Three Years of Hillslope Sediment Yields Following the Valley Complex Fires, Western Montana

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Abstract

The 2000 Bitterroot Valley wildfires provided an opportunity to measure post-fire effects and recovery rates. We established 24 small (0.01 ha [0.02 acre]) plots in four high-severity burn sites. We measured sediment yields at each site with silt fences. We also measured rainfall characteristics, soil water repellency, vegetative cover, and other site characteristics. The median sediment yield in post-fire year 1 was 8 Mg ha^{-1} yr^{-1} (3.6 ton $acre^{-1}$ yr^{-1}), and values ranged from 0.3 to 47 Mg ha^{-1} yr^{-1} (0.1 to 21 ton $acre^{-1}$ yr^{-1}). Sediment yields were lower in post-fire years 2 and 3, with medians of 2 and 0.3 Mg ha^{-1} yr^{-1} (0.9 and 0.1 ton $acre^{-1}$ yr^{-1}), respectively. The high variability in sediment yields was related to 10-minute maximum rainfall intensity (I_{10}), but not to soil water repellency or vegetative cover. The results of this study may assist in decisions about post-wildfire land management.

Keywords: erosion, rainfall intensity, soil water repellency, vegetative recovery, post-fire

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Introduction

Wildfires can dramatically affect forested landscapes by removing the canopy and protective forest floor components, such as litter and duff. Soil infiltration capacity and structure may also be altered. These effects then impact the hydrologic cycle, often producing more frequent and greater quantities of overland flow (Robichaud 2000). The increased overland flow also increases sheet, rill, gully, and channel erosion rates. Although these effects have long been recognized (Hendricks and Johnson 1944), until recently research into the post-fire effects has been sparse with large geographic gaps across the western United States. Recent research results suggest that post-fire erosion rates, as well as recovery of erosion rates to pre-fire levels, vary greatly in the diverse ecosystems of the western United States (Robichaud and others 2008b).

Research in the western United States has shown that post-fire erosion rates can vary by orders of magnitude and depend on several factors, including burn severity (Benavides-Solorio and MacDonald 2001, 2005), post-fire rainfall intensity (Inbar and others 1998), time since burning (Robichaud and Brown 1999; Benavides-Solorio and MacDonald 2001; Robichaud and others 2008b), and soil type (Benavides-Solorio and MacDonald 2005). Following the Valley Complex fires of 2000 in the Bitterroot Valley of Montana, Robichaud and others (2008a) measured sediment yields of 9 to 66 Mg ha^{-1} yr^{-1} (4 to 30 ton $acre^{-1}$ yr^{-1}) (median value of 20 Mg ha^{-1} yr^{-1} [9 ton $acre^{-1}$ yr^{-1}]) from four untreated burned hillslope plots during the first post-fire year. In another study following the Valley Complex wildfires, Spigel and Robichaud (2007) used hillslope plots to evaluate soil water repellency and first-year erosion rates. They reported event sediment yields of 9 to 82 Mg ha^{-1} (4 to 37 ton $acre^{-1}$) for a rain event with a greatest 10-minute rainfall intensity (I_{10}) of 78 mm hr^{-1} (3.1 inch hr^{-1}). Both studies found that the erosion rates increased with an increase in I_{10} (Spigel and Robichaud 2007; Robichaud and others 2008a). Robichaud and others (2008b) measured post-fire erosion rates from small watersheds (1.4 to 13.3 ha [3.5 to 33 acre]) established around the western United States. At the Bitterroot Valley site (3.6 ha [8.9 acre]), post-fire erosion rates were 0.6 Mg ha^{-1} (0.3 ton $acre^{-1}$) in the first post-fire year and between 0.09 and 0.9 Mg ha^{-1} (0.04 to 0.4 ton $acre^{-1}$) in post-fire years 2 through 4.

Following the 2000 Valley Complex Fires in western Montana, Spigel and Robichaud (2007) established hillslope sites to measure post-fire erosion rates. The sites were monitored for two additional years to determine the magnitude, variability, and short-term (1 to 3 years) recovery of post-fire erosion rates in the Bitterroot Valley. Analyses of these data provide region-specific, post-fire response information to land managers and researchers.

Methods

In 2000, a series of wildfires burned 144,000 ha (356,000 acre) of the Bitterroot Valley of western Montana, and about a third of this area burned at high severity (U.S. Department of Agriculture 2001). We studied the southern portion of the burned area (figure 1).

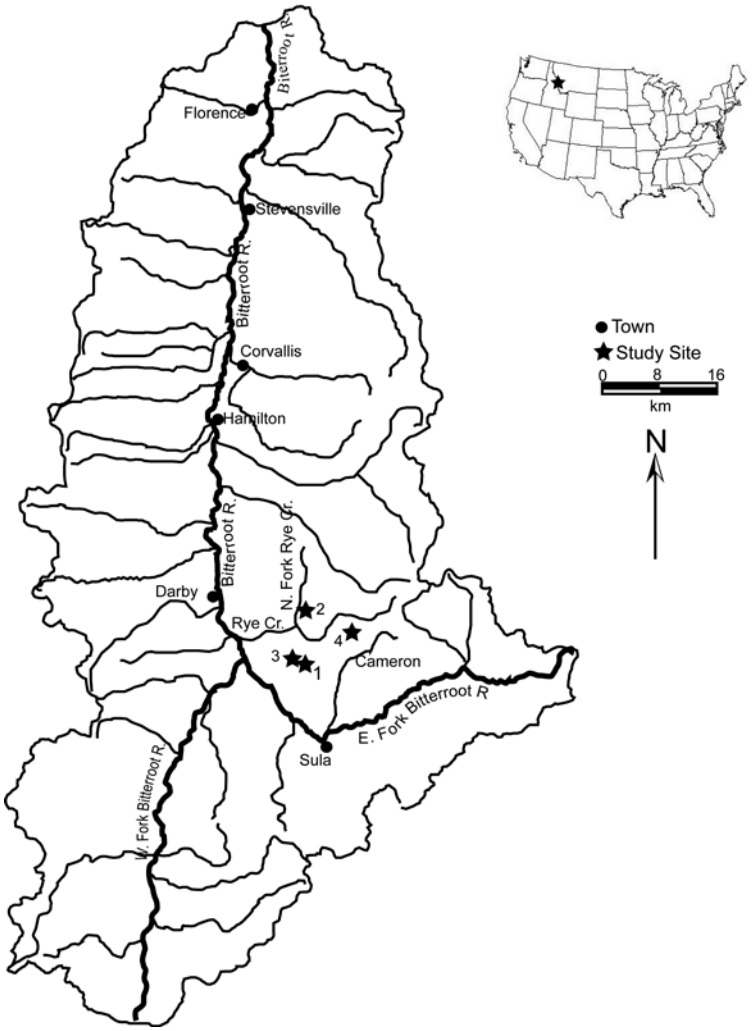

Figure 1—Map of study site locations in western Montana.

Table 1—Mean slope, elevation, aspect, and soil class for each site.

Site	Slope (%)	Elevation (m)	Aspect	Soil class
1	62	1710	NE	Haplustept[a]
2	54	1620	W	Argiustoll[b]
3	58	1800	N	Haplustept[a]
4	50	1740	E	Haplustept[a]

[a] Haplustept: *sandy-skeletal, mixed, frigid, typic haplustept*
[b] Argiustoll: *loamy-skeletal, mixed, typic, superactive argiustoll*

Four steep (50 to 62 percent) (table 1), severely burned hillslopes located within a 5-km (3.1-mi) radius (figure 1) were selected for measurement of hillslope sediment production, rainfall, water repellency, vegetative cover, burn severity index, and stand density (Spigel 2002). The sites (1 to 4) were located in stands of burned ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) with pre-fire understory of pinegrass (*Calamagrostis rubescens*), white spiraea (*Spiraea betulifolia*), and showy aster (*Aster spectabilis*) (Spigel and Robichaud 2007). The soils at sites 1, 3, and 4 were classified as sandy-skeletal, mixed, frigid, typic haplustepts derived from granitic colluvium; the soil at site 2 was a loamy-skeletal, mixed, superactive, frigid, typic argiustoll with a parent material of igneous/metasedimentary colluvium (Soil Survey Staff 1999) (table 1). Site elevation ranged from 1620 to 1800 m (5300 to 5900 ft) and slope aspects were north, east, northeast, or west (table 1). The sites were monitored for three post-fire years, from 2001 to 2003.

In each site, six plots measuring 5 m (16 ft) along the contour and 20 m (66 ft) along the slope gradient were established on planar hillslopes. We installed silt fences at the outlet of each plot to capture eroded sediment (Robichaud and Brown 2002). Hand-dug trenches, approximately 15 cm (6 inch) wide and deep, were installed across the top of each plot to prevent overland flow from entering the plot from above. We removed and weighed sediment after each sediment-producing event in post-fire year 1 and after three periods of accumulation in each of the second and third post-fire years. We summed sediment production rates by calendar year to produce annual production rates. We measured soil moisture on a sediment sample from each silt fence from each period of accumulation. The moisture content was used to calculate the dry sediment mass for each silt fence. Each dry mass was divided by the plot contributing area (0.01 ha [0.02 acre]) to produce a unit-area sediment production rate. Several trenches overfilled with runoff and sediment during the study; data for each of these occurrences were discarded since the plot contributing area for the sediment production was unknown.

Soil water repellency was measured in 2001 using the water drop penetration time (WDPT) test (DeBano 1981) at 32 points just outside each plot (to avoid additional surface disturbance within the plot). Measurements were taken at the mineral surface and at 1 cm (0.4 inch) depth increments until water repellency was encountered or to a maximum depth of 5 cm (2 inch). The degree of soil water repellency was calculated using the WDPT test results and the following classes: none, 0 to 5 seconds; slight, 6 to 60 seconds; moderate, 61 to 180 seconds; and severe, 181 to 300 or more seconds (DeBano 1981). We repeated the WDPT measurements in post-fire year 3 at eight points adjacent to each plot. Vegetative cover was estimated for each plot using an ocular or grid method (Spigel and Robichaud 2007). For the ocular method (sites 1, 3, 4 and plots 4 through 6 in site 2 in post-fire year 1; all plots in post-fire year 2), each plot was visually partitioned into areas of equal vegetative cover, the amount of cover was estimated, and the aggregate area-weighted vegetative cover was calculated. For the grid method (plots 1 through 3 in site 2 in post-fire year 1 and all plots in post-fire year 3), we laid a 1-m by 1-m (3.3-ft by 3.3-ft) frame on the ground surface at a randomly selected location in each plot. We visually estimated the amount of vegetative cover within the frame (Chambers and Brown 1983).

A tipping-bucket rain gauge was installed at each site. Individual rain events were defined by at least 5 minute duration and were separated by at least 6 hours with no rainfall. For each rain event, the total rainfall, 10-minute maximum rainfall intensity (I_{10}), and 30-minute maximum rainfall intensity (I_{30}) were calculated. If more than one rain event occurred before sediment could be removed from the silt fences, the measured sediment was associated with the storm that had the greatest I_{10}.

In all but post-fire year 1, the rain events that occurred between May 1 and October 31 were used to compare the total number of rain events to the number of sediment-producing events at site 1. Since rain gauges were installed the third week of June 2001, rain events were monitored over a shorter time frame (26 June through 31 October 2001) in post-fire year 1 than in other years.

Although the sites were originally selected and stratified by burn severity index and tree density, these characteristics varied little among the sites (Spigel 2002); for this study we treated the site as a fixed effect to reflect the original site selection method. We conducted repeated measures analyses on the annual sediment yields and the occurrence of each WDPT class. In each model, "plot" was the random component and "years since burning" and "site" were fixed-effects variables (Littel and others 1996). We used an autoregressive covariance structure for the sediment yield model since measurements were made repeatedly on each plot (Littel and others 1996). The occurrence of each WDPT class was defined as the ratio of the number of drops that were classified in a given water repellency class to the overall number of drops for that plot and measurement period. For the WDPT model, a binomial distribution was assumed and an unstructured covariance structure was selected (Littel and others 2006). We made pair-wise comparisons in each of these analyses using least-squares means (LSMeans) with a Tukey-Kramer adjustment (Littel and others 1996). The annual sediment yields were log-transformed to increase normality (Ott 1993). The significance level was 0.05 for all statistical tests. No statistical analyses were conducted on the vegetative cover data because of differences in methods among years and sites.

Results and Discussion

Significant differences existed in the occurrence of "slight" soil water repellency in post-fire year 1. Otherwise, there were no differences in WDPT among the four sites in either post-fire year 1 or 3. In post-fire year 1, the occurrence of soil water repellency averaged 17 percent in the top 5 cm (2 inch) across all sites (table 2). By post-fire year 3, the occurrence decreased, although not significantly, to 7 percent. In post-fire year 1, the greatest occurrence of soil water repellency occurred at 1 cm (0.4 inch) (figure 2). By post-fire year 3, soil water repellency was much less, with the greatest occurrence at 5 cm (2 inch) (figure 2). This shows that the fire-induced repellency diminished over time, which is consistent with other studies (Doerr and others 2006; MacDonald and Huffman 2004; Robichaud and others 2008a). Site 2 had the lowest occurrence of soil water repellency in post-fire year 1 (table 2). This may be related to the relatively fine soil texture in this site because post-fire water repellency generally increases with increasing sand fraction (Huffman and others 2001).

The mean amount of vegetative cover in post-fire year 1 (25 percent) increased in year 2 (50 percent) and year 3 (56 percent) (figure 3). In post-fire year 1, sites 1 and 3 contained the least vegetative cover (16 percent and 13 percent, respectively), but site 3 contained the most vegetative cover in post-fire years 2 and 3 (69 percent and 78 percent, respectively). These apparent differences in vegetative cover regeneration may reflect pre-fire differences in vegetation type and/or density. Because site 3 had a northern aspect and the largest change in vegetative cover over the three post-fire years, it is possible that aspect played a role in the vegetative recovery. Site 3 also had the largest post-fire mean tree diameter of the three sites measured (reported as stand 12 in Spigel 2002). Site 2, with a northeast aspect, had the second greatest vegetative recovery rate (figure 3). The other two sites had east or west aspects (table 1) and had similar, lower vegetative recovery rates.

Table 2—Mean occurrence of soil water repellency (%) by WDPT test (DeBano 1981). Data were summed over depths of 0 to 5 cm (0 to 2 inch) for each site in post-fire year 1 (2001) and year 3 (2003). Different letters within a column represent significant differences using LSMeans with a Tukey-Kramer adjustment (α = 0.05).

Site	Post-fire year	None (≤5 s)	Slight (6-60 s)	Moderate (61-180 s)[a]	Severe (>180 s)
1	1	76 a	11 abcd	3	10 a
	3	100 a	0 abcde	0	0 a
2	1	90 a	2 e	2	5 a
	3	93 a	4 abcde	0.3	2 a
3	1	78 a	14 b	4	4 a
	3	88 a	10 abcde	3	0.4 a
4	1	86 a	4 cde	3	7 a
	3	92 a	5 abcde	2	1 a

[a] Statistical model results were indeterminate for the moderate group.

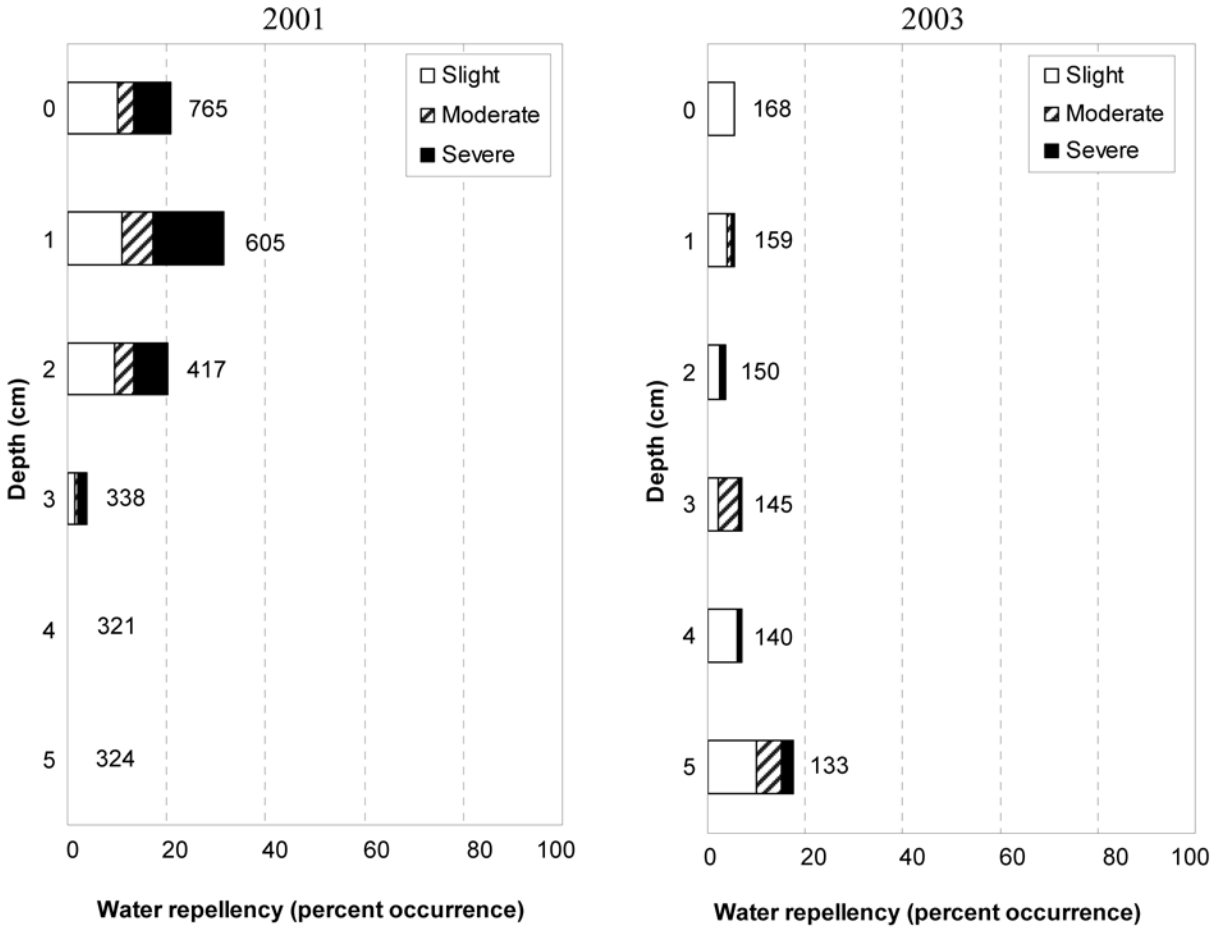

Figure 2—Occurrence and degree of soil water repellency by soil depth for post-fire year 1 (2001) and post-fire year 3 (2003). Measurements were repeated until water repellency was found or to a depth of 5 cm (2 inch). Degree was determined using the WDPT test (DeBano 1981) and the following classes: none, 0 to 5 seconds; slight, 6 to 60 seconds; moderate, 61 to 180 seconds; and severe, 181 to 300 seconds. The number of drops measured is shown next to each bar.

Only a small number of summer (May through October) rain events produced sediment. The comparison of total number of rain events and sediment-producing rain events differed slightly at each site; however, data from site 1 adequately represent the general trend. Thus, in site 1 there were six sediment-producing rain events out of the 25 that occurred during the shortened measurement period of post-fire year 1 (26 June through 31 October). Two out of 44 rain events produced sediment in post-fire year 2, and one out of 39 rain events produced sediment in post-fire year 3. The fact that nearly all the hillslope sediment yield came from a small number of rain events corroborates other post-fire studies (Robichaud and others 2008b).

In post-fire year 1, the average annual sediment yields ranged from 0.3 Mg ha^{-1} (0.1 ton acre^{-1}) in site 3 to 47 Mg ha^{-1} (21 ton acre^{-1}) in site 2, but the variability within site 2 was so high that even this seemingly large difference was not statistically significant (table 3). Sediment yields were lower in all sites in post-fire year 2, but the decline in sediment yields from the first post-fire year was only significant in site 3, which had the smallest sediment yields in both years. Sediment yields were lower again in post-fire year 3 in all sites except site 3, but these year-by-year declines were also not significant. Although changes in sediment yields between post-fire years 1 and 2 and between post-fire years 2 and 3 were not significant, there were significant reductions in sediment yield between post-fire years 1 and 3 in three of the four sites. This suggests some recovery in erosion rates occurred in the three post-fire years. The relative rank of sediment yields by site was the same in all three years; sediment yields were greatest in site 2, followed in declining order by sites 1, 4, and 3.

Despite the finer soil texture and lower occurrence of soil water repellency at site 2 (table 2), this site

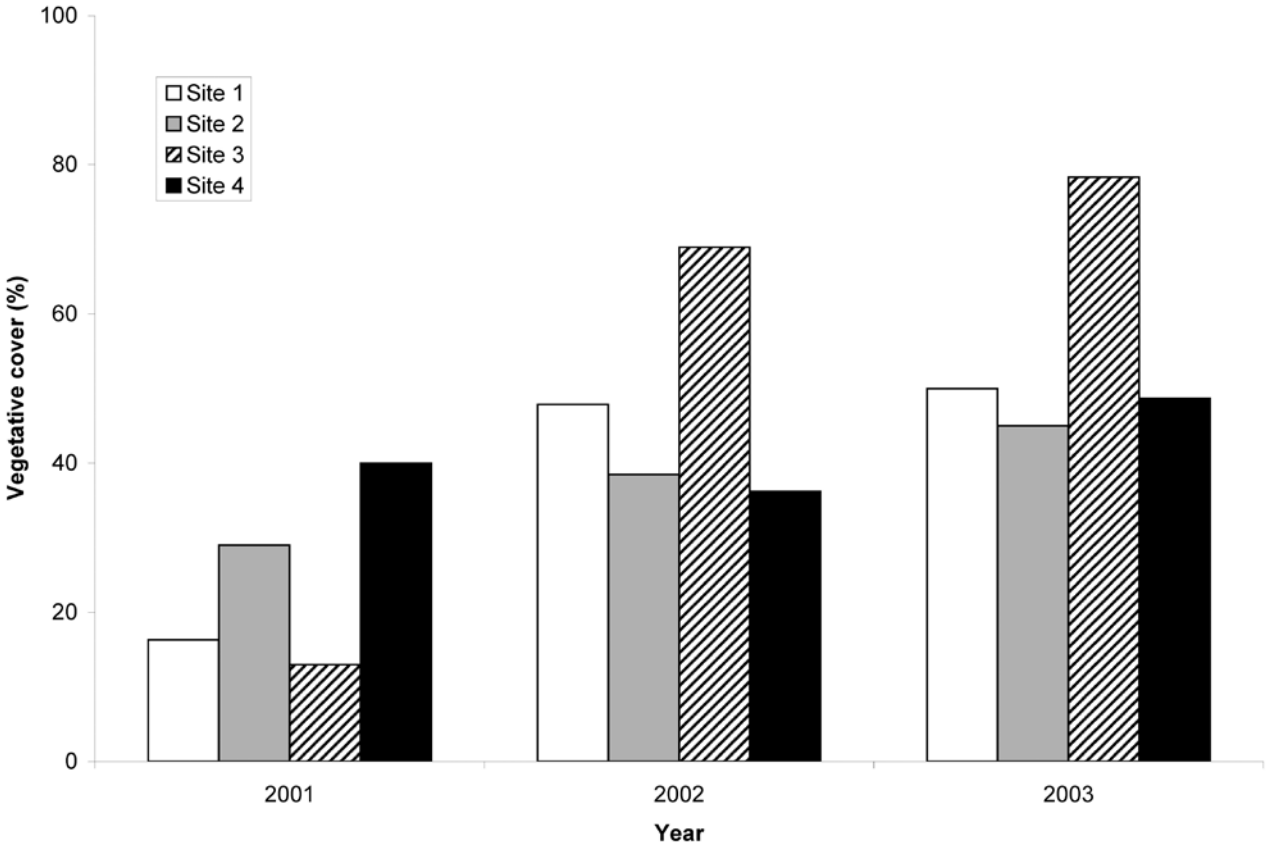

Figure 3—Mean vegetative cover by year and site. We used the grid method with half the plots in site 2 in post-fire year 1 and all the plots in post-fire year 3. All other data were from ocular estimates.

produced the greatest sediment yields in the study (table 3). This was probably because site 2 experienced the greatest I_{10} values in the first year (75 mm hour^{-1} [3.0 inch hour^{-1}]) (table 3). Lower rainfall intensities in the other sites generally produced lower sediment yields (table 3, figure 4), although none of these differences was statistically significant. For example, site 3, which had the lowest sediment yields, had the smallest maximum I_{10} value each year and the greatest amount of vegetative cover in post-fire years 2 and 3. The increase in annual sediment yields with increasing maximum I_{10} values (figure 4) was consistent with other research conducted in this region (Robichaud and others 2008a,b).

Although the measured I_{10} values at site 3 were the lowest of all sites for each year, the maximum measured value at this site in post-fire year 1 had a 10-year return period and the maximum values in post-fire years 2 and 3 had 2-year return periods (Miller and others 1973). In some areas of the western United States such as central Montana, the Colorado Front Range, and eastern California, storms with return periods of two or more years produced substantially more sediment than those in the current study (see Fridley, Hayman, and Cannon sites in Robichaud and others 2008b). But comparably sized storms in the Bitterroot Valley produced similar sediment yields to those in this study (see Valley Complex site in Robichaud and others 2008b).

Despite our observations of high vegetative cover and low sediment yields in site 3 in post-fire years 2 and 3, the vegetative cover data do not explain the site variability in sediment yields in this study. Also, soil water repellency does not correlate with the sediment yield data as might be expected. There probably were subtle site differences (for example, in pre- or post-fire soil condition, rainfall intensity, or non-vegetative and vegetative cover) within and among the sites that led to the large variability in sediment yields. However, of the measured factors, only increases in I_{10} resulted in increased sediment yields (figure 4). It may be that the impact of the I_{10} overshadowed the impact of other measured factors.

Table 3—Total rainfall, I_{10}, I_{30}, and mean sediment yields by date and site for rain events that produced sediment. The maximum I_{10}, maximum I_{30}, and total sediment yield are shown for each year and site in the summary line. Different letters in the summary rows represent significant differences in annual site sediment yields among sites and years using LSMeans with a Tukey-Kramer adjustment ($\alpha = 0.05$). "n/a" indicates data are not available. Standard deviations are shown in parentheses for individual events.

		Rainfall (mm)				I_{10} (mm hr^{-1})				I_{30} (mm hr^{-1})				Sediment yield (Mg ha^{-1})			
Date	**Site**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
27 Jun 2001		9.1	n/a	n/a	n/a	13.7	n/a	n/a	n/a	6.1	n/a	n/a	n/a	0.02 (0.03)	0 (0)	0 (0)	0 (0)
14 Jul 2001		17.0	0	0	4.8	24.4	0	0	10.7	12.2	0	0	3.6	0.09 (0.06)	0 (0)	0 (0)	0.01 (0.003)
15 Jul 2001		4.6	20.1	15.2	1.0	16.8	74.7	18.3	3.0	8.6	35.0	10.7	2.0	0.02 (0.01)	26 (17)	0.03 (0.02)	0.01 (0.004)
20 Jul 2001		30.2	13.0	25.9	20.6	73.2	73.2	50.3	64.0	29.5	25.9	23.4	39.1	10 (n/a)[a]	21 (17)	0.1 (0.2)	6 (4)
29 Jul 2001		29.5	11.1	30.7	34.8	6.1	19.5	6.1	10.7	4.6	11.0	4.6	8.6	0.07 (0.01)	0.3 (0.2)	0.1 (0.1)	0.5 (0.3)
5 Sep 2001		37.8	11.7	32.0	16.5	6.1	4.6	4.6	9.1	4.6	4.1	3.6	5.6	0.06 (0.08)	0 (0)	0.003 (0.006)	0 (0)
Post-fire year 1 summary						-----Maximum I_{10} in 2001----				----Maximum I_{30} in 2001----				----------Total sediment in 2001----------			
						73.2	74.7	50.3	64.0	29.5	35.0	23.4	39.1	10 ab	47 acde	0.3 cdf	6.5 abc
7 May 2002		4.1	19.8	2.3	3.0	4.6	n/a	3.0	4.6	3.6	n/a	1.0	3.0	0 (0)	0.3 (0.4)	0 (0)	0 (0)
19 Jul 2002		25.7	n/a	14.7	21.1	65.5	n/a	33.5	86.9	45.7	n/a	25.9	40.6	2 (2)	1 (2)	0.03 (0.03)	0.7 (1)
6 Aug 2002		0	31.0	0	6.8	0	n/a	0	6.1	0	n/a	0	4.6	0 (0)	22 (16)	0 (0)	0 (0)
15 Aug 2002		4.3	0	0	0	25.9	n/a	0	0	8.6	n/a	0	0	1 (2)	0 (0)	0 (0)	0 (0)
Post-fire year 2 summary						-----Maximum I_{10} in 2002-----				----Maximum I_{30} in 2002----				----------Total sediment in 2002----------			
						65.5	88.4	33.5	86.9	45.7	39.6	25.9	40.6	3 abcd	23 abcde	0.03 eg	0.7 cdef
1 Apr 2003		17.5	n/a	15.5	15.5	21.3	n/a	15.2	19.8	16.8	n/a	14.2	15.2	0.2 (0.1)	0 (0)	0.2 (0.1)	0 (0)
30 May 2003		14.5	n/a	14.0	13.7	44.2	n/a	39.6	44.2	15.7	n/a	13.7	15.2	0.1 (0.1)	1 (1)	0.03 (0.05)	0.2 (0.4)
3 Aug 2003		8.1	45.5	35.8	7.9	27.4	15.2	29.0	12.2	11.7	5.6	12.2	5.6	0 (0)	0.2 (0.1)	0.07 (0.1)	0 (0)
22 Aug 2003		10.7	9.7	9.9	58.9	12.2	9.1	13.7	47.2	6.1	7.6	7.1	20.3	0 (0)	0 (0)	0 (0)	0.06 (0.1)
Post-fire year 3 summary						-----Maximum I_{10} in 2003-----				----Maximum I_{30} in 2003----				----------Total sediment in 2003----------			
						44.2	15.2	39.6	47.2	16.8	7.6	14.2	20.3	0.3 cdef	1.2 bfg	0.3 cdf	0.3 def

[a] Data obtained from one silt fence; standard deviation could not be calculated.

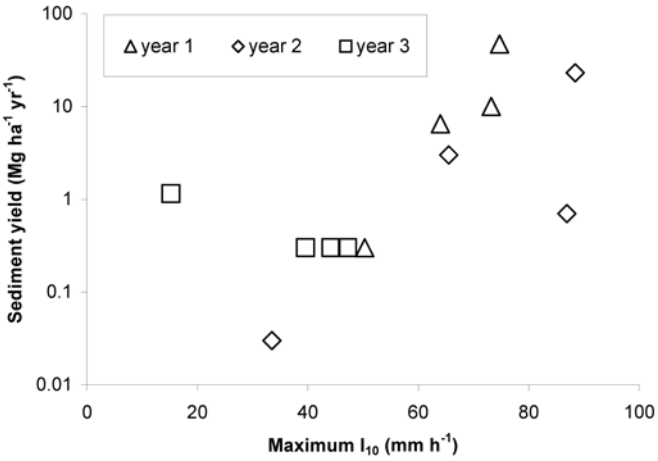

Figure 4—Average annual sediment yield for each site versus 10-minute maximum rainfall intensity (I_{10}) for post-fire years 1 to 3 (2001 to 2003).

Conclusions

In the four high burn severity sites, the first post-fire year erosion rates had a median value of 8 Mg ha^{-1} (3.6 ton acre^{-1}) and ranged from 0.3 to 47 Mg ha^{-1} (0.1 to 21 ton acre^{-1}). In the second post-fire year, the median sediment yield from the four sites was 2 Mg ha^{-1} (0.9 ton acre^{-1}). Although this was a 75 percent decline from the first year, this change was not statistically significant because of the high variability in sediment yields within and among sites. The median sediment yield dropped again in the third post-fire year to 0.3 Mg ha^{-1} (0.1 ton acre^{-1}), which was 85 percent less than the second post-fire year, and was a significant decline from the first post-fire year sediment yields in three of the four study sites.

In the first two post-fire years, the annual sediment yields increased with increasing maximum I_{10}. Although not rigorously tested, we found no relationship between sediment yield and other measured or observed factors, including vegetative cover and soil water repellency.

Management Implications

Knowledge and prediction of post-fire effects influence a myriad of management decisions after wildfire, from immediate stabilization treatment prescriptions developed by Burned Area Emergency Response (BAER) teams to long-term planning for future watershed management and resource use. This study corroborates other post-wildfire studies conducted in forested areas of the western United States that indicate that rainfall intensity is one of the key factors behind post-fire hillslope erosion, and that hillslope erosion during the first post-fire year can be on the order of 10 Mg ha^{-1} yr^{-1} (4 ton acre^{-1} yr^{-1}).

These results indicate that the erosion risk after a wildfire is greatest for the first two post-fire years. Also, the magnitude of that risk may be influenced by the rainfall intensity and the number of post-fire years. However, depending on what lies downstream of the burned area, even the erosion rates we measured in post-fire year 3 may be well above tolerable levels.

Our data may be useful for predicting wildfire effects in western Montana. For example, the site characteristics described in this study, such as changes in soil water repellency over time, can be used to select appropriate input parameters for post-fire hydrologic and/or erosion models. In addition, our reported sediment yields can be directly compared to model predictions to confirm the validity of those predictions before using the models for post-fire treatment decisions.

Because wildfires commonly occur in western Montana, land managers must consider the potential wildfire effects in any long-range planning process. The post-fire responses reported in this study, combined with other regional data, can assist in land management decisions such as fuel reduction treatments, fire suppression, and wildland fire use.

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