediment retention structure captured

Table 5
Event and annual hillslope sediment yields (Mg ha^{-1}) in Sevier and Middle Canyons, by catchment pair, sediment retention structure location, event date, and post-fire year.

	Sevier Canyon						Middle Canyon			
Catchment pair	A	B	C	D	E	F	G	H	I	J
Fence location	upslope	base of slope	upslope	base of slope	base of slope	upslope	upslope	base of slope	base of slope	upslope
Event date	- - - (Mg ha^{-1}) - - -						- - - (Mg ha^{-1}) - - -			
8 Jul 2011	87.6	84.3*	12.7	18.3	31.1*	22.9	5.1	0	12.1	23
27 Jul 2011	2.4	0.6	2.0	0.6	0.2	0.7	0.1	n/a	2.9	0.9
3 Aug 2011	12.4	33.1	6.1	6.1	24.8*	7.9	0.9	0	4.3	7.5
25 Aug 2011	0.6	0	0.8	0.1	0.1	0.1	0.5	0	4.3	4.2
6 Oct 2011	n/a	1.7	0.4	0.3	5.3	0.2	0.2	0	0.9	n/a
1st post-fire year	103.5	119.7	22.0	25.4	61.5	31.8	6.8	0	24.5	35.6
16 Jul 2012	n/a	3.4	1.1	0.3	0	n/a	0.1	0	11.4	25.5
1 Aug 2012	2.0	4.4	2.3	0.7	20.6	3.2	5.9	0.2	4.4	42.7
14 Aug 2012	22.6	38.6	9.5	8.1	23.7	7.4	0	0	0.3	0.3
10 Sep 2012	0.4	0.8	1.0	0.6	0.1	0.2	0.5	0.1	2.7	8.8
2nd post-fire year	25.0	47.2	13.9	9.7	44.4	10.8	6.5	0.3	18.8	77.3

n/a: animal disturbance introduced sediment into the fence; it was not included in measured sediment yield.
*Hillslope fence overtopped by sediment during event. These values are the measured sediment yields, which understate the actual sediment delivery.

Table 6
Event and annual paired catchment sediment yield (Mg ha^{-1}), straw bale check dam trap efficiency (%) and sediment yield treatment: control ratios. The 8 Jul 2011 event overtopped or caused sediment retention structures failure in five of the ten catchments. The 3 Aug 2011 event overtopped sediment retention structures in three of the ten catchments.

	Sevier Canyon						Middle Canyon			
Catchment pair	A	B	C	D	E	F	G	H	I	J
	Treated	Control	Control	Treated	Control	Treated	Treated	Control	Control	Treated
Event date			- - - - (Mg ha^{-1}) - - -					- - - (Mg ha^{-1}) - - -		
8 Jul 2011	7.5*†	25.3	Failed*	11.7*	Failed*	11.3*	2.5	6.6	11.4	0.4
27 Jul 2011	0.08	0.02	0.02	0.04	0.03	0.09	0.01	0.0	0.0	0.01
3 Aug 2011	9.6*	7.3	9.4	8.2	12.9*	13.0*	0.5	4.2	5.4	1.4
25 Aug 2011	0.3	0.2	0.1	0.2	0.08	0.05	0.5	1.2	0.5	0.5
6 Oct 2011	2.1	0.7	1.0	0.5	1.2	1.3	0.7	0.9	1.9	1.2
1st post-fire year	19.6‡	33.5	10.5‡	20.6‡	14.2‡	25.7‡	4.2	12.9	19.2	3.5
Straw bale check dam sediment trapped	10.5			3.4		7.7	4.3			5.9
Trap Efficiency	n/a		n/a		n/a		50%		49%	
Treat:Control Ratio	n/a		n/a		n/a		0.33		0.18	
16 Jul 2012	0.02	0.01	0.2	0.02	0.06	0.04	0.0	0.09	2.3	1.1
1 Aug 2012	1.5	0.1	1.3	0.4	16.8	1.4	3.2	11.1	12.4	8.5
14 Aug 2012	10.5	5.7	8.3	6.0	16.8	9.3	0.01	0.07	0.3	0.2
10 Sep 2012	1.0	0.4	0.4	0.4	0.5	0.5	0.6	1.8	2.2	2.2
2nd post-fire year	13.1	6.2	10.2	6.8	34.1	11.2	3.8	13.1	17.2	12.0
Straw bale check dam sediment trapped	10.5**			3.4**		7.7**	4.3**			5.9**
Trap Efficiency	24%		11%		17%		35%		18%	
Treat:Control Ratio	2.11		0.67		0.33		0.29		0.70	

†Sediment accumulated from events on 15 Jun 2011 and 8 Jul 2011.
‡1st post-fire year totals are minimum values due to overtopping or failure of sediment retention structures.
*Values indicate one sediment retention structure failed and this is a conservative value. "Failed" indicates both sediment retention structures had failures, and no sediment was captured.
**Straw bale check dams were full by the end of the 1st post-year, therefore no additional sediment was trapped.

2.5 Mg ha^{-1} of sediment that was transported past three empty or partially full straw bale check dams that were closest to the catchment outlet of the six total check dams. In catchment J, the sediment retention structure captured 0.4 Mg ha^{-1} of sediment that was transported past an empty straw bale check dam located closest to the catchment outlet while the other two upstream check dams were full. In 2011, Middle Canyon pairs G-H and I-J had a mean treated to control paired catchment ratio of 0.25 (Table 6).

In Sevier Canyon, the sediment retention structures were cleaned out four times during 2012 with no failures or overtopping of bedload sediment. Two of the four events in Sevier Canyon accounted for 92 to 98% of the total 2012 annual sediment yields. The annual sediment yields from the control catchments was 6.2 to 34.1 Mg ha^{-1}. The sediment yields from the straw bale check dam treated catchments ranged from 6.8 to 13.1 Mg ha^{-1} even after the straw bale check dams were completely filled in 2011 (Table 6). The largest sediment yields occurred during the 14 Aug 2012 rain event, but control catchment E also had a large sediment yield during the 1 Aug 2012 event (Tables 3 and 6).

In Middle Canyon during 2012, both the control catchments in pairs G-H and I-J had larger annual sediment yields than the treated catchments. In paired catchment G-H, treated catchment G had annual sediment yield of 3.8 Mg ha^{-1} (Table 6), and the control catchment H had 13.1 Mg ha^{-1}. The event on 16 Jul 2012 had a 5-year return period I_{30} intensity and produced 0 to 13% of the annual 2012 sediment yields in the four Middle Canyon catchments, while the 31 Jul 2012 event and the 1 Aug 2012 event with I_{30}s less than a 1-year return period produced 71 to 85% of the total 2012 sediment yield likely due to high soil moisture conditions from the previous events. There was no significant difference in sediment yields between treated and control catchments in Sevier or Middle Canyons in 2012 (Table 6). The overall mean paired treated to catchment ratio in 2012 was 0.82 (Table 6).

3.5. Straw bale check dams

All straw bale check dams trapped sediment, and none of the dams moved. All the straw bale check dams in Sevier Canyon catchment A filled to the spillway height and overtopped during the events on 15 Jun 2011 (2-year return period I_{30}) and 8 Jul 2011 (1-year I_{30}). The straw bale check dams filled to capacity during the event on 8 Jul 2011 in the other two Sevier Canyon treated catchments (Tables 3 and 6). Even though the 8 Jul 2011 event was less than a 1-year I_{30} in Middle Canyon, this event also filled the majority of straw bale check dams to their maximum sediment holding capacity.

The mean volume of sediment trapped by the straw bale check dams was 1.0 m^3, equivalent to 1.3 Mg of sediment per check dam assuming the same mean sediment bulk density that we measured in the sediment retention structures. The mean mass of sediment trapped per catchment area was 5.9 Mg ha^{-1}.

Treated catchment sediment yields and straw bale check dam trap efficiency calculations suggest that large amounts of sediment flowed past the check dams, and that trap efficiencies decreased as cumulative sediment yields increased with successive erosive events (Fig. 5). Middle Canyon had trap efficiencies of 49–50% in 2011 (Table 6) and 18 to 35% in 2012 (Table 6).

4. Discussion

4.1. Rainfall effects

Short-duration high-intensity rainfall greatly influenced both hillslope and catchment sediment yields (Moody and Martin, 2009). The first few measured rain events had >1- or 2-yr return period rainfall

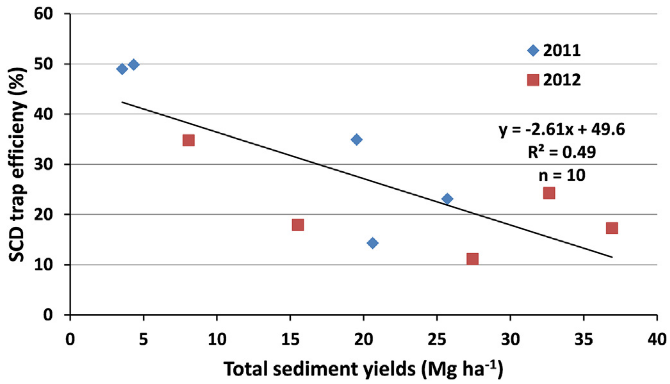

Fig. 5. Straw bale check dam (SCD) trap efficiency (%) and total annual sediment yield for treated catchments during 2011 and 2012.

intensities which filled the straw bale check dams to capacity. Other rain events during the first monsoon season were similar to intensities measured on the Colorado Front Range which also produced high hillslope and catchment sediment yields (Benavides-Solorio and MacDonald, 2005; Robichaud et al., 2013a, 2013b). However, the occurrence of 2–5 year rainfall intensity events was greater than observed in the Colorado Front Range in the first two post-fire years after the Bobcat Fire (Benavides-Solorio and MacDonald, 2005) or Hayman Fire (Robichaud et al., 2013a, 2013b).

4.2. Ground cover

Hillslope ground cover significantly increased between years by vegetation regrowth (18 to 30%) but was still slow to recover as compared to other post-fire recovery rates (Benavides-Solorio and MacDonald, 2005). Pannkuk and Robichaud (2003) suggest that at least 60–70 ground cover is needed to have a marked decrease in sediment yields thus the high sediment yields in the second post-fire year is not surprising. Channel regrowth responded better than the hillslopes regrowth likely due to the higher soil moisture conditions in the channel at the base of the hillslopes. High hillslope and catchment sediment yields occurred in both the first and the second years indicating that there was still ample mineral soil exposed (39–42% in year 2) to detach and transport with the high intensity rainfall events.

4.3. Hillslope sediment yield

High hillslope sediment yields were observed on these highly weathered silt loam *Aridic Argiustoll* and *Aridic/Typic Haplustoll* soils. All the study catchments were in high soil burn severity areas on steep slopes, thus were highly erodible and had conditions for ample sediment supply and transport. First year hillslope sediment yields were higher than the second year's yields, although the two years were not significantly different.

Middle Canyon annual hillslope sediment yields were less than those in Sevier Canyon, likely due to lower rainfall intensities (Table 4). Although we anticipated greater per-unit-area sediment yields from the upslope plots compared to the base of hillslope plots (Wagenbrenner and Robichaud, 2014), the sediment yields between the two scales were not significantly different (Table 5). At larger hillslope plot scales, there is greater variability in surface ground cover conditions leading to lower connectivity and greater potential for sediment deposition (Wagenbrenner and Robichaud, 2014). Our sediment yields were greater than other monsoon-influenced post-fire sediment yields from comparable scales (Robichaud et al., 2013a; Benavides-Solorio and MacDonald, 2005; Schmeer et al., 2018).

4.4. Catchment sediment yield response

In the first post-fire year (2011) there was no significant difference in catchment sediment yields between straw bale check dam treated and control catchments. The treatment did little to mitigate sediment produced from relatively commonly occurring rain events when rainfall intensities were equal to or less than a 1-year return period. Instead, the straw bale check dam structures filled to capacity during the first substantial rain event (Table 4). The remaining empty or partially full structures in these catchments were filled to capacity during a second event with less than a 1-yr I_{30} intensity.

A number of environmental factors could have influenced the large differences in paired catchment ratios that were not closer to a 1:1 ratio (Table 6). Rainfall events may have had unequal rainfall intensities between the paired catchments, despite the fact the pairs were adjacent. Our network of six rain gauges showed variability in rainfall intensities, though the rain gauge density was approximately 1 gauge per 1.3–4 ha across the two canyons, this was not sufficient to capture the spatial variability in rainfall intensity (Table 4).

Another factor potentially influencing the large difference in sediment yields could be rill patterns within the catchments. Treated catchment F had an annual sediment yield of 25.7 Mg ha^{-1} in 2011 and may have developed an efficient rill network that carried much of the loose or weakly held sediment during high intensity rain events (e.g., on 8 Jul and 3 Aug 2011). While in catchment E maybe the efficient rill network had not developed in the first year due to a deeper soil horizon of weakly held aggregates, thus a 1-yr I_{10} return period rain event eroded much larger sediment yields in 2012.

Also, the number of channel heads and their locations and the catchment shape may affect how efficiently sediment is transported out of the catchment. The Control catchment B is a wide catchment that has two tributary channels that join together halfway down the catchment, whereas treated catchment A is a longer and narrower, single-channel catchment (Table 1). The routing of hillslope runoff into one channel in catchment A may result in higher velocities and channel transport capacity rates compared to cumulative channel transport capacity rates for the three small channels in catchment B that split up the same amount of hillslope runoff (Pallard et al., 2009). This may be one reason why the A:B catchment ratio during the second post-fire year is 2.1. These topographical differences highlight the variability even between two closely spaced and paired catchments.

4.5. Straw bale check dam effectiveness

A properly functioning straw bale check dam will capture only a fixed amount of sediment, and the capacity of that sediment retention can be determined at installation. The straw bale check dams will slowly decompose over time, which will decrease the sediment storage capacity or release the stored sediment over time (Fig. 6; Wagenbrenner, 2013). The mean storage capacity of our straw bale check dams was 1.0 m^3 or about 1.3 Mg. This was similar to the storage capacities of 1.1 m^3 found by Miles et al. (1989). The channel gradient did not have significant influence ($p = 0.26$) on the mass of sediment trapped behind straw bale check dams (Storrar, 2013), probably because of the relatively narrow range of very steep channel gradients in our study. At a treatment rate of four straw bale check dams ha^{-1}, the dams trapped a slightly higher mean mass measured of 5.9 Mg ha^{-1} or 4.4 m^3 ha^{-1}. In contrast, post-fire brush debris dams in France stored sediment at a rate of only 0.3 m^3 ha^{-1} when installed at a rate of 0.25 dams ha^{-1} which resulted in low trap efficiency (13%) (Fox, 2011).

Spillway heights strongly correlated to sediment storage capacity. In the treated catchments A and F, large woody debris (0.3 m long × 0.1 m diam.) and cobbles (>0.1 m diam.) mobilized by overland flow were trapped by the protruding tops of the wooden stakes securing the straw bales to the ground. The trapped debris raised the spillway elevations and increased the straw bale check dam trap volumes. This added

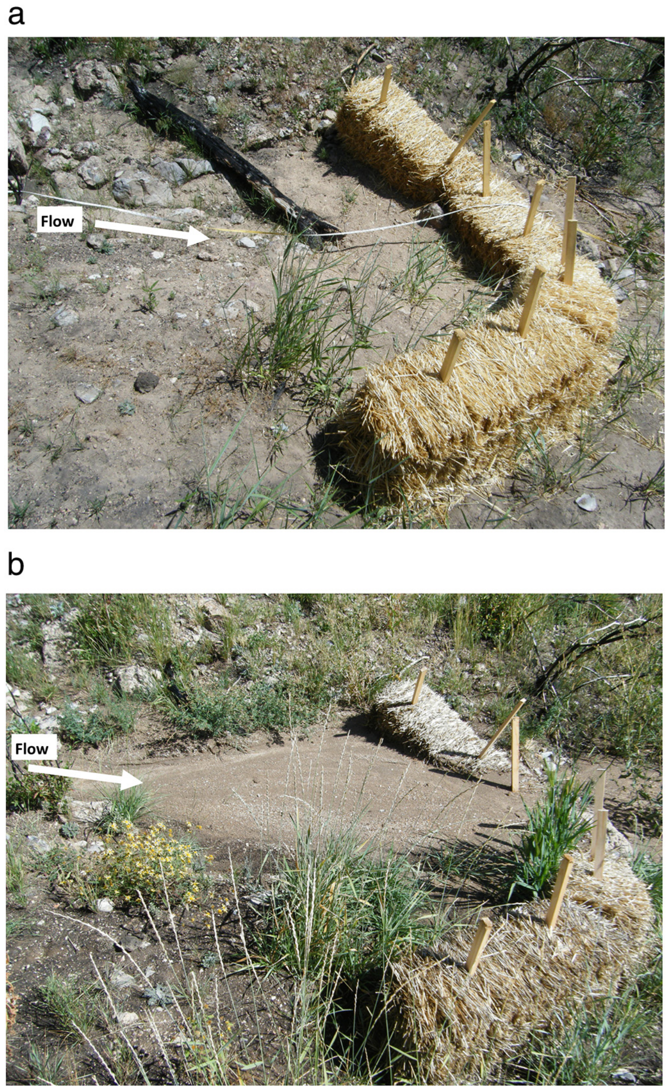

Fig. 6. a) Empty straw bale check dam at time of installation of catchment G in Middle Canyon. b) Same straw bale check dam filled to maximum sediment holding capacity after four rain events (8 Jul, 27 Jul, 3 Aug, and 25 Aug 2011, Table 5). The volume of sediment trapped by this straw bale check dam was 0.64 m^3 or a trapped mass of 0.79 Mg after 44 mm of total rainfall with a maximum I_{30} of 15 mm h^{-1}.

storage capacity was offset by the flow routing around the outside of the straw bales, resulting in scour.

The straw bale check dams were stable for the first events and once they were filled with sediment. No visual degradation or sediment occurred during subsequent events through the second post-fire year.

Our results indicate that straw bale check dams were not effective at reducing sediment yields given their low trap efficiencies and treatment density. However, the trap efficiency of straw bale check dams is a function of the annual post-fire sediment yield, the storage capacity of the check dams, and the treatment density. Although the total sediment yields in Sevier Canyon were unknown because of sediment retention structure failures or overtopping, the check dams in Sevier Canyon had relatively low trap efficiencies as compared to Middle Canyon (~50%) during the first year (Table 6; Fig. 6b). This also accounts for low trap efficiencies as sediment was transported past the full straw bale check dams in subsequent events (Fig. 6b). Trap efficiencies would probably be higher in areas such as the Pacific and Sub-Pacific regions described by Moody and Martin (2009) with their relatively low rainfall intensities. Since the treatment rate was constant across the catchments, the potential mass of sediment trapped per unit area was nearly the same among all treated catchments. Although slope was not a predictor of storage capacity in our steep channels, additional capacity would be attained in channels with shallower gradients (Napper, 2006).

The USDA Forest Service guidance for check dam installation suggests using a head-to-toe spacing on much less steep channels (Napper, 2006). The estimated storage capacity in the Twitchell Fire sites would have been 9 m^3 ha^{-1} using this approach. To trap all the measured sediment in our study, 12 check dams ha^{-1} would be necessary which would not have been feasible because the maximum spacing using the head-to-toe guideline would be 4–5 check dams ha^{-1} due to the steep gradient (29%). The high treatment density would produce an aggrading installation as defined by Wagenbrenner (2013). Careful analysis of possible site installation conditions (i.e. low slope channel) and post-fire sediment yields may lead to more effective treatment results (Napper, 2006). While straw bale check dams did not significantly reduce sediment yields for most monsoonal rain events in our study, other treatments such as mulching using various materials have been shown to significantly reduce sediment delivery rates under similar rainfall regimes (Robichaud et al., 2010).

The stable ephemeral channels in our catchments are likely due to the characteristics of the Sevier River Formation unit that appears to be resistant to knick point migration and scour (Storrar, 2013). The channel cross-sectional areas changed little suggesting channels were resistant to both scour and aggradation (Storrar, 2013). In this case, straw bale check dams were not necessary for curtailing knick point migration, although this may be justification for the use of check dams in knick point prone environments.

5. Conclusions

High hillslope and catchment sediment yields were observed for the first two monsoon seasons after the 2010 Twitchell Canyon Fire. High intensity rainfall during many of the measured events rapidly mobilized exposed soil on the high severity burned hillslopes which was easily transported down the steep slopes and channels. Some vegetation regrowth helped reduced catchment sediment yields in post-fire year 2. The high yields and low treatment rate of 4 check dams ha^{-1} resulted in little effect of straw bale check dams on sediment yields. There were no movement of straw bale check dams during the two-year study, reflecting proper installation and a relatively stable channel which prevented spillway scour undermining the structure. Increasing the straw bale check dam treatment rate to increase straw bale dam trap efficiency might be feasible in future installations to achieve greater sediment yield reduction.

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