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Post-fire mulching for runoff and erosion mitigation
Part I: Effectiveness at reducing hillslope erosion rates

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ABSTRACT

Mulch treatments often are used to mitigate post-fire increases in runoff and erosion rates but the comparative effectiveness of various mulches is not well established. The ability of mulch treatments to reduce sediment yields from natural rainfall and resulting overland flow was measured using hillslope plots on areas burned at high severity following four wildfires in the western United States. Wheat straw mulch, wood strand mulch, and hydromulch were evaluated along with untreated control plots on multiple fires for 4 to 7 years after burning. Needle cast from fire-killed conifer trees was evaluated in an area of moderate burn severity at one fire, and seeding with genetically native seed was tested, with and without hydromulch, at another fire. Rainfall, ground cover, and soil water repellency were measured in each treatment site at all 4 fires. Mean sediment yields on the control plots ranged from 0.3 to 7.5 Mg ha^{-1} in the first post-fire year, from 0.03 to 0.6 Mg ha^{-1} in the second, and from 0 to 0.4 Mg ha^{-1} in the third and fourth post-fire years. Assuming a linear fit between sediment yield and rainfall intensity, storms with equivalent rainfall intensities produced nearly an order of magnitude less sediment on the control plots in the second post-fire year as compared to the first post-fire year. Large storms (at least a 2-year return period, 10-min maximum rainfall intensity) produced sediment on all fires in all years where they occurred; however, sediment yields produced by large storms that occurred in the first post-fire year were larger than the sediment yields from equivalent storms that occurred in later years at the same fire.

Sediment yields decreased as ground cover increased and all the mulch treatments increased total ground cover to more than 60% immediately after application. However, the longevity of the mulches varied, so that the contribution of the treatment mulch to total ground cover varied by mulch type over time. The wood strand mulch was the most long-lived of the mulch treatments and was observed in ground cover assessments throughout the study period (4 and 7 years) at two fires. The wheat straw mulch decreased nearly twice as fast as the wood strand mulch, and no hydromulch was detected after the first post-fire year on either fire where it was tested.

Mulch treatment effectiveness varied when data were analyzed separately for each fire. Wood strand mulch reduced sediment yields at both fires where it was tested, wheat straw mulch reduced sediment yields at 2 of the 4 fires where it was applied, and the hydromulch tested at 2 fires did not reduce sediment yields on either. When data were normalized and analyzed by treatment across all fires, wood strand mulch reduced sediment yields for the first four post-fire years, but wheat straw mulch and hydromulch did not significantly reduce sediment yields in any post-fire year. The greater variability in the combined data resulted in fewer statistically significant treatment effects being observed as compared to the individual fire analyses. We believe the fire-specific results provide the more accurate representation of potential post-fire mulch treatment effectiveness.

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1. Introduction

Wildfire is often the cause of large landscape changes within and downstream of the burned area. Increases in post-fire runoff and erosion, and subsequent increases in flooding, debris flows, and sedimentation are well documented (Bento-Gonçalves et al., 2012; Kunze and Stednick, 2006; Lane et al., 2006; Moody and Martin, 2009; Moody et al., 2008a,b; Nyman et al., 2011; Shakesby and Doerr, 2006; Silins et al., 2009). In areas where wildfire conditions will be aggravated by drought, earlier spring snow melt, and other effects of climate change, the number and severity of wildfires is likely to increase (Brown et al., 2004; Flannigan et al., 2000; Miller et al., 2009; Westerling et al., 2006). In addition, the number of people living in and around forested areas continues to increase. This adds human life and safety, infrastructure, buildings, and roads to the natural and cultural resources (e.g., drinking water quality, aquatic habitat, and historically significant sites) at risk from the secondary effects of wildfire (Stewart et al., 2003; Theobald and Romme, 2007). Consequently, post-fire management efforts may include the use of mitigation treatments to reduce increases in runoff

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and erosion rates and thereby attempt to protect public health and safety and reduce the potential for damage to resources resulting from increased flooding, erosion, and sedimentation (Robichaud et al., 2010a).

Studies conducted over the past decade have identified the most important factors in determining post-fire erosion rates: the degree of burn severity (Doerr et al., 2006; Moody et al., 2008a), the amount of bare soil exposed (Benavides-Solorio and MacDonald, 2005), the rainfall intensity (Benavides-Solorio and MacDonald, 2005), the amount and degree of post-fire soil water repellency (DeBano, 2000; Shakesby and Doerr, 2006), and the time since the fire (Gimeno-García et al., 2007). Some of these factors are incorporated in soil burn severity, a classification of the degree of soil disturbance based on residual ground cover, ash color and depth, effects on soil structure and fine roots, and changes in soil water repellency (Neary et al., 2005; Parsons et al., 2010).

While post-fire treatments (mulches) do not change the soil burn severity classification, they may reduce post-fire erosion rates by providing immediate ground cover for exposed soil and protection from raindrop impact and overland flow (Foltz and Wagenbrenner, 2010; Robichaud et al., 2010a; Wagenbrenner et al., 2006). There are few data that relate post-fire hillslope mulch cover amounts and erosion reduction; however, some researchers have suggested that at least 60% ground cover is needed to reduce post-fire hillslope erosion rates (Benavides-Solorio and MacDonald, 2005; Robichaud et al., 2000).

Several short-term studies of post-fire wheat straw mulch treatment effectiveness have reported reductions in erosion rates of 48 to 99% in the first two post-fire years, with the greatest reductions obtained when the wheat straw mulch provided 70% or more ground cover (Badia and Marti, 2000; Bautista et al., 1996; Groen and Woods, 2008; Rough, 2007; Wagenbrenner et al., 2006). Some of these studies and anecdotal evidence indicate that wheat straw mulch is susceptible to dislocation by wind and that windblown wheat straw mulch treatments can leave exposed slopes in some areas and deep piles of straw in other areas. Thick mulch layers can prevent sunlight from reaching the soil surface and physically obstruct emerging natural and seeded vegetation (Bautista et al., 2009; Beyers, 2004). In addition, agricultural straw often contains seeds and the mulch can be a source of non-native vegetation (Bautista et al., 2009; Beyers, 2004; Kruse et al., 2004; Robichaud et al., 2003).

Other materials, such as hydromulches and dry mulches made from forest materials (e.g., wood strands, wood chips, or wood shreds), have been developed, tested, and in some cases applied as post-fire hillslope treatments to avoid some of the disadvantages inherent to agricultural straw mulches. Hydromulches are various combinations of short fibers (wood shreds, paper, flax, etc.), tackifier, suspension agent, seed, and/or fertilizer that are mixed with water to form a slurry. The slurry is sprayed on the soil surface either aerially or from ground-based equipment where it generally binds to the soil surface and dries to form a thin dense mat (Napper, 2006). These characteristics initially make hydromulch very wind-resistant — a desirable characteristic for use on exposed hillslopes and in areas where high winds are common. However, the hydromulch generally decomposes within a year of application, which depending on the vegetative recovery, may leave the burned soil relatively bare and subject to elevated post-fire erosion rates (Hubbert et al., 2012; Napper, 2006; Robichaud et al., 2010a).

There are limited data on the effectiveness of hydromulch treatments for post-fire erosion mitigation. Hubbert et al. (2012) studied hydromulch effectiveness in decreasing hillslope sediment yields following the 2003 Cedar fire in southern California. Hillslope plots were established on two soil types in areas burned at high severity. The ground cover provided by the hydromulch decreased rapidly and was mostly gone within months of its application; no effect on sediment yields was detected (Hubbert et al., 2012). In a study done after the 2002 Hayman fire in central Colorado, Rough (2007) established paired swales up to 0.5 ha in size on hillslopes burned at high severity. Aerially applied hydromulch (wood fiber mulch, guar tackifier, polyacrylamide [PAM] soil stabilizer, and a seed mix) reduced erosion 95% in the first post-fire year and 50% in the second post-fire year as compared to the controls. However, another wood-based hydromulch without PAM was applied to other paired swales using a ground-based sprayer and the hydromulch did not reduce erosion as compared to the controls (Rough, 2007). These results suggest that hydromulch treatment effectiveness is specific to the formulation used in the study and may not be applicable to other hydromulch mixtures, application rates, or specific site conditions.

Dry wood-based mulches have been developed from wood manufacturing waste (e.g., wood strands such as WoodStraw® [Forest Concepts, LLC, Auburn, WA]), wood shreds or wood chips from burned timber or forest thinning and harvest operations, and shredded forest floor material from nearby unburned areas (Bautista et al., 2009; Robichaud et al., 2010a). A clear advantage of these materials is that they are derived from forest materials and are less likely to carry non-native seeds and/or agricultural chemical residues (Foltz and Dooley, 2003). In addition, recent laboratory studies have established that wood strands have greater resistance to wind displacement as compared to agricultural straw (Copeland et al., 2009) and both wood strands and wood shreds provide equal or greater protection from erosion as compared to wheat straw mulch at equal areal coverage rates (Foltz and Dooley, 2003; Foltz and Wagenbrenner, 2010; Yanosek et al., 2006). These laboratory data are promising, but wood strands have only recently been field-tested for effectiveness in reducing post-fire hillslope erosion rates.

Needle cast occurs when needles from burned conifer trees fall and increase ground cover. Needle cast is rarely found in areas of high vegetation burn severity where tree crowns are fully consumed (DeBano et al., 2005; Parsons et al., 2010), but it may reduce post-fire erosion in areas of moderate and low burn severity, or in areas of high soil burn severity where the tree crowns were not consumed (Cerdà and Doerr, 2008; Prats et al., 2012). In an indoor study using a combination of rainfall and overland flow simulations on burned soils, 50% needle cover (with either *Pinus ponderosa* or *Pseudotsuga menziesii* needles) reduced interrill erosion rates by 60 to 80% and rill erosion rates by 20 to 40% as compared to bare plots (Pannkuk and Robichaud, 2003).

Extensive research on effectiveness of non-native annual or short-lived perennial grass seeding has been conducted around the western U.S., but especially in California (Beyers, 2004, 2009; Peppin et al., 2010). These studies have concluded that seeding has limited ability to reduce erosion especially in the first post-fire year due to the need for favorable precipitation and the time required for plant establishment. For example, a recent study from Spain used plots burned at high severity to compare the erosion reduction of post-fire treatments. They reported that rye grass seeding reduced sediment yields 34–42% in the first 4 months after application, but that straw mulching was more than twice as effective with erosion reductions of 73–94% in the same time period (Díaz-Raviña et al., 2012).

This is the first of a two-part study to evaluate the effectiveness of various mulches in reducing post-fire runoff and erosion rates. Specific objectives for part I were to: 1) determine if mulches of wheat straw, wood strands, wood-based hydromulch, needle cast or native seeding result in smaller sediment yields from treated hillslope plots than untreated plots in the first post-fire year; 2) determine if any of the treatments affected sediment yields beyond the first post-fire year; 3) relate rainfall characteristics (amount and intensity) to post-fire hillslope erosion rates; and 4) compare mulch treatment application and performance characteristics (ground cover, longevity, and effects on vegetation recovery) for potential links to any measured reduction in erosion rates. Part II of this study (Robichaud et al., 2013) explores the effects of wheat straw mulch and hydromulch on reducing runoff and erosion rates in small matched catchments.

2. Methods

2.1. Study site descriptions

Between 2002 and 2005, hillslope-scale study sites were established on areas with high soil burn severity within weeks after each of four large wildfires: Hayman in Colorado (2002); Hot Creek and Myrtle Creek in Idaho (2003); and School in Washington (2005) (Fig. 1) (USDA Forest Service, 2002, 2003a, 2003b, 2005). Hillslope plots were installed with sediment fences at the bottom of the plot to capture and measure sediment yields from natural rainfall (adapted from Robichaud and Brown, 2002). Barriers or hand-dug trenches were installed at the upper plot boundary to keep non-plot runoff from being transported into the plot (Fig. 2). The average plot contributing area varied among sites with Hayman and Myrtle Creek having the smallest plots (22–58 m^2) and School having the largest plots (147–331 m^2) (Table 1). Site elevations ranged from 1122 m (Myrtle Creek) to 2447 m (Hayman), with generally steep slopes (17–72%), and various aspects (Table 1).

At each fire, the sites were located in relatively close proximity to minimize differences in soils, topography, rainfall, pre-fire vegetation, and soil burn severity; in contrast, there was considerable variation in these traits among the four fires. The historic annual precipitation for each fire location was determined from the nearest weather station and ranged from 400 mm (Hayman) to 1382 mm (School) (Table 2), and all fire areas receive a portion of their annual precipitation as snowfall (National Atmospheric Deposition Program, 2010; National Climate

Fig. 2. A wood strand mulch plot at the Hayman fire. The photo was taken immediately after plot installation from the top of the plot looking downslope into the fence.

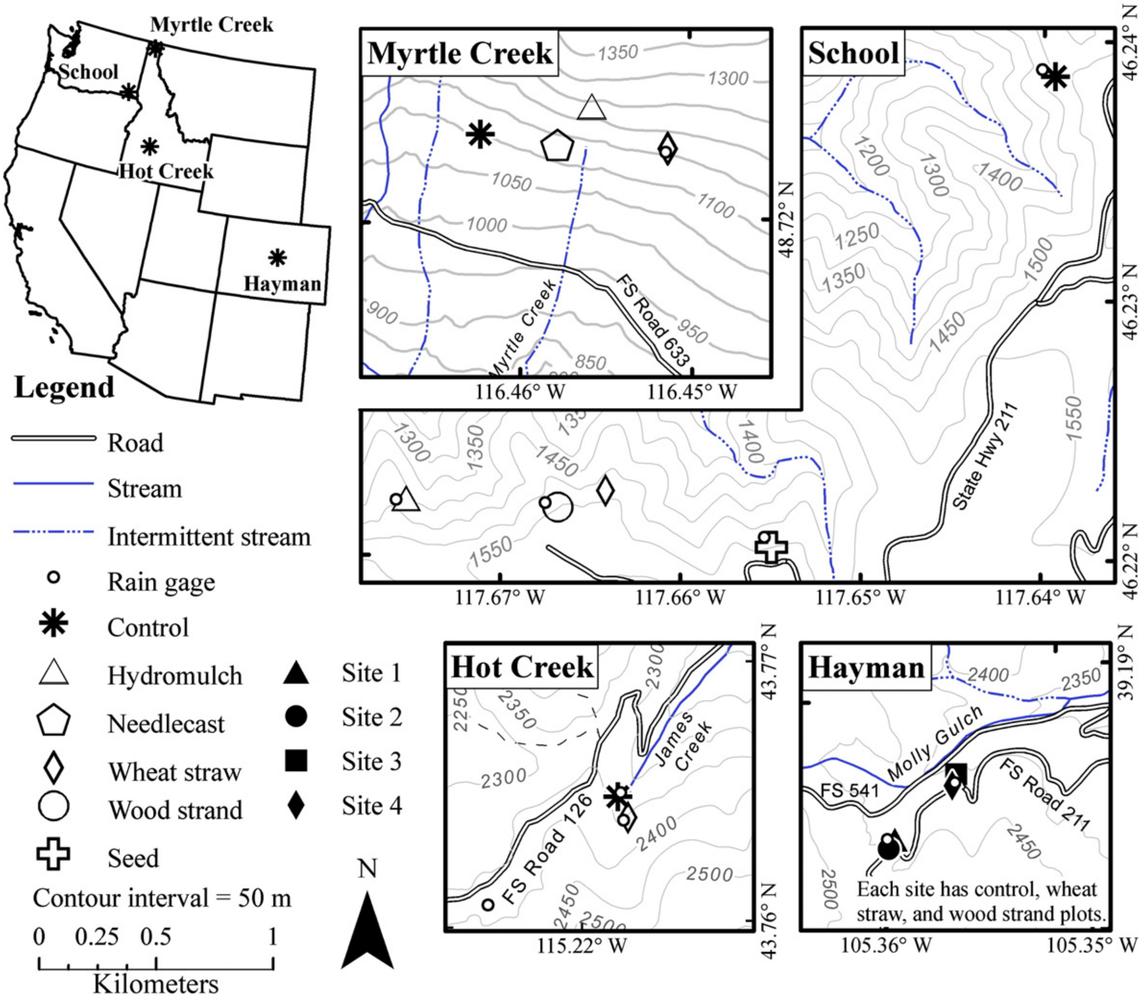

Fig. 1. Location of four post-wildfire hillslope mulch treatment effectiveness research studies in the western USA and individual topographic maps of each study location.

Table 1
Fire, treatments, mean elevation, aspect, total number of plots per fire, number of plots per treatment (per site at Hayman), mean and range of plot area and slope by treatment or site (Hayman), nominal mulch or seed application rate, and the measured treatment cover within one month of treatment application. nd = no data available; Straw = wheat straw mulch; Wood = wood strand mulch; Hydro = hydromulch; and Needle = needle cast. Mulches were applied by hand at the Hayman and Hot Creek fires and aerially at the Myrtle Creek and School fires.

Fire	Site	Elev. (m)	Aspect (dir)	Plots (#)	Plot area (m^2)		Plot slope (%)		Treatment	Nominal application rate (Mg ha^{-1})	Treatment cover (%)
					Mean	Range	Mean	Range			
Hayman	1[a]	2437	NE	9	28	22–33	41	37–44	Straw	2.2	56
	2[a]	2447	E	6	31	25–35	23	22–24	Wood[b]	12.5	51
	3[a]	2410	NE	3	35	30–39	39	37–40			
	4[a]	2403	NE	6	44	28–58	18	17–19			
Hot Creek	Straw	2336	N	6	72	nd	55	38–68	Straw	2.2	68
	Control	2342	N	6	72	nd	45	41–49			
Myrtle Creek	Straw	1154	S	6	27	22–30	53	nd	Straw	4.5–6.7	87
	Hydro[c]	1122	SW	6	35	26–54	69	nd	Hydro[c]	0.6	53
	Needle[d]	1126	S	6	29	25–34	48	nd	Needle[d]	none	50[e]
	Control	1143	SW	6	23	20–25	60	nd			
School	Straw	1530	NW	7	228	156–282	65	57–69	Straw	2.2	57
	Hydro[f]	1419	NE	7	179	147–213	66	60–71	Hydro[f]	1.1	56
	Wood[g]	1544	NW	7	205	162–249	62	51–72	Wood[g]	4.5	54
	Seed[h]	1547	N	7	198	160–237	65	56–70	Seed[h]	nd[h]	nd
	Control	1457	W	7	250	160–331	65	62–68			

[a] Hayman had 4 plot sites with between 1 and 3 replicates of randomly assigned treatments of wheat straw, wood strands, or no treatment (controls) in each site for a total of 8 reps per treatment.

[b] WoodStraw® (Forest Concepts LLC, Auburn, WA): test mix of 3 to 4 mm thick wood strands in two lengths (120 and 60 mm) and two widths (4 and 16 mm).

[c] Hydromulch formulation: 60% recycled paper and 40% wood fiber mulch (EcoFibre® [Profile Products, Buffalo Grove, IL]) and a commercial tackifier (SoilSET® [Sequoia Pacific Research, Draper, UT]).

[d] Scorched needles from burned *Pinus ponderosa* trees fell when dislodged by the wind, rain, or other natural means; no application or rearrangement was used.

[e] Cover value includes all litter, a large majority of which was needles from dead trees.

[f] Hydromulch formulation: wood fiber mulch (Soilguard® [Mat Inc., Floodwood, MN]) and guar gum tackifier (Super Tack® [Rantec Inc., Ranchester, WY]).

[g] WoodStraw® (Forest Concepts LLC, Auburn, WA) LS64-100 commercial mix: wood strands (5 mm wide and 2.5–3.1 mm thick) of two lengths (64 and 100 mm).

[h] Genetically native seed mix (270 pure-live-seed [pls] ha^{-1}) 73% mountain brome (*Bromus marginatus*); 19% blue wildrye (*Elymus glaucus*); 5% Idaho fescue (*Festuca idahoensis*); 3% bluebunch wheatgrass (*Pseudoroegneria spicata*); and endomycorrhizal inoculum.

Table 2
Fire and mean site elevation (Elev), the name and elevation (Elev) of the nearby long-term weather station, the distance from the study sites to the weather station, the mean annual precipitation, and record length at the weather station, the post-fire year (post-fire year 0 is the year the fire occurred) and annual precipitation at the weather station during the years of the study, and the dominant pre-fire overstory and understory vegetation.

	Weather station							
Fire Elev (m)	Name Elev (m)	Distance to sites (km)	Mean annual precipitation (mm)	Record length (yr)	Post-fire year	Annual precipitation (mm)	Dominant overstory species	Dominant understory species
Hayman 2423	Manitou Exp. Forest 2387	24	400	73	0	137	Ponderosa pine(*Pinus ponderosa*) Douglas-fir(*Pseudotsuga menziesii*)	Common juniper(*Juniperus communis*) Kinnikinnick(*Arctostaphylos uva-ursi*) Pine dropseed(*Blepharoneuron tricholepis*)
					1	316		
					2	329		
					3	291		
					4	399		
					5	450		
					6	260		
					7	397		
Hot Creek 2339	Atlanta Summit SNOTEL 2310	2	1103	27	0	1085	Douglas-fir(*P. menziesii*) Subalpine fir(*Abies lasiocarpa*)	Geyer's sedge(*Carex geyeri*) Grouse whortleberry(*Vaccinium scoparium*)
					1	1041		
					2	935		
					3	1427		
					4	831		
					5	1125		
Myrtle Creek 1137	Priest River Exp. Forest 805	50	790	93	0	758	Douglas-fir(*P. menziesii*) Ponderosa pine(*P. ponderosa*)	Ninebark (*Physocarpus malvaceus*) Dwarf huckleberry (*Vaccinium caespitosum*)
					1	788		
					2	697		
					3	815		
					4	767		
					5	865		
School 1500	Touchet SNOTEL 1686	21	1382	27	0	960	Douglas-fir(*P. menziesii*) Grand fir(*Abies grandis*)	Bluebunch wheatgrass (*Pseudoroegneria spicata*) Pinegrass(*Calamagrostis rubescens*) Geyer's sedge(*C. geyeri*)
					1	1483		
					2	1334		
					3	1735		
					4	1664		

Data Center, 2010; National Water and Climate Center, 2010). Short duration high intensity summer monsoonal rainfall was common at the Hayman fire, but the other fires were located in areas with continental climates and received occasional high-intensity rainfall only during summer convective storms.

All study sites were located in burned coniferous forests, but differences among the four burned areas were reflected in the various dominant pre-fire overstory and understory vegetation used to identify the habitat type (Table 2) (Cooper et al., 1987; Johnson and Clausnitzer, 1992; Steele et al., 1981). Hayman, the most arid of the four fires, was dominated by ponderosa pine (*P. ponderosa*) with some Douglas-fir (*P. menziesii*). Myrtle Creek was also populated with Douglas-fir and ponderosa pine, but being less dry than Hayman, it had occasional lodgepole pine (*Pinus contorta*) as well. The wetter fire areas, Hot Creek and School, were dominated by firs (Douglas-fir, subalpine fir [*Abies lasiocarpa*], and grand fir [*Abies grandis*]). The pre-fire understory species at three of the four fires included shrubs, but the understory at the School fire was dominated by grasses and forbs (Table 2).

Soils at three fires were sand or sandy loam from granitic parent material, but the loamy sand found at the School fire originated from basalt (Table 3). The surface (top 1 cm) soil particle size distribution (Gee and Bauder, 1986) and soil bulk density at 0–5 cm and 5–10 cm depths (Blake and Hartage, 1986) were measured from soil samples taken at each fire (Table 3).

2.2. Experimental design

Each fire had six to eight replicates of burned, untreated control plots and the same number of replicates in up to four types of treatment (Table 1). The research sites at all four fires were located in areas of high soil burn severity, with the exception of the needle cast site at Myrtle Creek which burned at moderate severity. At Hot Creek, Myrtle Creek, and School the treated sites were selected and hillslope plots were established within larger treated areas and a nearby burned but untreated area was used for the control site; thus, the study plots were grouped by treatment type (Table 1). All sites were maintained for a minimum of 4 years. The Hayman fire, in contrast, had four research sites where hillslope plots were established and treatments (wheat straw, wood strands, or control) were randomly selected and hand-applied in each plot. Each of the 4 sites had 1–3 replicated treatment plots which resulted in a total of eight replicates per treatment (Table 1). In addition, each of the four Hayman hillslope sites fell into one of two slope classes (nominally 20% and 40%); the slope class did not affect the sediment yield results, so this dichotomy was not maintained in the analyses. The plots at the Hayman sites were used for simulated runoff experiments (methods following Robichaud et al., 2010b; results not included here) prior to installation of the sediment fences. The four Hayman sites were maintained for seven years.

Treatments at all fires included certified weed-free wheat (*Triticum aestivum* L.) straw mulch. The target application rate was 2.2 Mg ha^{-1} at all sites except Myrtle Creek where it was 5 Mg ha^{-1} (Table 1). Wood strand mulch (WoodStraw® [Forest Concepts LLC, Auburn, WA]) was applied at the Hayman and School sites, but because the product was still under development when the Hayman fire occurred, the strand dimensions differed at the two sites. A test mix of longer, wider, and thicker wood strands was hand-applied at a rate of 10–12 Mg ha^{-1} at the Hayman sites while a commercially available standardized wood strand mix was aerially applied at a rate of 4.5 Mg ha^{-1} at the School site (Table 1).

Different hydromulch formulations were aerially applied at different rates at the Myrtle Creek and School sites (Table 1). The hydromulch site at the School fire contained the same seed mix and application rate as the seeded areas, so the seeded plots were used as a second control for the hydromulch and a treatment in the overall experimental design. In an area burned at moderate severity, needles remained in the crowns of burnt and dead ponderosa pine (*P. ponderosa*) trees. The needles later dropped to the ground to form a ground cover of scorched needles (Fig. 3), which was evaluated as separate treatment (Table 1).

2.3. Precipitation

Rainfall characteristics were measured for each site using recording tipping bucket rain gages. Rainfall events that occurred in a single erosive season within the calendar year were grouped by post-fire year. The year of fire occurrence was identified as post-fire year zero and ended on 31 October. Subsequent post-fire years ran from 1 November through 31 October. Since little erosion occurred during the winter months or during snowmelt, the "erosive" season was defined by the snow-free season (April through October) when most of the precipitation occurred as rainfall.

Each fire had rain gage(s)—one each at Hot Creek and Myrtle Creek, two at Hayman, and four at School—placed within 750 m of the hillslope plots (Fig. 1). The rain gage at Myrtle Creek malfunctioned after the second post-fire year. The Myrtle Creek snow telemetry (SNOTEL) site (NWCC, 2010), located about 200 m from the control plots, provided data that were used when our rain gage data were not available. Rain events were separated by a 6-h period with no rainfall. For each event the total rainfall (mm), duration (min), and 10-min and 30-min maximum rainfall intensities (I_{10} and I_{30}, respectively, mm h^{-1}) were calculated. Generally, the rainfall characteristics of any sediment-producing storm were derived from the nearest functioning rain gage. Because the two rain gages at Hayman represented different numbers of plots (15 vs. 9) the reported rainfall characteristics were weighted averages based on the number of plots assigned to each rain gage. Return periods were calculated for each fire using a rainfall-frequency atlas (Arkell and Richards, 1986; Miller et al., 1973). Storms were categorized as "large" if the I_{10} equaled or exceeded the 10-min, 2-year return interval rainfall amount for the site: Hayman, 53 mm h^{-1}; Hot Creek, 38 mm h^{-1}; Myrtle Creek, 35 mm h^{-1}; and School, 39 mm h^{-1}.

Table 3

The soil series (if defined), taxonomic class, and parent material as delineated by the U.S. Department of Agriculture soil classification system (NRCS, 2010, 2011). The mean bulk density (0–5 cm depth) and the clay, silt, and sand fractions of surface composite soil samples (top 1 cm of soil) taken after establishment of study sites at each fire were measured. Textural class was determined from the particle size distribution of the surface sample.

Fire	Soil series [taxonomic class]	Parent material	Bulk density (g cm^{-3})	Clay/silt/sand fraction (%)	Textural class
Hayman	Legault [*sandy-skeletal micaceous, shallow Typic Cryorthents*]	Granite	1.39	1/11/88	Gravelly coarse sand
Hot Creek	Soil series not defined [*loamy skeletal mixed Typic Cryorthent, Typic Xerochrept*]	Granite	1.11	4/25/71	Sandy loam
Myrtle Creek	Soil series not defined [*Andic Dystrudept, Typic Udivitrands, Vitrandic Dystroxerepts*]	Granite	1.11	3/7/90	Ashy sand
School	Klicker-like [*Loamy-skeletal, isotic, frigid Vitrandic Argixerolls*]	Basalt	0.69	1/20/79	Ashy loamy sand

Fig. 3. The needle cast study site (moderate burn severity) at the Myrtle Creek fire eight months after the fire (May, 2004).

2.4. Soil water repellency

The degree of soil water repellency was evaluated for each study site using the water drop penetration time (WDPT) test (DeBano, 1981). WDPT tests were conducted in or near the study plots where the surface was fairly uniform and not affected by trees, animal burrows, etc. Measurements were made at 1 cm below the soil surface. Eight drops were placed 5–10 mm apart on an exposed soil surface at the measurement depth with either a bulb dropper or a dropper bottle with a 2 mm diameter nozzle. The mean WDPT was used to categorize the soil water repellency into classes—"none" (0–5 s); "low" (6–60 s); "moderate" (61–180 s); and "high" (181–300 s) (Table 4).

2.5. Ground cover

A gridded quadrat was used to measure ground cover (Bonham, 1989) on one to three 1-m^2 quadrats within each plot. A single ground cover type (litter, ash, woody debris, mineral soil, live vegetation, rock, gravel, or treatment material [i.e., straw, wood strands, or hydromulch]), the type at the highest point, was recorded for 100 points within the quadrat on a 10 cm by 10 cm grid; thus, if mulch was on the soil surface beneath plant leaves, the cover type would be recorded as live vegetation. Total ground cover included litter, woody debris, treatment material, live vegetation, and rock larger than 25 mm. Gravel with a median axis less than 25 mm, mineral soil, and ash were combined as bare soil.

Locations of the quadrats within each plot were marked and subsequent measurements were taken at the same locations throughout the study. Ground cover was assessed in late summer or early autumn each year at each site. Ground cover also was measured in the spring after snow melt at the Hayman and School sites. If more than one ground cover measurement was available, the values from the measurements made nearest the time of the sediment clean out were associated with the sediment yield value.

2.6. Sediment yields

Sediment was collected from the sediment fences in the spring and fall and, on some occasions, after sediment-producing storms throughout the summer. Large intact organic material, such as mulch treatment material, leaves, woody debris, and grass, if present, were not included in the calculated sediment yields. Large quantities of collected sediment were weighed in the field and sub-sampled for moisture and other laboratory analyses. If the total sediment yield

Table 4
Mean WDPT test values and soil water repellency classifications at 1 cm below the soil surface by fire and by site for post-fire years 1–5. N = no repellency (WDPT ≤ 5 s); L = low repellency (WDPT = 6–60 s); M = moderate repellency (WDPT = 61–180 s); H = high repellency (WDPT = 181–300 s); PF = post-fire; nd = no data.

Fire	Site	Soil water repellency class (mean WDPT [s])				
		PF year 1	PF year 2	PF year 3	PF year 4	PF year 5
Hayman	1	nd	H (206)	L (56)	L (51)	N (0)
	2	nd	H (260)	L (7)	N (0)	N (0)
	3	nd	M (68)	N (1)	N (0)	N (0)
	4	nd	H (300)	N (3)	N (0)	N (0)
Hot Creek	Wheat straw	M (155)	H (255)	M (179)	nd	M (65)
	Control	H (182)	H (199)	L (21)	nd	M (121)
Myrtle Creek	Wheat straw	L (22)	L (20)	L (13)	L (57)	N (3)
	Hydromulch	M (60)	L (5)	N (2)	N (0)	N (2)
	Needle cast	M (109)	L (25)	L (20)	L (7)	N (2)
	Control	M (167)	L (9)	N (1)	L (54)	N (1)
School	Wheat straw	M (123)	L (24)	N (1)	N (2)	N (<5)[a]
	Hydromulch	L (52)	L (6)	N (1)	N (0)	N (<5)[a]
	Wood strand	M (82)	L (12)	N (4)	N (0)	N (<5)[a]
	Seed	M (62)	L (52)	N (1)	nd	N (<5)[a]
	Control	L (25)	L (15)	N (0)	N (1)	N (<5)[a]

[a] Data from the fifth post-fire year at the School fire were not included in other parts of this study; water repellency data are included here for a 5 year comparison across the 4 fires.

from a plot was small enough, the entire yield was collected and returned to the laboratory where it was dried. Field sediment weights were adjusted by the moisture content. The dry sediment weights and plot contributing areas were used to calculate the unit-area sediment yields. When runoff overtopped an upslope trench bordering a plot (occurred on only 26 occasions out of more than 1500 observations during the study) or when any other disturbance compromised the sediment collection, the subsequent sediment yield was discarded.

Spring cleanouts were completed when sites were clear of snow. Sediment from these cleanouts was not attributed to a single rainfall event because of the possible contribution of sediment via spring snowmelt. The fall cleanout was generally completed in September or October, and the sediment collected during these cleanouts, as with sediment from other cleanouts when more than one rain event occurred since the previous site visit, was attributed to the event with the greatest I_{10} since the previous site visit. Although there was some degree of uncertainty in this approach, there are several studies that indicate the rainfall intensity, as a surrogate for rainfall kinetic energy, as the most important rainfall characteristic driving post-fire hillslope erosion rates in western forests outside southern California (Moody and Martin, 2001, 2009; Robichaud et al., 2008; Spigel and Robichaud, 2007). In many cases at the Hayman fire and several instances at the School fire, site visits and/or measured runoff in nearby experimental watersheds allowed specific rainfall event characteristics to be attributed to specific measured sediment yields. In these cases, the known associated data were used in analyses.

2.7. Analysis

2.7.1. Ground cover and live vegetation

The ground cover for each plot was averaged across quadrats by cover category. Each plot was then treated as an independent observation of ground cover and live vegetation for each treatment and site. Repeated-measures analyses were conducted for each site using each plot as the subject and the post-fire day as the period of repetition. Least significant differences were used to compare differences in least-squares means between total ground cover and live vegetation by fire, treatment, and year (Littell et al., 2006; SAS Institute Inc., 2003).

2.7.2. Sediment yields

A non-parametric correlation analysis (Spearman rank-order correlation [SAS proc Spearman]; SAS Institute Inc., 2003) was first used to identify variables related to sediment yield. The significant variables fell into three main categories: rainfall variables (total precipitation or I_{10}) which had positive correlations to sediment yield; and time since fire (post-fire day or year) and ground cover (cover or treatment), which had negative correlations to sediment yield. Multiple regression analyses with forward selection and a stepwise regression were then used to examine these controlling factors for predicting sediment yield by fire and treatment. A rainfall variable, a time-since-fire variable and a cover or treatment variable were included as covariates in each model. Ground cover was highly significant in sediment yield model development; however, ground cover was not independent of treatment, thus was not included in any subsequent analysis with treatment as a class variable. The results from these model-building exercises are not shown; however, they were useful for identifying the primary factors that controlled sediment yield in the current study — I_{10}, post-fire year, and treatment.

To compare data across the four fires, sediment yield and I_{10} values were normalized. Normalized sediment yield values were the measured sediment yield divided by the mean sediment yield from the fire's control plots in the first post-fire year; thus, the divisors were: Hayman 7.3 Mg ha^{-1}; Hot Creek 0.8 Mg ha^{-1}; Myrtle Creek 1.7 Mg ha^{-1}; and School 0.3 Mg ha^{-1}. Normalized I_{10} values were the measured I_{10} values divided by the site's 2-year return interval I_{10} (Section 2.3).

A linear mixed-effects statistical model was used to compare the normalized sediment yields among treatments and post-fire years and to determine whether the normalized sediment yields depended on the normalized I_{10}. The normalized sediment yields and I_{10} data were first log-transformed to homogenize the variance of the residuals (Helsel and Hirsch, 2002). A small value (0.005 Mg ha^{-1}) was added to all normalized sediment yield data so that the zero value data could be log-transformed. The model related the transformed, normalized sediment yield for each plot, event, and site to the plot's treatment, the number of years since burning (both fixed effects), and the normalized I_{10} for each event (a covariate). The covariance structure of the repeated measures on each plot was modeled using a spatial power function and the number of days between burning and the rainfall event (Littell et al., 2006). The site and plot within a site were random effects in the model. Differences in the log-transformed, normalized sediment yields were compared using the least squares mean estimates for each treatment and post-fire year. A Tukey–Kramer adjustment was used for comparisons of multiple least-squares means. Statistical models were created to compare all treatments at each site; a treatment was considered as 'effective' if there was a significant difference in sediment yield between the treatment and the control, except in the case of the needle cast plots, which had no moderate burn severity untreated controls. Separate models were calculated across sites that included the same treatments for the common period of record; in these models, fire was added as a random variable. The significance level (α) was 0.05 for all significance tests.

The non-normalized event sediment yields were averaged for each fire, treatment, and event and these means were summed for each calendar year to estimate an annual sediment yield for each fire and treatment. These values were compared to available measurements of sediment yields from unburned forests in the same areas.

3. Results

3.1. Precipitation

The four study areas were in different climatic regions and the precipitation varied over the study years at each fire. The Hayman fire, the most arid area in the study, received only 137 mm of precipitation, just 35% of the long-term average, during the year of the fire (2002). Precipitation was 73–82% of the long-term average for the next 3 years, but varied more widely post-fire years 4 to 7 (Table 2). The Hot Creek fire had nearly average precipitation in the year of the fire and the first post-fire year but the second and fourth post-fire years were 16% and 25% below average. In the intervening year (post-fire year 3), precipitation was 30% higher than average with nearly 90% falling as winter snow. Annual precipitation at the Myrtle Creek fire only varied from the long-term average by about 10% during the 6 years of the study. The School fire received 960 mm of precipitation (less than 70% of the long-term annual average) in the year the fire occurred; however, the School fire received 1334–1735 mm of precipitation annually (average to 25% above average) during the following four years of the study (Table 2).

Although precipitation amounts and intensities varied by fire and by year throughout the study, all large storms ($I_{10}\geq$2-year return interval I_{10}) produced sediment at all fires irrespective of the post-fire year in which they occurred (Tables 5–8). The relatively infrequent occurrence of large storms (4 in 7 years at Hayman; 1 in 5 years at Hot Creek; 2 in 5 years at Myrtle Creek; and 2 in 4 years at School) generally reflected the expected 2-year return interval on which the large verses small storm differentiation was based. At each fire, sediment yields were also attributed to small storms ($I_{10}\leq$2-year return interval I_{10}) and to spring clean-outs that included sediment from snowmelt as well as any spring rainfall (Tables 5–8).

3.2. Soil water repellency

Soil water repellency classes generally were moderate to high for a year or two after each fire and then decreased to low or undetectable levels by the end of the observation periods (Table 4). A high degree of soil water repellency was measured through post-fire year two at both the Hayman and Hot Creek fires while moderate levels were measured only in the first post-fire year at Myrtle Creek and School fires (Table 4). The moderate class of soil water repellency persisted into the fifth post-fire year at the Hot Creek sites, and this was the only fire in the study where water repellency was detected 5 years after burning (Table 4).

3.3. Ground cover

The initial mean cover values on the untreated control plots were 22% at Hayman, 19% at Hot Creek, 15% at Myrtle Creek, and 7% at School, but these initial cover amounts were not indicative of the relative rates of increase in ground cover at the sites (Fig. 4). The control plots at both the Hayman and Hot Creek fires had no change in total ground cover between the initial cover count and the value in the first post-fire year. Starting in the second post-fire year, the ground cover in the Hayman sites slowly and steadily increased to nearly 60% by the end of the third post-fire year and nearly 70% by the end of the study period (post-fire year seven). The control plots at the Hot Creek fire showed an even smaller increase in ground cover after the first post-fire year; the ground cover never exceeded 30% during the study (Fig. 4). In contrast, the control sites at both the Myrtle Creek and School fires had relatively rapid increase in ground cover — both had mean ground cover values over 40% at the end of the first post-fire year and over 60% by the second post-fire year. The total cover at both Myrtle Creek and School exceeded 80% by the end of the study.

3.3.1. Treatment cover

The greater straw application rate at the Myrtle Creek site as compared to the other three sites (Table 1) resulted in a greater proportion of straw cover (87%) in the initial measurement at this site as compared to initial measurements at the other sites (56 to 68%). The greater coverage also resulted in greater longevity of the straw cover. By the fall of the first post-fire year, the Myrtle Creek site straw cover had decreased to 60%, but straw cover ranged from 13 to 53% at the other three fires (Fig. 4). The wheat straw mulch component was still 9% at Myrtle Creek by the end of the third post-fire year, and only negligible amounts of straw mulch were detected by the end of the third post-fire year at any of the other three fires (Fig. 4).

The initial ground cover provided by the wood strand mulch was nearly the same at the Hayman and School sites (51 and 54%, respectively) and both of these values were lower than all the initial wheat straw mulch coverage (Fig. 4). The subsequent decrease in the wood strand cover was slower at the Hayman fire than at School. At the Hayman site the wood strand mulch cover remained above 50% until the second post-fire year, when it decreased to 35% and stayed relatively consistent until decreasing to 19% in post-fire year seven (Fig. 4). The decrease in wood strand mulch cover was more rapid at the School fire, where the cover was 45% in the first post-fire year, 23% in the second post-fire year and only 10% by the fourth post-fire year (Fig. 4). The shorter, narrower pieces of wood strand used at the wetter School site (Table 1) may have decayed more rapidly than the wood strands applied at Hayman. Another, more likely explanation is that the increase in vegetative cover at both fires made the detection of the wood strands less likely in the ground cover assessments and therefore the greater vegetative cover at the School site resulted in a greater reduction in wood strand cover as compared to the Hayman site.

The initial hydromulch cover values were similar at the Myrtle Creek and School sites (56% and 53%, respectively), which was about the same as the cover provided by the wheat straw (excluding the Myrtle Creek wheat straw site) and the wood strand mulches in the various sites where they were applied (Fig. 4). However, no hydromulch was detected in either site by the fall of the first post-fire year.

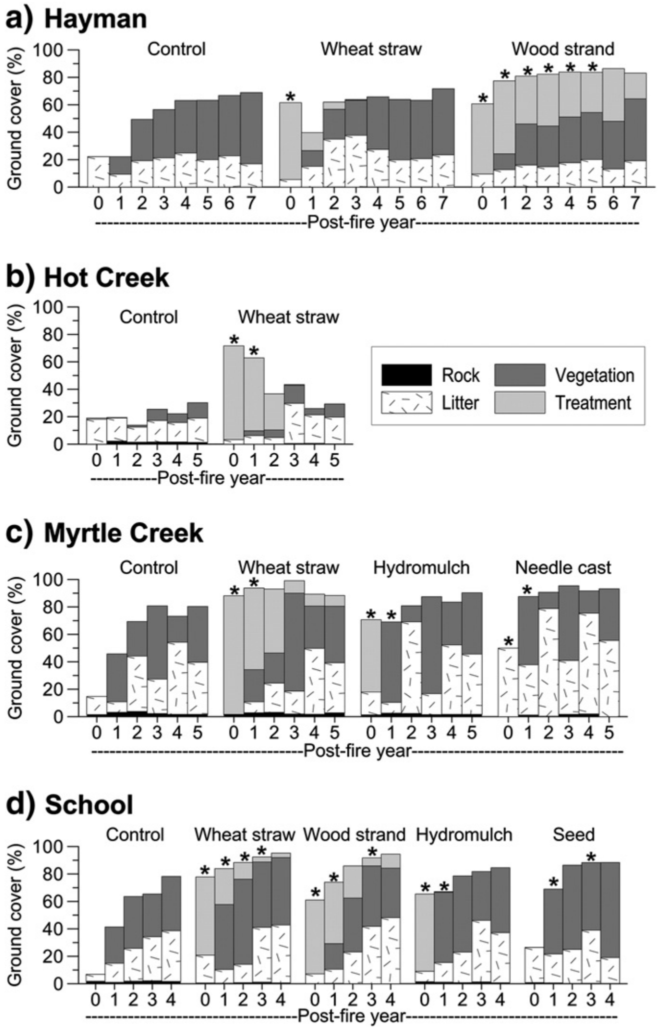

Fig. 4. The mean proportion of rock (>25 mm), litter, live vegetation, and mulch treatment are shown by treatment and post-fire year for the a) Hayman, b) Hot Creek, c) Myrtle Creek, and d) School fires as measured in the fall of each study year. The years when the mean total ground cover on a treated site was significantly different as compared to the control site are designated by an asterisk (*) at the top of the bar in the treated plot. Post-fire year 0 designates the year the fire occurred. Litter includes needle cast at all sites.

The needle cast site at the Myrtle Creek fire had 50% litter cover in the year of the fire. The litter composition in the first post-fire year was mainly needles cast from the burnt ponderosa pine canopy (Fig. 3). The total cover did not change significantly in the needle cast site after the year of the fire, but the dominant cover type alternated between litter and vegetation. The vegetative cover dominated the total cover during the first and third post-fire years while the litter cover dominated during the second, fourth, and fifth post-fire years. Myrtle Creek had more vegetation cover in post-fire year three as compared to post-fire years two and four (Fig. 4), and this was probably due to the timing of the cover assessment in that year (1 August as compared to 27 and 17 September, in the second and fourth post-fire years, respectively). The understory vegetation was likely still green and growing (classified as vegetation) in early August, but by mid- to late-September these perennial plants would have died back, turned brown, and dropped their leaves and would be classified as litter in ground cover assessments (Fig. 4).

Table 5
Hayman rainfall characteristics and sediment yields. The cleanout dates and post-fire year, number of days since last cleanout, and rainfall amount (for summer only) are shown. The event date, rainfall amount, and 10-min maximum intensity (I_{10}) are listed for the rain event with the maximum I_{10} value that occurred during the sediment accumulation period. Mean sediment yield is shown by treatment. Rainfall and I_{10} are the values from the nearest rain gage. Data for large storms ($I_{10} \geq 53$ mm h^{-1}, the 2-year return period) are in bold type. Each spring cleanout, denoted by an "S" after the post-fire year, has sediment yield only. Sediment yield values greater than 0.00 but less than 0.01 Mg ha^{-1} are shown as <0.01.

Cleanout date [post-fire year]	Time between cleanouts (days)	Rainfall between cleanouts (mm)	Maximum I_{10} event			Sediment yield (Mg ha^{-1})		
			Date	Rainfall (mm)	I_{10} (mm h^{-1})	Control	Wheat straw	Wood strand
21 May 03 [1][a]	234		1 Oct 02[a]	15.3	8	0.20	0.05[b]	0.03
3 Aug 03 [1]	73	59.2	29 Jul 03	5.1	27	0.66	0.09	0
12 Aug 03 [1]	8	24.2	**9 Aug 03**	**22.4**	**72**	**19**	**19**	**2.7**
6 Sep 03 [1]	24	40.2	30 Aug 03	10.7	22	2.7	2.3	1.9
24 May 04 [2S]	261					0	0	0
17 Jun 04 [2]	23	3.9	17 Jun 04	3.9	14	0.06	0	0
29 Jun 04 [2]	11	20.9	27 Jun 04	20.9	35	2.4	1.3	0.40
17 Aug 04 [2]	48	5.8	5 Aug 04	5.8	22	0.30	0.14	0.07
23 Aug 04 [2]	5	19.3	19 Aug 04	19.3	32	0.72	0.62	0.12
1 Sep 04 [2]	8	8.2	27 Aug 04	8.2	27	0.09	0.04	0.01
4 Oct 04 [2]	32	2.9	27 Sep 04	2.9	14	0.03	0.02	0.01
17 May 05 [3S]	224					0	0	0
26 Aug 05 [3]	35	11.5	20 Aug 05	11.5	31	0.10	0.07	0.05
10 May 06 [4S]	234					0	0	0
13 Jul 06 [4]	63	21.6	5 Jul 06	21.6	38	0.08	0.06	0.02
7 Aug 06 [4]	24	9.7	25 Jul 06	9.7	22	0.03	0.02	0.01
9 Aug 06 [4]	1	13.0	09 Aug 06	13.0	39	0.02	0.02	<0.01
29 Aug 06 [4]	19	9.1	13 Aug 06	9.1	12	0.02	0.02	0.01
6 Sep 06 [4]	7	7.0	31 Aug 06	7.0	34	0.02	0.01	0.01
13 May 07 [5S]	247					0	0	0
24 Jul 07 [5]	71	10.3	19 Jul 07	10.3	33	0.08[c]	0.09	0.02
21 Aug 07 [5]	27	17.1	4 Aug 07	17.1	43	0.09	0.04	0.01
12 Sep 07 [5]	21	60.2	**29 Aug 07**	**60.2**	**107**	**0.76**[d]	**0.78**[d]	**0.75**
18 May 08 [6S]	248					0	0	0
25 Aug 08 [6]	98	143.2	**5 Aug 08**	**22.1**	**78**	**1.2**[e]	**0.54**[e]	**0.10**[e]
9 Oct 08 [6]	44	56.9	11 Sep 08	37.2	35	0.08	0.03	<0.01
18 May 09 [7S]	220					0	0.01	0.01
3 Aug 09 [7]	77	231.4	**21 Jul 09**	**40.4**	**96**	**1.3**[f]	**0.56**	**0.08**[f]

[a] Although the cleanout occurred in the spring, sediment was attributable to a rainstorm on 1 Oct 2002.
[b] One wheat straw plot failed; datum was not included in mean.
[c] One control plot failed; datum was not included in mean.
[d] One control and one wheat straw plot failed; data were not included in means.
[e] One control, two wheat straw, and one wood strand plot failed; data were not included in means.
[f] Two control and two wood strand plots failed; data were not included in means.

3.3.2. Vegetation cover

Within each fire, there were no significant differences in the mean live vegetation cover values among treatments for any post-fire year, with the exception of post-fire year one at Myrtle Creek where the 59% live vegetation on the hydromulch site was greater than the 23% on the wheat straw site (Fig. 4). Live vegetation was observed at all sites in the first year after the fire and generally increased in subsequent years, with the exception of the Hot Creek fire. Within the Hayman fire, the rate of increase in live vegetation generally decreased in post-fire years three through seven (4% per year average) as compared to post-fire years one and two (14% per year average). The scant live vegetation observed at the Hot Creek fire (13% or less in all post-fire years) reflected a lack of recovery during the study and was an anomaly among the four fires (Fig. 4). The vegetation cover generally was greater in the wetter Myrtle Creek (71% maximum) and School (69% maximum) fires than in the Hayman (48% maximum) or Hot Creek (13% maximum) fires (Fig. 4). At the School fire, although the mean vegetation values within each treatment varied from year to year, there were no significant differences in vegetation among post-fire years one through four (Fig. 4).

3.4. Sediment yields

The magnitude of the sediment yields varied widely among treatments, rain events, and sites. Generally the greatest sediment yields occurred in the control sites at each fire, but the sediment yields in the treated sites were not always significantly smaller. The greatest sediment yields were measured in the first post-fire year and declined in the second post-fire year.

The single-event mean sediment yields measured in the control sites in the first post-fire year ranged from 0.01 Mg ha^{-1} (with an associated I_{10} of 8 mm h^{-1}) at the School fire to 19 Mg ha^{-1} (I_{10} 72 mm h^{-1}) at the Hayman fire (Tables 5–8). Similar-intensity small storms (18–22 mm h^{-1}) in the first post-fire year produced sediment yields of 2.7 Mg ha^{-1} at the Hayman fire, 1.2 Mg ha^{-1} at the Hot Creek fire, 0.44 Mg ha^{-1} at the Myrtle Creek fire, and 0.02 and 0.09 Mg ha^{-1} (two storms) at the School fire (Tables 5–8).

At both the Hayman and Myrtle Creek fires, the largest single-event sediment yields occurred as a result of large storms in the first post-fire year. The 9 August 2003 storm at the Hayman fire, with an I_{10} of 72 mm h^{-1}, produced a mean sediment yield of 19 Mg ha^{-1} in the

Table 6
Hot Creek rainfall characteristics and sediment yields. The cleanout dates and post-fire year, number of days since last cleanout, and rainfall amount (for summer only) are shown. The event date, rainfall amount, and 10-min maximum intensity (I_{10}) are listed for the rain event with the maximum I_{10} value that occurred during the sediment accumulation period. Mean sediment yield is shown by treatment. Rainfall and I_{10} are the values from the nearest rain gage. Data for large storms ($I_{10} \geq 38$ mm h^{-1}, the 2-year return period) are in bold type. Each spring cleanout, denoted by an "S" after the post-fire year, has sediment yield only. Sediment yield values greater than 0.00 but less than 0.01 Mg ha^{-1} are shown as <0.01.

Cleanout date [post-fire year]	Time between cleanouts (days)	Rainfall between cleanouts (mm)	Maximum I_{10} event			Sediment yield (Mg ha^{-1})	
			Date	Rainfall (mm)	I_{10} (mm h^{-1})	Control	Wheat straw
10 Jun 04 [1S]	238					0	0
8 Jul 04 [1]	28	29.5	1 Jul 04	13.0	18	1.2[a]	0.11[a]
30 Aug 04 [1]	52	78.7	**16 Aug 04**	**18.0**	**38**	**0.52**	**0.32**
25 Jun 05 [2S]	298					0.58	0
12 Aug 05 [2]	47	49.3	8 Jul 05	4.6	26	0.04	0.03
1 Jun 06 [3S]	292					0.09	0.04
11 Sep 06 [3]	101	60.2	9 Jun 06	8.1	15	0.38	0.14
11 Jun 07 [4S]	271					0.35	0.19
26 Sep 07 [4]	106	50.5	22 Sep 07	16.0	15	0.22	0.15
11 Sep 08 [5S]	351					0.26	0.36

[a] One control and three straw plots failed; data were not included in means.

control plots (Table 5), while the 4 July 2004 storm at the Myrtle Creek fire (I_{10} of 59 mm h^{-1}) produced 3.2 Mg ha^{-1} in the control plots (Table 7). For comparison at the Hayman fire, a similar large storm in the sixth post-fire year, with an I_{10} of 78 mm h^{-1} produced a much smaller mean sediment yield of 1.2 Mg ha^{-1} (Table 5). The largest storm during the study occurred in post-fire year five and resulted in a mean sediment yield of only 0.76 Mg ha^{-1} from an I_{10} of 107 mm h^{-1}. Also at the Hayman fire, in addition to the large storms described above, 9 small storms in the first two post-fire years with I_{10} values between 8 and 35 mm h^{-1} produced sediment yields of between 0.03 Mg ha^{-1} and 2.7 Mg ha^{-1} on the control plots. Nonetheless, 74% of the total sediment yield from the control plots during the 7 years of this study was attributed to the 4 large storms that occurred (Table 5). At Myrtle Creek, 80% of the 5-year sediment yield from the control plots was attributed to the 2 large storms that occurred (Table 7). In contrast, the greatest sediment yields in the first post-fire year at the Hot Creek and School fires (1.2 Mg ha^{-1} at each site) were attributed to small storms with I_{10} values of 18 and 26 mm h^{-1}, respectively (Tables 6 and 8).

Both I_{10} and post-fire year were significant factors in predicting event sediment yields in the statistical models. Based on regression analysis, there was nearly an order of magnitude decrease in sediment yields in post-fire year two as compared to post-fire year one for the same I_{10} (Fig. 5). Given the 2-year return interval I_{10} (normalized value of 1), the estimated mean sediment yield in the control sites across all fires was 1.2 Mg ha^{-1} in the first post-fire year and 0.12 Mg ha^{-1} in the second post-fire year (Fig. 5). The ratio of normalized sediment yields was similar for the more frequently occurring rainfall intensities (normalized I_{10} values < 1.0 in Fig. 5) as for the 2-year return interval I_{10} storms. For example, for a storm with a normalized I_{10} value of 0.5, the predicted mean sediment yields were 0.65 Mg ha^{-1} in the first post-fire year and 0.04 Mg ha^{-1} in the second post-fire year. However, the lack of storms with I_{10}s larger than the 2-year return interval in the second

Table 7
Myrtle Creek rainfall characteristics and sediment yields. The cleanout dates and post-fire year, number of days since last cleanout, and rainfall amount (for summer only) are shown. The event date, rainfall amount, and 10-min maximum intensity (I_{10}) are listed for the rain event with the maximum I_{10} value that occurred during the sediment accumulation period. Mean sediment yield is shown by treatment. Rainfall and I_{10} are the values from the nearest rain gage. Data for large storms ($I_{10} \geq 35$ mm h^{-1}, the 2-year return period) are in bold type. Each spring cleanout, denoted by an "S" after the post-fire year, has sediment yield only. Sediment yield values greater than 0.00 but less than 0.01 Mg ha^{-1} are shown as <0.01. nd = no data available.

Cleanout date [post-fire year]	Time between cleanouts (days)	Rainfall between cleanouts (mm)	Maximum I_{10} event			Sediment yield (Mg ha^{-1})			
			Date	Rainfall (mm)	I_{10} (mm h^{-1})	Control	Wheat straw	Hydromulch	Needle cast
24 May 04 [1S]	208					0	0	0	0
12 Jul 04 [1]	40	131.6	**4 Jul 04**	**41.7**	**59**	**3.2**[a]	**0.03**	**2.8**[a]	**0.07**
5 Oct 04 [1]	69	81.8	12 Sep 04	9.9	20	0.44	0.02	0.33	0.01
3 May 05 [2S]	209					0.39	0.10	1.3	<0.01
6 Sep 05 [2]	37	117.9	**10 Jun 05**	**12.4**	**40**	**0.10**	**0**	**0.42**	**0**
20 Jun 06 [3S]	285					0	0	0.05	0
17 Aug 06 [3]	57	226.1	11 Aug 06	25.4	nd[b]	0	0	0.12	0
30 Mar 07 [4S]	217					0	0	0	0
9 May 08 [5S]	223					0.01	0	<0.01	0

[a] One control plot and three hydromulch plots failed; data were not included in means.

[b] The site rain gage malfunctioned; total rainfall was from the Myrtle Creek SNOTEL and the I_{10} was not available.

Table 8

School rainfall characteristics and sediment yields. The cleanout dates and post-fire year, number of days since last cleanout, and rainfall amount (for summer only) are shown. The event date, rainfall amount, and 10-min maximum intensity (I_{10}) are listed for the rain event with the maximum I_{10} value that occurred during the sediment accumulation period. Mean sediment yield is shown by treatment. Rainfall and I_{10} are the values from the nearest rain gage. Data for large storms ($I_{10} \geq 39$ mm h^{-1}, the 2-year return period) are in bold type. Each spring cleanout, denoted by an "S" after the post-fire year, has sediment yield only. Sediment yield values greater than 0.00 but less than 0.01 Mg ha^{-1} are shown as <0.01.

Cleanout date [post-fire year]	Time between cleanouts (days)	Rainfall between cleanouts (mm)	Maximum I_{10} event			Sediment yield (Mg ha^{-1})	
			Date	Rainfall (mm)	I_{10} (mm h^{-1})		
Control						Control	
23 May 06 [1S]	189					0.01	
5 Jun 06 [1]	13	42.4	2 Jun 06	15.7	20	0.09	
15 Jun 06 [1]	9	19.6	13 Jun 06	5.1	26	1.2[a]	
19 Jul 06 [1]	33	6.6	5 Jul 06	3.3	18	0.02	
2 Oct 06 [1]	74	25.9	19 Sep 06	3.0	8	0.01	
24 May 07 [2S]	234					0.22	
9 Oct 07 [2]	137	77.5	31 Aug 07	9.7	35	0.03	
01 Jul 08 [3S]	265					0.02	
27 Oct 08 [3]	117	69.3	18 Aug 08	7.1	18	0.04	
28 May 09 [4S]	213					<0.01	
8 Oct 09 [4]	98	86.9	12 July 09	9.7	15	0.04	
Wheat straw and wood strand[b]						Straw	Wood
23 May 06 [1S]	189					0.01	0.01
5 Jun 06 [1]	13	32.8	2 Jun 06	9.7	8	0.02	0.01
15 Jun 06 [1]	9	19.3	13 Jun 06	6.1	29	0.01	0.01
19 Jul 06 [1]	33	4.6	5 Jul 06	2.0	9	0	0.01
2 Oct 06 [1]	74	29.2	19 Sep 06	3.8	8	<0.01	0.01
24 May 07 [2S]	234					0.02	0.02
9 Oct 07 [2]	137	109.5	**31 Aug 07**	**24.4**	**81**	**0.01**	**0.01**
1 Jul 08 [3S]	265					0.01	<0.01
27 Oct 08 [3]	117	75.2	18 Aug 08	6.9	17	<0.01	<0.01
28 May 09 [4S]	213					0	0.04
12 Sep 09 [4]	72	67.3	**12 Jul 09**	**24.6**	**91**	<0.01	<0.01
Hydromulch						Hydromulch	
23 May 06 [1S]	189					0.04	
5 Jun 06 [1]	13	45	2 Jun 06	15.0	15	0.03	
15 Jun 06 [1]	9	22.9	13 Jun 06	6.9	35	0.34	
19 Jul 06 [1]	33	4.6	5 Jul 06[c]	2.0	9	0.03	
2 Oct 06 [1]	74	36.6	19 Sep 06	6.6	9	0.02	
24 May 07 [2S]	234					0.11	
9 Oct 07 [2]	137	119.6	**31 Aug 07**	**24.4**	**81**	**0.06**	
1 Jul 08 [3S]	265					0.04	
27 Oct 08 [3]	86.6	5.8	18 Aug 08	5.8	11	0.03	
28 May 09 [4S]	213					0.02	
12 Sep 09 [4]	72	71.6	**12 Jul 09**	**21.3**	**72**	**0.20**	
Seed						Seed	
23 May 06 [1S]	189					0.04	
5 Jun 06 [1]	13	44.7	2 Jun 06	14.0	21	0.07	
15 Jun 06 [1]	9	25.0	13 Jun 06	8.1	37	0.13	
19 Jul 06 [1]	33	4.6	5 Jul 06	2.3	11	0.03	
2 Oct 06 [1]	74	36.6	19 Sep 06	4.8	12	0.02	
24 May 07 [2S]	234					0.01	
9 Oct 07 [2]	137	109.5	**31 Aug 07**	**21.3**	**88**	**0.03**	
1 Jul 08 [3S]	265					<0.01	
27 Oct 08 [3]	86.6	93.2	18 Aug 08	8.6	18	<0.01	
28 May 09 [4S]	213					0	
23 Oct 09 [4]	113	126.5[d]	**12 Jul 09**[d]	**24.6**[d]	**91**[d]	<0.01	

[a] One control plot failed; datum was not included in mean.

[b] The wheat straw and wood strand mulch plots shared a single rain gage located between the two treated areas.

[c] The rain gage in the hydromulch treatment area malfunctioned; the nearest gage (wheat straw treatment area) was used.

[d] The rain gage in the seed treatment area malfunctioned; the nearest gage (wheat straw treatment area) was used.

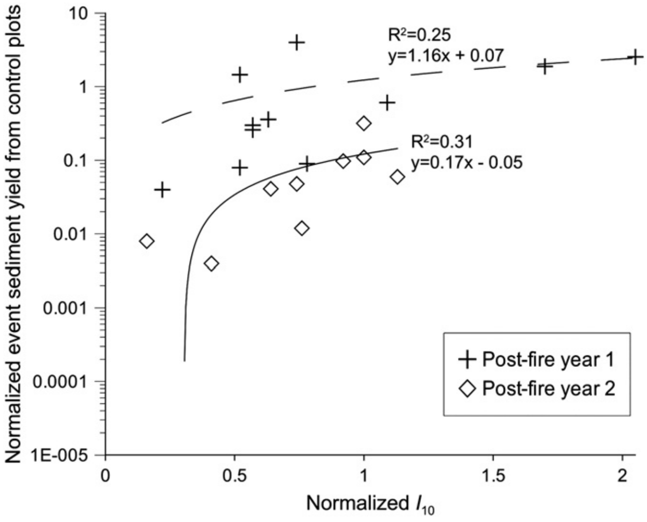

Fig. 5. Normalized event sediment yield in the control plots versus the normalized maximum 10-min rainfall intensity (I_{10}) in the first and second post-fire years for all fires. Normalized sediment yields are the ratios of the mean of the measured values and the mean sediment yield in the first post-fire year at that fire. Normalized I_{10} values are the ratios of the mean of the observed I_{10}s for the event and the 2-year return interval I_{10} for the fire. In the first post-fire year there were 2–4 events per fire (total n = 10) while in the second post-fire year there were more events at the Hayman fire (n = 6) than the other fires (n = 1 each).

post-fire year precludes any comparisons of these data for larger storms (Fig. 5).

At the two fires, Hayman and School, where we had more frequent site visits, the number of rainfall events that produced sediment decreased as time since fire increased. Although this trend may have been the same at the Hot Creek and Myrtle Creek fires, a fewer number of site visits precluded us from observing sediment yields after individual rain events.

3.4.1. Sediment yield by fire

At the Hayman fire, there was no difference in the model estimated sediment yields between the wheat straw mulch plots and the controls during the study period (Fig. 6a). In contrast, the wood strand plots had significantly lower sediment yields than the control plots in the first two post-fire years (Fig. 6a). Over all treatments, sediment yields decreased significantly through the fourth post-fire year, after which there were so statistical differences despite the increases in the mean values in years five through seven. There were large storms (I_{10} values of 107, 78, and 96 mm h^{-1}) in years five, six, and seven respectively, which led to increased sediment production on all plots (Table 5).

At the Hot Creek fire, sediment yields from the wheat straw mulch plots, the only treatment at this fire, were not significantly different than the sediment yields in the control plots (Fig. 6b). The largest sediment yields were measured in the first post-fire year and the sediment yields in subsequent years were all significantly less than those in the first post-fire year. The smallest yields were measured in the second post-fire year (Table 6), which was also the second driest year of the study at this fire (Table 2).

At the Myrtle Creek fire, sediment yields decreased significantly between the first and second post-fire years. Sediment yields from the wheat straw mulch site was significantly less than the sediment yields from the control site in the first post-fire year, but there was no difference in the sediment yields between the hydromulch and the control sites in either year (Fig. 6c). The moderate burn severity needle cast plots had less sediment than the high burn severity control sites.

At the School fire, sediment yields were significantly less in the second through fourth post-fire years compared to the first year. Model estimates of sediment yields from the wheat straw and wood strand mulches were significantly less than from the control plots in the first, third, and fourth post-fire years but there were no differences among treatments in the second post-fire year. There were no differences in sediment yields between the hydromulch plots and the control plots in any year (Fig. 6d, Table 8), but the sediment yield in the hydromulch site in the fourth post-fire year was greater than that of the seeded site. Sediment yields from the seeded plots were significantly less than the control in the third and fourth post-fire years.

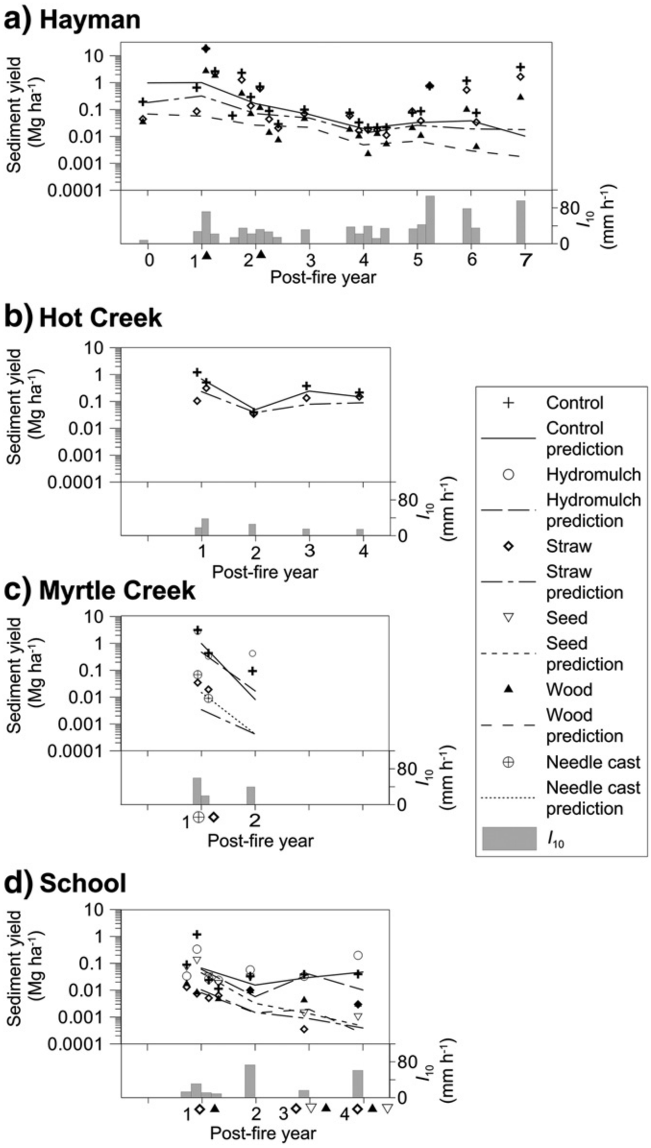

Fig. 6. The observed event and predicted annual sediment yields vs. number of post-fire years and maximum 10-min rainfall intensity (I_{10}) for each fire: a) Hayman; b) Hot Creek; c) Myrtle Creek; and d) School. Only the post-fire years with complete rainfall data were modeled and are shown. The bars represent the I_{10} associated with the mean observed sediment yields for each event. Predicted annual sediment yields are shown with lines (style varies by treatment). Treatment symbols located next to the post-fire year labels on the X-axis indicate significant differences ($\alpha = 0.05$) in modeled mean annual sediment yields between the treatment indicated by the symbol and the controls in that post-fire year. Wheat straw mulch is referred to as "Straw" and wood strand mulch is referred to as "Wood" in the legend.

3.4.2. Sediment yield by treatment

With all sites combined, neither the wheat straw mulch nor the hydromulch significantly reduced estimated sediment yields compared to the control plots for any year of the study (Fig. 7). In contrast,

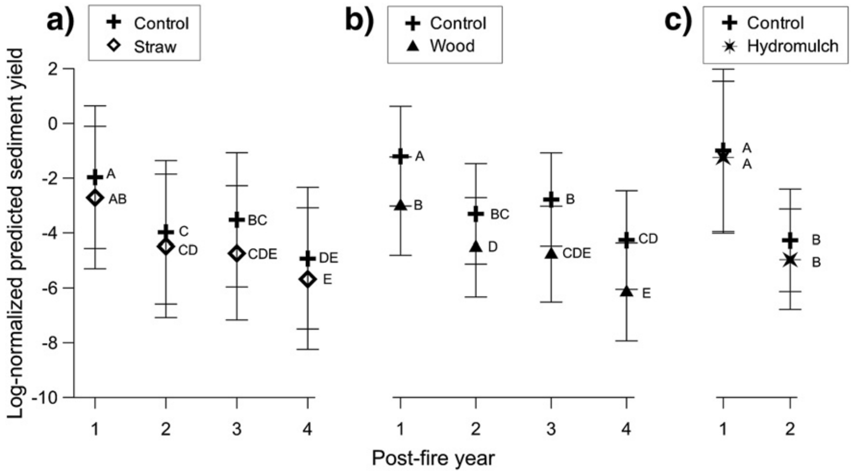

Fig. 7. The predicted (modeled), $\log_{10}$-transformed, normalized sediment yield vs. post-fire year by treatment: a) straw mulch and their controls (all fires); b) wood strands and their controls (Hayman and School fires); and c) hydromulch and their controls (Myrtle Creek and School fires). Data are normalized to allow comparisons by treatment without differentiating by fire. The number of post-fire years in each plot depends on the availability of rainfall data for each treatment. The error bars represent 95% confidence limits around the predicted values and different letters indicate significant differences ($\alpha = 0.05$) among treatments within each of the three figures (a, b, and c).

the wood strand mulch significantly reduced estimated sediment yields compared to the control plots in first four post-fire years (Fig. 7).

4. Discussion

Sediment yields varied among fires, rainfall events, and over time as well as by treatment. Attributing sediment yield reduction to mulch treatment effectiveness is complicated by the inherent variations in sediment yields generated by the differences within and among sites (climate, soil, vegetation, etc.), precipitation during the study, and fire effects (soil burn severity, soil water repellency, disaggregation of soil, etc.). In addition, site differences likely interact with the treatments to further increase the variation in sediment yield response for a given treatment. For example, slope lengths in the plots at the School fire were 3–5 times longer than the slope lengths at any of the other three fires, yet unexpectedly, rilling was not observed in the School fire plots. The lack of rilling may have been because no high intensity storms occurred in the first post-fire year and when high intensity storms did occur in the second post-fire year, the vegetation, which had recovered quickly after the fire, was sufficient to prevent rilling. Rilling was observed within the shorter plots at Hayman, Myrtle Creek, and to a minor extent at Hot Creek and was generally related to the large storms and sediment yields. Previous studies have shown that burn severity, rainfall intensity, ground cover, and time since burning are the dominant factors that impact post-fire sediment yield rate (for example, Benavides-Solorio and MacDonald, 2005; Doerr et al., 2006; Gimeno-García et al., 2007). Thus, we will address each of these factors with respect to their impact on our results.

4.1. Effects of observed rainfall on post-fire vegetation and sediment yields

Precipitation totals and rainfall intensities varied widely by fire and post-fire year during the study and influenced sediment yields directly via rainfall kinetic energy and amount of runoff, and indirectly through vegetation recovery. The Hayman and Hot Creek fires both experienced lower than average precipitation in the first two post-fire years and periodically after that (Table 2). Despite the low precipitation, live vegetation on the Hayman control plots increased by about 15% during each of the first two post-fire years, and by about 5% a year after that. The Hot Creek fire lagged well behind the Hayman fire re-vegetation rate with an average of only 10% vegetation cover on the control plots in the fifth post-fire year (Fig. 4). This slow revegetation is likely due to circumstances beyond precipitation amount, and may include the proportion of precipitation that fell as snow versus rain and the northerly aspect of all the sites at Hot Creek in addition to the factors that impact sediment yields listed above. Precipitation at the Myrtle Creek and School fires was generally at or above normal during the study, which encouraged steady vegetation recovery. Sites at both fires attained 40–50% vegetation cover by the third post-fire year.

Sediment yields generally increased with increasing I_{10} at all fires, but the overall response decreased between the first and second post-fire year, regardless of I_{10} magnitude (Fig. 5). After 4 years of downward trending sediment yields, the sediment yields at Hayman fire increased in post-fire years 5 to 7 in response to a high intensity rainstorm ($I_{10} \geq 2$-year return interval I_{10}) in each of those years (Table 5; Fig. 6a). The corresponding sediment yields (0.76 to 1.3 Mg ha^{-1} on the control plots) were relatively large indicating that rainfall intensity was still an important factor in erosion rates and that the Hayman fire had not yet fully recovered by the seventh post-fire year.

4.2. Ground cover recovery

Unburned forests often have nearly complete ground cover of litter, vegetation, or woody debris. We used ground cover (litter and vegetation) values from unburned forests near each of the study sites to identify reference values for ground cover recovery. Of the four fires in this study, the Hayman fire, with its relatively low soil productivity and short growing season, had the lowest unburned ground cover value of 82% (P. Robichaud unpublished data). A mean ground cover value of 91% was measured in unburned forest plots near the Hot Creek study sites (P. Robichaud unpublished data). The vegetation and litter cover in two unburned small watersheds near the Myrtle Creek fire was 89% (Elliot and Glaza, 2009) and some unburned forested areas near the School fire had 99% ground cover (P. Robichaud unpublished data). The ground cover values on the control plots at the four fires in this study did not reach the ground cover values of their respective unburned reference conditions during the four to seven post-fire years of the study. However, many of the mulched sites reached or nearly reached (within 5%) their recovery benchmark: the wood strand sites at the Hayman and School fires, the straw mulch sites at the Myrtle Creek and School fires, and the hydromulch and moderate severity needle cast plots at the Myrtle Creek fire (Fig. 4).

The mulch treatments did not statistically affect the vegetation recovery in the current study. Assuming our treated hillslopes would have had similar responses in vegetation cover if they had been left untreated, some responses that may be attributed to mulch cover were still notable. The Hayman wood strand mulch plots had the least vegetation in the last three years of the study. At the Myrtle Creek fire, the straw mulch site—even with its relatively heavy application rate—and the hydromulch site had more vegetation than the control or needle cast sites in post-fire years three through five. At the School fire, more vegetation was measured each year on the wheat straw mulch, hydromulch, and seeded sites than in the control or wood strand sites (Fig. 4). Given that wood strand mulch decays more slowly and is displaced less easily than wheat straw mulch (Copeland et al., 2009) or hydromulch, it may have a longer and/or greater impact on revegetation as compared to more rapidly decaying and displaced mulches. Mulch thickness as well as proportion of cover may affect post-fire vegetation density. Dodson and Peterson (2010) reported that vegetation response was negatively impacted when mulch cover exceeded 70% and when mulch depth exceeded 5 cm, but we did not detect any similar impact at our Myrtle Creek straw mulch site where straw mulch exceeded 80% coverage (Fig. 4). Kruse et al. (2004) found that seeding and barley straw mulching hindered post-fire conifer establishment but did not significantly affect understory plants. Hubbert et al. (2012) and Robichaud et al. (2013) found that hydromulch did not appear to impede post-fire plant recovery. Given the short-lived hydromulch cover within the research sites, no adverse effect on vegetation recovery was anticipated. However, these data do not provide any insight on the effects of hydromulch thickness or proportion of coverage on post-fire vegetation recovery.

Among the four fires in this study, the slow vegetative recovery at Hot Creek stands out (Fig. 4). The dominant understory plants in the area of the Hot Creek fire (Table 2) regenerate from surface and below-surface rhizomes and generally re-sprout and spread quickly after wildfires (Crane and Fischer, 1986). However, the high degree of soil water repellency (Table 4) and lack of duff across the hillslope where the sites were located (field observations) imply that the wildfire subjected the soils to high temperatures of sufficient duration and depth to have killed the rhizomes of these dominant plants (DeBano et al., 2005; Neary et al., 2005). The area where the Hot Creek fire occurred is not conducive to the germination and growth of plants from seed. Most of the precipitation received by this area is snowfall and only 4 to 10% of the total annual precipitation fell as rain in the short summers during the study. With no soil cover or shade from a canopy, soil moisture near the surface likely would have evaporated quickly giving seeds little opportunity to survive following germination. In addition, the persistent soil water repellency (Table 4) likely reduced water infiltration, which would further reduce water availability to plants (Madsen et al., 2011). Thus, vegetation was slow to recover and sediment yields remained high on the control plots and increased on the wheat straw mulch plots in post-fire years three and four as the straw cover disappeared.

4.3. Soil water repellency

Despite the fact that all sites except the needle cast site at Myrtle Creek were classified as high burn severity, the occurrence and degree of soil water repellency were highly variable within and among the sites. Such spatial variability over a relatively small scale has been documented in other studies (e.g., Lewis et al., 2006; Woods et al., 2007). Fire induced or enhanced soil water repellency is directly related to soil burn severity (Doerr et al., 2006; Parsons et al., 2010) and is often implicated in increases in post-fire runoff and erosion (Benavides-Solorio and MacDonald, 2001; DeBano, 2000; DeBano et al., 2005; Letey, 2001; Shakesby et al., 2000). Recent studies have indicated that fire-induced soil water repellency changes may be less important than other controls such as decreased infiltration due to soil sealing in determining erosion rates at the hillslope scale (Doerr et al., 2006; Larsen et al., 2009). Given that sediment yields at all four fires generally declined during the study, it might be assumed that soil water repellency, which also declined throughout the study, had impacted post-fire sediment yields; but other factors such as vegetation cover also changed over time at most of the sites (Fig. 4), and sediment yields above the background level continued after the water repellency was gone at three of the fires. The idea that post-fire increases in erosion rates are related to fire-induced or -enhanced soil water repellency was neither supported nor contradicted by our data.

4.4. Recovery and time since burning

Erosion rates from long unburned and otherwise undisturbed forests are normally quite low, but they vary by climate, vegetation, geology, topography, etc. Measured erosion rates from undisturbed areas near our study sites include: 1) 0.28 Mg ha^{-1} yr^{-1} on the Spring Creek watershed near the Hayman sites (Moody and Martin, 2001); 2) 0.13 Mg ha^{-1} yr^{-1} from four 1–2 km^2 watersheds near the Hot Creek sites (Clayton and Megahan, 1986); 3) 0 Mg ha^{-1} yr^{-1} measured over 4 years on two 5 ha watersheds near the Myrtle Creek sites (Elliot and Glaza, 2009); and 4) 0.01 Mg ha^{-1} yr^{-1} from a 3 km^2 watershed near the School sites (Harris et al., 2007). These values were all measured in watersheds that were much larger than the plot sizes used in the current study, and other research suggests the sediment yields at these larger spatial scales may be greater than at the scale of the hillslope plots in the current study (de Vente et al., 2007) because they include channel erosion and transport processes. While the sediment yields at the larger scales may not be the best comparison for the annual sediment yields measured on the hillslope plots in this study (Table 9), they do provide some measure for comparison. In addition, these watershed values suggest that hydrologic recovery differs among the four sites. While negligible erosion may be expected from a fully recovered hillslope in the Myrtle Creek and School fires, it is likely that measurable erosion may occur in the Hayman and Hot Creek fires

Table 9
Mean annual sediment yields by fire and treatment. Data include all measured sediment removed from the plots. Footnotes for Tables 5–8 indicate specific plots that were not included in the mean values by cleanout. Sediment yield values greater than 0.00 but less than 0.01 Mg ha^{-1} are shown as <0.01.

Fire	PF year	*n* cleanouts	Treatment (Mg ha^{-1} yr^{-1}) Control	Wheat straw	Wood strands	Hydromulch	Needle cast	Seed
Hayman	1	3	22.0	21.0	4.6			
	2	6	3.6	2.1	0.60			
	3	1	0.10	0.07	0.05			
	4	5	0.18	0.12	0.05			
	5	3	0.82	0.91	0.78			
	6	2	1.3	0.57	0.11			
	7	2	1.3	0.57	0.09			
Hot Creek	1	2	1.8	0.15				
	2	2	0.62	0.03				
	3	2	0.47	0.17				
	4	2	0.56	0.34				
	5	1	0.26	0.36				
Myrtle Creek	1	2	3.6	0.05		2.9	0.08	
	2	2	0.49	0.10		1.7	<0.01	
	3	2	0	0		0.18	0	
	4	0	0	0		0	0	
	5	1	0.01	0		<0.01	0	
School	1	5	1.3	0.04	0.05	0.46		0.29
	2	2	0.25	0.03	0.03	0.17		0.04
	3	2	0.06	0.01	<0.01	0.08		<0.01
	4	2	0.04	<0.01	0.04	0.22		<0.01

even after the burned area has recovered to pre-fire status. The Colorado Front Range, where the Hayman fire occurred, receives the highest intensity rainfall (2-year $I_{10} = 53$ mm h^{-1}) and maintains the lowest ground cover (82% in unburned forest) of the four areas where our study sites were located. Consequently, it is not surprising that a sediment yield of approximately 0.3 Mg ha^{-1} yr^{-1} was measured in a relatively undisturbed watershed near the Hayman fire (Moody and Martin, 2001).

At the Hayman fire, the annual sediment yields on the control hillslope plots were the same order of magnitude as the undisturbed forested watershed by the third post-fire year which was relatively dry and had no high-intensity rainfall; but in response to large, high intensity storms in post-fire years five ($I_{10} = 107$ mm h^{-1}), six ($I_{10} = 78$ mm h^{-1}), and seven ($I_{10} = 96$ mm h^{-1}), annual sediment yields were similar to those measured in the second post-fire year and an order of magnitude larger than those reported for a nearby undisturbed watershed (Table 9). The wheat straw and wood strand mulch plots followed similar patterns in that the smallest sediment yields occurred in post-fire years three and four with increased sediment yields in post-fire years five through seven (Table 9). The longer-term effects of the wood strand mulch may have been implicated in the favorable comparison of the mean annual sediment yields at the wood strand site in the sixth and seventh post-fire years and the recovery reference value (0.28 Mg ha^{-1} yr^{-1} [Moody and Martin, 2001]) from a nearby undisturbed watershed (Table 9). The values were the same order of magnitude despite the high intensity rainfall on the Hayman sites.

At the Hot Creek fire, all of the annual sediment yields, except the yield from the straw mulch plots in the second post-fire year (Table 9), were larger than the 0.13 Mg ha^{-1} yr^{-1}, the reference value for recovery (Clayton and Megahan, 1986). Based on this and the characteristics already discussed, we concluded that the Hot Creek sites had not recovered as of the fifth post-fire year.

The Myrtle Creek control plots produced no sediment in the third and fourth post-fire years and only 0.01 Mg ha^{-1} yr^{-1} in the fifth post-fire year. Of the treated plots, only the hydromulch produced any sediment after the second post-fire year (Table 9). While the value produced in the control plots in the fifth post-fire year was larger than the reference value for recovery (0 Mg ha^{-1} yr^{-1} [Elliot and Glaza, 2009]), this value also was the smallest detectable sediment yield for this plot size and method.

The School fire control site had greater annual sediment yields than the reference value for recovery (0.01 Mg ha^{-1} yr^{-1} (Harris et al., 2007)) in each of the four post-fire years (Table 9). The annual sediment yields in the seeded site were less than the reference value in the third and fourth post-fire years, and sediment yield in the straw mulch site was less than the reference value in the fourth post-fire year only (Table 9). Although the annual sediment yield in the control site did not fall below the 0.01 Mg ha^{-1} yr^{-1} threshold, it had declined over the four post-fire years of the study and sediment yields from large storms in the second and fourth post-fire years were less than the sediment yields from a storm with a lower I_{10} in the first post-fire year (Table 8). The sediment yields at the School sites may not have been fully recovered, but they were close to that point at the end of the fourth post-fire year.

Post-fire sediment yields tended to decrease over time in this study and "time since burning" has been a significant factor in other studies that measured post-fire sediment yields for multiple years (e.g., Benavides-Solorio and MacDonald, 2005; Robichaud et al., 2008; Wagenbrenner et al., 2006). The increase in ground cover over time is often suggested as the most significant factor in the decrease in erosion over time. However, soil properties, such as infiltration capacity, aggregate size and stability, organic matter content, and soil sealing, can be significantly affected by fire and are known to impact post-fire erosion (Larsen et al., 2009; Martinez-Mena et al., 2002). The recovery of the soil toward its pre-fire condition may contribute to erosion rate recovery (Bronick and Lal, 2005). In the absence of specific measurements of these and other soil properties, time since burning became a composite factor that incorporated the change over time of variables that were not directly measured in this study.

4.5. Post-fire treatment effectiveness in reducing sediment yields

4.5.1. Wheat straw mulch

On the Myrtle Creek and School fires, wheat straw mulch reduced sediment yields as compared to the control sites, and the reduction was significant during the first post-fire year at both fires and in the third and fourth post-fire years at the School fire (Figs. 6 and 7). However, the wheat straw mulch treatment did not significantly reduce the sediment yields at the Hayman or Hot Creek fires. These results were surprising as it reduced sediment yields at the watershed scale in a nearby site on the Hayman fire (Robichaud et al., 2013) and several studies have found wheat straw mulch to be effective at reducing post-fire erosion (Badia and Marti, 2000; Groen and Woods, 2008; Rough, 2007; Wagenbrenner et al., 2006). In contrast, straw mulch reduced sediment yields at the Myrtle Creek and School sites; we attribute the difference in effectiveness between the two pairs of fires to differences in vegetative recovery at the sites. The proportion of wheat straw mulch in the ground cover decreased in all study sites during the first post-fire year, but the live vegetation and litter cover increased at the Myrtle Creek and School straw mulch sites resulting in net increases in total ground cover. In contrast, the vegetation and litter cover did not increase sufficiently at the Hayman and Hot Creek straw mulch sites to make up for the lost mulch cover, and this resulted in net decreases in total cover at those sites (Fig. 4). The contrasting responses at the four fires in this study indicate that the interaction among treatment application rates, natural vegetative recovery, and rainfall patterns may impact sediment yields beyond the longevity of the straw mulch.

4.5.2. Wood strand mulch

Wood strand mulch reduced sediment yields in the first two post-fire years compared to the untreated control plots at the Hayman fire, and in the first, third, and fourth post-fire years at the School fire (Fig. 6). The initial mulch cover values were similar for the straw and wood strands at both fires — between 51% and 57% for both treatments and fires. Yet, at the Hayman fire, wood strand mulch provided about 45% ground cover through the third post-fire year while almost none of the wheat straw mulch was observed on the plots by the end of the first post-fire year (Fig. 4). Given the longevity of the wood strands and the impact of ground cover at reducing post-fire sediment yields, it is not surprising that the sediment yields from the Hayman wood strand plots were smaller than the sediment yields on the straw mulch and control plots at that fire (Tables 5 and 9). However, on the School fire where the vegetation more than made up for the loss of wheat straw ground cover in the first post-fire year, there were no differences in the relatively small magnitude sediment yields between the wood strand site and wheat straw site (Table 8). The longer-lived wood strand mulch provided protection to the soil surface longer than the wheat straw mulch, and so the wood strand mulch was more effective at reducing sediment yields through the second post-fire year and beyond (Table 9, Fig. 6).

4.5.3. Hydromulch

Hydromulch did not significantly reduce sediment yields as compared to the untreated controls at either the Myrtle Creek or School fire. Hydromulch initially increased the ground cover on the treated sites at both fires, but the hydromulch rapidly degraded and only negligible amounts were measured in the first post-fire year (Fig. 4). As described above, the post-fire vegetation recovery was more rapid at the Myrtle Creek and School fires than at the Hayman or Hot Creek fires, and the vegetation component of the ground cover compensated for the loss of the hydromulch in the first post-fire year, resulting in no significant difference in total cover between the hydromulch and the control sites in post-fire year 2 and beyond.

At the School fire, there was more vegetative cover in the hydromulch site than in the control site in the second through fourth post-fire years, but there was no difference in sediment production between the hydromulch and control sites in any of the 4 years. However, the vegetative cover in the hydromulch site was less than the vegetative cover in the seeded site where the same seed mix had been applied, and there was no difference in sediment yields between the hydromulch and seeded sites at the School fire until the third post-fire year, when the seeded plots produced less sediment than both the hydromulch and control plots. Differences among the control, hydromulch, and seeded sites (e.g., aspect) likely influenced native grass establishment which was much greater on the seeded site than on the hydromulch site.

The tackifiers used in the hydromulch mixes applied at the Myrtle Creek and School fires were estimated to last only months when exposed to natural weather conditions and the relatively short, thin fiber strands in the hydromulch degraded and washed away more quickly than the larger strands of the dry wheat straw and wood strand mulches. The hydromulch application rate at both sites resulted in minimal treatment cover—53% at Myrtle Creek and 56% at School—especially on the steep slopes of these sites. Increased coverage may have impacted longevity and/or effectiveness but was not tested in this study. Hubbert et al. (2012) and Robichaud et al. (2013) also found that the hydromulch treatments tested after the 2003 Cedar fire in southern California were quickly degraded and washed away and that they had no effect on sediment yields at either the hillslope or catchment scales. Many other hydromulch formulations are available besides the two tested in the current study, and various formulations and application rates are being evaluated for their capacity to reduce post-fire sediment yields.

4.5.4. Needle cast and seeding

The sediment yields in the needle cast site at the Myrtle Creek fire were significantly lower than the yields in the control site in the first two post-fire years. Also, there was no difference in sediment yields between the needle cast site and the straw mulch site (Fig. 6). However, the control and straw mulch sites at Myrtle Creek had burned at high severity while the needle cast site was in an area with moderate burn severity. As in this study, needle cast from burned trees may provide substantial amounts of ground cover in forested areas of low or moderate burn severity and likely contribute to the lower post-fire sediment yields from these areas as compared to areas of high burn severity (Benavides-Solorio and MacDonald, 2005). If needles are generally present over an area, it is reasonable to assume that needles will fall during the first winter and provide broad coverage; however, in areas where the burn severity leaves a mosaic and areas of needle availability are interspersed with areas lacking needles, coverage is less assured.

The seeded site on the School fire produced significantly less sediment as compared to the controls in the third and fourth post-fire years — past the point when the largest sediment yields were measured at this fire. Although post-fire seeding may be justified for reasons other than erosion mitigation, the lack of effectiveness in the first two years of this study corroborates results reported by others. In a recent review of post-wildfire seeding treatments in U.S. western forests, Peppin et al. (2010) reported that seeding did not reduce sediment yields in the first two post-fire years in 11 of the 12 studies that compared sediment yields from seeded and unseeded areas. Germination and vigor of seeded plants depends on favorable growing conditions. If seeded grasses are to provide effective erosion mitigation, they must receive adequate amounts of rainfall in the first spring following the fire (or seed application) (Beyers, 2004). Such favorable conditions occurred at the seeded site after the School fire and the seeded native grasses flourished at that site; yet, the differences in measured sediment yields were not significant until the third post-fire year when yields were relatively small on all sites.

4.5.5. Beyond ground cover

The primary function of post-fire mulch treatments is to increase ground cover and thereby reduce runoff and soil erosion. We observed that increases in ground cover reduced the development of rills even on the long, steep hillslopes at the School fire. The wheat straw mulch, wood strand mulch, and hydromulch treatments increased ground cover to over 60% as compared to the controls at all sites; yet the mulch treatments were not all equally effective at reducing sediment yields. This suggests that mulch treatment effectiveness depended on site and/or mulch characteristics other than initial ground cover. The amount of ground cover needed to significantly reduce soil erosion differed by site and time since the fire, as did the processes that affect ground cover amounts, such as precipitation, natural re-vegetation, and litter accumulation. Cover was an important factor, but may not have been the only factor, in reducing the sediment yields (Larsen et al., 2009).

The reduction in mulch cover over time, although not directly tested, was generally attributed to redistribution by wind and water as well as decay. Mulch longevity or persistence differed among the three mulches, with hydromulch being particularly short-lived (months), wheat straw mulch having moderate longevity (2 to 3 years, depending to some degree on application rate), and wood strands persisting for more than 4 years (more than 7 years at the Hayman fire) (Fig. 4). Part of the decision about what mulch, if any, to use for post-fire hillslope stabilization requires matching mulch longevity to expected recovery time. Another part of the decision depends on the fates of the residual materials and decay products of mulches and the impacts of these products on the burned ecosystem. Some studies have been conducted on the ecological effects of mulches, which may have significant impacts on the vegetative cover, species richness, and tree seedling densities (Dodson and Peterson, 2010; McCullough and Endress, 2012). The ecological effects of the hydromulches, where tackifier and soil binding components often are proprietary chemicals, are not well-known.

The mechanisms by which mulch treatments reduce hillslope erosion are not completely understood, but some aspects have become clear. Mulches reduce rain drop splash erosion by physically covering the soil surface (Groen and Woods, 2008). Mulches, like duff on an unburned forest floor, also increase the surface roughness of the overland flow path, thereby reducing the flow depth and velocity (Robichaud et al., 2010b). The shallower flow reduces the shear stress applied to soil particles, which leads to smaller soil detachment rates. The lower flow velocity leads to lower sediment transport capacities (Wagenbrenner et al., 2010) and may lead to greater infiltration rates. Additionally, mulches can create mini-debris dams which further slow flow and increase infiltration and sediment deposition (Foltz and Dooley, 2003). Mulches shade the soil surface and protect it from wind, resulting in lower soil temperatures, lower evaporation rates and increases in soil water retention. These factors are transient and depend on the degradation and decay rates of the mulch, which also depend on the mulch type.

5. Conclusions

The effectiveness of post-fire treatments at reducing sediment yields was measured with sediment fences on hillslope plots for 4 to 7 years after four wildfires in the western United States. Wheat straw mulch, wood strand mulch, and hydromulch treatments initially increased total ground cover to more than 60% but not all the mulches reduced sediment yields nor did the effectiveness of the mulches last the same amount of time. Wood strands reduced annual sediment yields by 79% and 96% during the first post-fire year at the two fires where it was tested and also reduced sediment yields in various later post-fire years at both fires. Wheat straw mulch reduced annual sediment yields by 97–99% in the first post-fire year at two of the four fires where it was tested, and, to a lesser degree, in the third and fourth post-fire years at one of the fires. Hydromulch did not reduce sediment yields compared to the controls at either of the fires where it was studied. In general, the effects of these mulches on sediment yields corresponded with their longevity. The measured reductions in sediment yields mostly were attributed to the increase in total cover, which included the persistent straw or wood strand mulch cover as well as the increases in litter and vegetation.

Along with the treatments, post-fire year and I_{10} were significantly related to sediment yields. The erosion rates decreased with the amount of time since fire and increased with higher rainfall intensities. Sediment yields were measured on all fire and treatment combinations in the first post-fire year, and the single-event sediment yields ranged from 0.01 to 19 Mg ha^{-1} in the first post-fire year. The regression of sediment yields vs. I_{10} suggested that sediment yields decreased by nearly an order of magnitude in the second post-fire year. Large storms (I_{10} with at least a 2-year return interval) produced sediment on all fires in all years where they occurred; however, on the two fires where large storms occurred after the first post-fire year, the amount of sediment produced for an equivalent I_{10} was smaller than the sediment produced in the first post-fire year.

Vegetative cover in the control plots increased over time, as did total ground cover, although the increase was much less pronounced at one of the four fires. The increase in vegetation over time was not linear or consistent on all fires, and the amount of vegetation was influenced by the amount of precipitation as well as the fire characteristics and general conditions.

At the Myrtle Creek fire, a single site with moderate soil burn severity and a measurable quantity of ponderosa pine needle cast produced significantly less sediment than the high burn severity control plots in the first post-fire year. Native seeding at the School fire increased the ground cover starting in the second post-fire year and reduced sediment yields starting in the third post-fire year as compared to the control site.

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