HYDROLOGICAL PROCESSES
Hydrol. Process. **21**, 998–1005 (2007)
Published online 27 February 2007 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/hyp.6295

First-year post-fire erosion rates in Bitterroot National Forest, Montana†

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Abstract:

Accelerated runoff and erosion commonly occur following forest fires due to combustion of protective forest floor material, which results in bare soil being exposed to overland flow and raindrop impact, as well as water repellent soil conditions. After the 2000 Valley Complex Fires in the Bitterroot National Forest of west-central Montana, four sets of six hillslope plots were established to measure first-year post-wildfire erosion rates on steep slopes (greater than 50%) that had burned with high severity. Silt fences were installed at the base of each plot to trap eroded sediment from a contributing area of 100 m^2. Rain gauges were installed to correlate rain event characteristics to the event sediment yield. After each sediment-producing rain event, the collected sediment was removed from the silt fence and weighed on site, and a sub-sample taken to determine dry weight, particle size distribution, organic matter content, and nutrient content of the eroded material. Rainfall intensity was the only significant factor in determining post-fire erosion rates from individual storm events. Short duration, high intensity thunderstorms with a maximum 10-min rainfall intensity of 75 mm h^{-1} caused the highest erosion rates (greater than 20 t ha^{-1}). Long duration, low intensity rains produced little erosion (less than 0·01 t ha^{-1}). Total C and N in the collected sediment varied directly with the organic matter; because the collected sediment was mostly mineral soil, the C and N content was small. Minimal amounts of Mg, Ca, and K were detected in the eroded sediments. The mean annual erosion rate predicted by Disturbed WEPP (Water Erosion Prediction Project) was 15% less than the mean annual erosion rate measured, which is within the accuracy range of the model. Published in 2007 by John Wiley & Sons, Ltd.

KEY WORDS hillslope erosion; forest fire; silt fences; WEPP; rainfall intensity; water repellency; site productivity

Received 15 June 2005; Accepted 3 November 2005

INTRODUCTION

In the past decade, wildfires have become an important public concern, especially in the western United States, owing to the severity of recent wildfire seasons and the impacts on resources (loss of water quality, degradation of municipal water supplies, destruction of homes and other structures, etc.). Public and private landowners have increased their efforts to mitigate potential post-fire impacts that stem from fire-induced changes in ground surface, soil properties, and hydrology (Swanson, 1981).

Fire impacts on hillslope hydrology

The extent to which wildfires impact a landscape is a function of burn severity, fire intensity, burn area, topography, soil properties, climate, and channel proximity (Baker, 1988; Beschta, 1990; DeBano *et al.*, 1998; Robichaud, 2000). Fires can reduce soil infiltration capacity and increase runoff and erosion. The magnitude of post-fire increases of runoff and erosion is highly sensitive to the extent of fire-induced soil disturbances, such as decreased soil organic matter (OM), weakened stability of soil aggregates, loss of interceptive vegetation, reduced hydraulic roughness, and formation of water repellent soil conditions (Morris and Moses, 1987; Robichaud, 2000; Shakesby *et al.*, 2000). Because fires increase the amount of bare soil exposed to raindrop impact and overland flow, raindrops striking the soil surface break down soil structure and increase sediment loss (McNabb and Swanson, 1990; Robichaud and Waldrop, 1994; DeBano *et al.*, 1998; DeBano, 2000; Robichaud, 2000).

Several studies have documented the variability of post-wildfire erosion in various environments. Rich (1962) and Campbell *et al.* (1977) reported erosion rates as high as 12 t ha^{-1} after a coniferous forest wildfire in Arizona, and Megahan and Molitor (1975) reported erosion rates of 120 t ha^{-1} after a wildfire in central Idaho. Robichaud and Waldrop (1994) measured the erosion rate at just over 2 t ha^{-1} for a rain event with a peak 10-min rainfall intensity (I_{10}) of approximately 89 mm h^{-1} in South Carolina. Robichaud and Brown (2000) found first-year erosion rates to be as high as 2·5 t ha^{-1} on a 60% slope burned at high severity in eastern Oregon.

Mechanisms of nutrient loss

Ecosystem productivity is dependent upon the continual cycling of the nutrients required for plant growth (DeBano *et al.*, 1998), mainly nitrogen (N), potassium

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(K), calcium (Ca), and magnesium (Mg) (Pyne *et al.*, 1996). Nitrogen has the potential to affect site productivity more than any other nutrient (Maars *et al.*, 1983) and is often measured to track site productivity changes. Reports regarding actual N responses to fire are conflicting; some studies show increases in N while others show losses (DeBano *et al.*, 1998).

Organic matter within the soil, which facilitates nutrient retrieval and storage (Harvey *et al.*, 1989), can be rapidly combusted during fires. McNabb and Cromack (1990) found that the degree to which OM and nutrient concentrations are affected by fire is a function of fire intensity, burn time, antecedent OM concentrations, nutrient cycling mechanisms, and changes in soil biota. The loss or gain of nutrients owing to forest fires have been attributed to a variety of mechanisms including leaching, volatilization, and erosion: DeBell and Ralston (1970); Grier (1975); Clayton (1976); Stark (1977); Little and Ohmann (1988); DeBano (1990); Robichaud *et al.* (1994); Robichaud and Brown (2000); Newland and DeLuca (2000). However, few studies have focussed on the effects of fire on nutrient losses that are transported in sediment, as opposed to dissolved in the runoff, from smaller upland watersheds (DeBano *et al.*, 1998).

Valley Complex Fires

Beginning in 1998, a recurrent weather phenomenon known as La Niña began to affect weather patterns of the western United States (USDA Forest Service, 2000). A direct consequence of this system was below normal precipitation (summer and winter) in 1999. As a result, moisture levels in forest fuels decreased during the summer of 1999 and remained low into the following year. Precipitation was below normal for a 7-month period starting in February 2000 and, when exacerbated by high summer temperatures, the understory vegetation wilted and leaves/needles were shed onto an already dry forest floor. Frequent lightning storms and lack of moisture were responsible for most of the July 2000 Valley Complex Fires in the Bitterroot Valley (USDA Forest Service, 2000).

Approximately 20% (144 000 ha) of Bitterroot National Forest burned in the Valley Complex fires of 2000. Roughly one-third of the burned area was classified as having burned with high severity (Richardson, 2001), which meant that all duff was consumed and 70–100% of the trees were killed directly by fire or indirectly owing to a fire-weakened structure that was more susceptible to disease and/or insect infestation (Monnig *et al.*, 2000).

These fires provided an opportunity to measure post-wildfire hillslope erosion to further understand fire effects and validate post-disturbance erosion modelling efforts. After the Valley Complex fires of 2000, first-year post-fire erosion rates were measured on a rain event by rain event basis. The specific objectives were to (a) directly measure first-year erosion rates on steep hillslopes that had burned with high severity, (b) test the significance of the selected site and rainfall parameters on post-fire erosion rates, (c) measure OM and nutrient concentrations in the eroded sediments, and (d) compare the measured erosion rates with the predictions generated by the disturbed Water Erosion Prediction Project (WEPP) model (Elliot *et al.*, 1999).

METHODS

Fuel moisture content, rate of spread of fire, and wind velocity were used to calculate the burning index value for a specific day and location (Chandler *et al.*, 1983). Using the burning index, four study sites were located roughly within a 10 km^2 area in high burn severity areas as designated by both the burning index and the burn severity map produced for the Burned Area Emergency Response (BAER) team (Figure 1). All four sites were on steep slopes (50–62%) (Table I) with a dominant pre-fire overstory of ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) and understory of pinegrass (*Calamagrostis rubescens*), white spiraea (*Spiraea betulifolia*), and showy aster (*Aster spectabilis*). The soil at Sites 1, 3, and 4 was classified as *sandy-skeletal, mixed, frigid, typic haplustalf* with a parent material of granitic colluvium; however, Site 2 soil was classified as *loamy-skeletal, mixed, typic, superactive argiustoll* with a parent material of igneous/metasedimentary colluvium (Soil Survey Staff, 1999).

Sediment collection

A total of 24 plots, six in each site, were established, and following Robichaud and Brown (2002), silt fences (5 m long and approximately 0·5 m high) were installed at the base of each plot to collect eroded sediment from the plot. Silt fences allow water to pass through the mesh (0·03–0·08 cm) and have a documented trapping efficiency of 68 to 93% (Barrett *et al.*, 1998; Robichaud *et al.*, 2001; Robichaud and Brown, 2002). The plot contributing area was defined by a hand-dug trench (20 cm wide by 25 cm deep, diagonal to the contour) located 20 m upslope from the silt fence. This trench at the uphill edge of the plot collects eroded sediment coming from above the plot and diverts runoff beyond the side edges of the plot. The individual contributing areas of each plot (100 m^2, 0·01 ha) provided a total hillslope study area of approximately 1·0 ha in each of the four sites. After each sediment-producing rain event, the collected sediment was removed from the deposition

Table I. The burn index and mean values for slope and ground cover by site. Different letters within a column indicate significant differences at $\alpha = 0{\cdot}05$

Site	Burn index	Slope (%)	Ground cover (%)
1	74a	62a	16a
2	76a	54ab	29b
3	74a	58ab	13a
4	76a	50b	40b

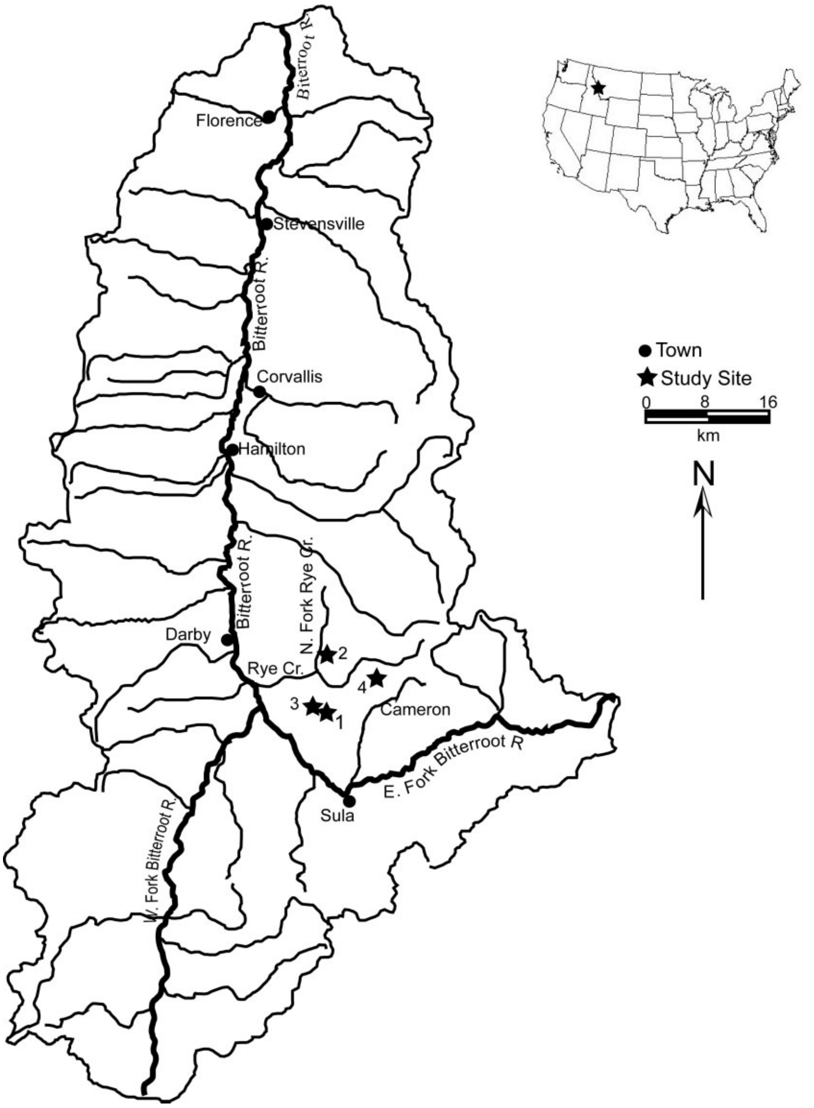

Figure 1. Map of a portion of the Bitterroot River valley with the four erosion monitoring sites identified

areas behind the silt fences and weighed. A sample of the collected sediment was taken for laboratory analysis and the non-sampled portion was discarded on site.

A tipping bucket rain gage with a data logger was installed at each of the four study sites to correlate rainfall characteristics with sediment yield. Rain events were separated by a 6-h period with no rainfall. Total rainfall duration, the 10-min and 30-min maximum rainfall intensities (I_{10} and I_{30}, respectively), and rainfall erosivity were calculated for each rain event.

Laboratory analyses of eroded sediment

Sediment samples taken from deposits behind each silt fence were evaluated for particle size distribution, OM content, and nutrient content. Additionally, the sediment samples were oven dried to calculate the dry weight correction factor to be applied to all trapped sediments. A vacuum pipetting system was used in the particle size analyses as described by Das (1985). Percent OM was calculated by loss on ignition following the method of Smith and Atkinson (1975). Total C and total N were determined with a Leco CN-2000 Dry Combustion Analyzer (Wright and Bailey, 2001). Cation concentrations were found using the ammonium acetate (pH 7) method of extraction (Sumner and Miller, 1996).

Ground cover

At three of the plots, ground cover estimates were made using a 1-m^2 point frame with wire intersections at 10-cm intervals (i.e. 81 intersections per frame). Using this 81-point frame, ground cover was characterized at each wire intersection within the frame and repeated at five random locations within a plot contributing area, for a total of 405 observations. The measured values were used to calibrate the ocular estimates, which were replicated 5 times for each of the remaining 21 plots by a single observer.

Water repellent soil

Two configurations of the Water Drop Penetration Time (WDPT) test (DeBano, 1981) were performed to evaluate the severity, thickness, and depth of water repellent soils within the study sites. Four 1-m^2 sampling areas adjacent to each plot were tested at the soil surface (with the ash removed) and at depths of 1, 2, 3, 4, and 5 cm. In one configuration, two water drops were placed side-by-side using a 0·5-l squeeze bottle at four random locations within the 1-m^2 sampling area. This was repeated at all six depths. In an effort to determine the lateral extent of water repellency, the second configuration placed one drop of water every 2 cm along a 40-cm transect that was randomly located within the sample area and repeated at all six depths. For both configurations, the time for the water drop to infiltrate the soil was determined from 0 to 300 s, and the WDPT was classified as none (0–5 s), slight (6–60 s), moderate (61–180 s), and severe (more than 180 s). Any WDPT over 5 s is considered water repellent, and the longer the WDPT time, the greater the degree of water repellency (DeBano, 1981; Dekker and Ritsema, 1994; Robichaud and Hungerford, 2000). Given the lack of a discernable relationship among the WDPTs in the trench configuration, each WDPT test from both configurations was considered an independent measurement of soil water repellency at that location. The 28 measurements per depth per sample area resulted in a total of 672 measurements adjacent to each plot. These data were used to calculate the percentage of water repellent soil within each sampling area, which was used as an estimate of the water repellent soil within each plot.

Statistical analyses

A stepwise linear regression (S-Plus Professional, 1999) was performed for each storm to determine the significance of the following independent variables: I_{10}, ground cover, slope steepness, and water repellent soil. The event erosion rate, which was a dependent variable, was log-transformed to obtain a more normal distribution. A separate variance t-test (Ott, 1993) was used to determine the significance of ground cover, water repellent soil conditions, and sediment OM and nutrient content on erosion rates.

Rainfall intensities were not the same at the four sites for any given storm, thus, no direct statistical tests could be made regarding similarities or differences between erosion rates from the four sites or between the 24 individual plots. In order to assist comparisons, a rainfall erosivity weighted (REW) erosion rate was calculated by dividing the erosion rate (t ha^{-1}) by the rainfall erosivity (Mj-mm ha-h^{-1}) to provide a rainfall erosivity-normalized erosion rate (t-h Mj-mm^{-1}). This value permitted direct comparisons of erosion rates between and within research sites.

Model predicted erosion

The USDA Forest Service Disturbed WEPP model was run using high severity burned site characteristics with measured ground cover, slope, and soil type from each of the 24 plots (Elliot *et al.*, 1999). To adjust the climate for site locations, the Parameter-Regressions on Independent Slopes Model (PRISM) was used to generate climatic events based on latitude, longitude, and elevation (Daly *et al.*, 1997). Predicted annual erosion amounts calculated by the Disturbed WEPP model are based on probable rain events of five different return intervals: 2·5, 5, 10, 25, and 50 years. Methods described by Miller *et al.* (1973) and Arkell and Richards (1986) were used to calculate recurrence intervals for rain events that occurred in the study area during the summer of 2001. A 25-year event closely matches the rainfall intensities observed; therefore, the 25-year recurrence interval results were used to compare observed and predicted erosion rates at each plot. Plot predictions and observations were combined to compare sites and the study area as a whole.

RESULTS AND DISCUSSION

Rainfall intensity and erosion rates

Hillslope erosion rates increase by orders of magnitude as rainfall intensity increases; consequently, erosion rates were log-transformed to obtain a normal distribution. The maximum 10-min rainfall intensity (I_{10}) was the only significant variable, and accounted for 75% of the variance in the logarithm of the first-year post-fire erosion rate ($\alpha = 0{\cdot}01$). A linear relationship exists between the logarithm of erosion rate and I_{10}, as described by the following equation:

$$\mathrm{ER}_{\log} = 0{\cdot}04\ \mathrm{I}_{10} - 2{\cdot}0 \quad (1)$$

$$R^2 = 0{\cdot}76,\ n = 72$$

where $\mathrm{ER}_{\log}$ is the logarithm of the erosion rate (t ha^{-1}) and I_{10} = maximum 10-min rainfall intensity (mm h^{-1}) (Figure 2).

The first substantial rain event occurred on 15 Jul 01. Site 2 had an I_{10} of 78 mm h^{-1}, which was 4 to 12 times greater than the I_{10}'s at Sites 1, 3, and 4 for the same storm (Table II). Site 2 had the maximum observed event erosion rate (81·7 t ha^{-1}) and a mean event erosion rate of 38·3 t ha^{-1} (Figure 3); whereas, Sites 1, 3, and 4 had mean event erosion rates of less

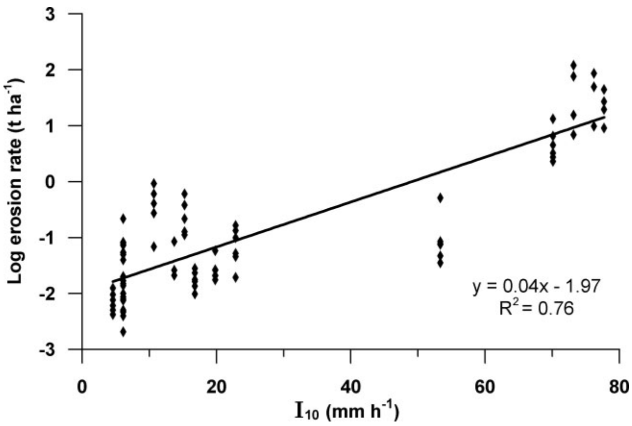

Figure 2. Log-transformed erosion rate verses I_{10} showing two orders of magnitude increase in erosion rates with high intensity rainfall

Table II. I_{10}, I_{30}, total rainfall, rainfall duration, and rainfall erosivity by site for three major rainfall events in 2001. Mean erosion rates, minimum and maximum erosion rates, and mean REW erosion rate by site for each rain event

Rainfall event (date)	Site	I_{10} (mm h^{-1})	I_{30} (mm h^{-1})	Total rainfall (mm)	Rainfall duration (min)	Rainfall erosivity (Mj-mm ha-h^{-1})	Erosion rate			Mean REW[a] erosion rate (t-h Mj-mm^{-1})
							Mean (t ha^{-1})	Min. (t ha^{-1})	Max. (t ha^{-1})	
15 Jul	1	16·8	8·6	4·8	—[b]	52·8	0·02	0·01	0·03	0·000
	2	77·7	35·6	20·1	66	218·5	38·3	9·14	81·7	0·176
	3	19·2	11·4	5·3	84	69·9	0·03	0·02	0·06	0·000
	4	6·1	2·0	3·1	701	12·3	0·01	0·00	0·01	0·001
20 Jul	1	76·2	29·5	14·7	54	181·0	30·1	9·80	49·9	0·166
	2	73·2	25·9	13·0	19	159·0	24·3	6·93	76·7	0·153
	3	53·3	23·4	12·2	70	143·6	0·14	0·04	0·51	0·001
	4	70·1	39·1	20·6	103	239·9	5·44	2·31	13·3	0·023
30 Jul	1	6·1	4·6	29·5	2146	28·2	0·07	0·05	0·08	0·002
	2	15·2	5·6	27·9	1060	34·0	0·26	0·11	0·60	0·008
	3	6·1	5·1	30·7	2476	31·3	0·01	0·00	0·02	0·000
	4	10·7	8·6	34·8	2165	52·7	0·48	0·07	0·93	0·009

[a] REW = rainfall erosivity weighted.
[b] —indicates these data are not available.

Figure 3. Photograph of 800 kg of eroded sediment trapped in the silt fence at Site 2-plot A after the 15 Jul 01 rain event

than 0·03 t ha^{-1} (Table II). It was not feasible to reach each site immediately after the 15 Jul 01 rain event, and additional rainfall was recorded at Sites 3 and 4. The I_{10}'s for this additional event were of lower magnitude (3–12 mm h^{-1}) than the 15 Jul 01 event. Combined sediment yields from both rain events were used to calculate the event erosion rates for Sites 3 and 4.

A second major rain event occurred on 20 Jul 01 and produced I_{10}'s between 53 and 76 mm h^{-1} at all four sites and was followed by a rain event of weaker magnitude (I_{10}'s of 15 to 40 mm h^{-1}) the following day. The combined sediment yields resulted in the highest overall mean event erosion rate (15·0 t ha^{-1}) observed during the study. Mean event erosion rates for Sites 1 and 2 (30·1 and 24·3 t ha^{-1}, respectively) were greater than for Sites 3 and 4 (0·14 and 5·4 t ha^{-1}, respectively). The I_{10}'s for Sites 1 and 2 (76·2 and 73·2 mm h^{-1}, respectively) were also greater than for Sites 3 and 4 (53·0 and 70·1 mm h^{-1}, respectively). The greater I_{10} at Sites 1 and 2 accounts for the much larger event erosion rates at those sites. However, the I_{10} at Site 4 was similar to Sites 1 and 2 and even had the highest event rainfall erosivity (239·9 Mj-mm ha-h^{-1}) among any site. Yet, the mean event erosion rate was 4 to 5 times less than that for Sites 1 and 2, which is probably due to the higher ground cover (40%) (Table I). Site 3 had the lowest event I_{10} (53 mm hr^{-1}) and significantly ($\alpha = 0{\cdot}01$) more coarse material (greater than 2·0 mm) in surface soils than Sites 1, 2, and 4. Although I_{10} was the only statistically significant measured variable affecting erosion rates, it is likely that other site characteristics moderate the effect of rainfall intensity on erosion rates.

The third major storm occurred on 30 Jul 01 with I_{10}'s ranging from 6·1 to 15·2 mm h^{-1}, with the lowest overall mean I_{10} of the three major rain events; nevertheless, the rain event duration exceeded 24 h and all the sites received greater total rainfall than in either of the previous rain events (Table II). Despite greater rainfall amounts, event erosion rates were less than those generated by the short duration, high intensity storms that occurred on 15 Jul 01 and 20 Jul 01. With higher intensity rain events, a dense network of rills was observed in the plots upslope from the silt fences; however, fewer rills developed after the 30 Jul 01 rain event. During lower intensity rain events, site factors are likely to have a greater influence on the variability of erosion rates, and no single variable accounts for the variability in the erosion rates for the 30 Jul 05 event in this study.

DOI: 10.1002/hyp

Site characteristics and erosion rates

Sites 2 and 4 have significantly greater ($\alpha = 0.01$) estimated ground cover than Sites 1 and 3; however, the average ground cover values were within a range of 13 to 40% (Table I). No significant correlation between ground cover and REW erosion rate was detected; thus, differences in REW erosion rates are not explained by ground cover alone (Figure 4). This supports recent work showing that there must be at least 60% ground cover to have any significant effect on erosion (Robichaud, 2000). Although the mean ground cover for any site did not exceed 40%, Plot D in Site 4 had greater than 80% ground cover, and this plot often had the lowest sediment yield for any rain event. Likewise, plot F in Site 2 had 9% ground cover (as well as highly water repellent soil conditions), and this plot often had the highest event sediment yields.

The occurrence of soil water repellency ranged from 16 to 88% among individual plots, reflecting the spatial variability of this soil condition. The mean depth of the water repellent layer was 11 mm. The mean soil water repellency in Site 1 (58%) was significantly ($\alpha = 0.05$) greater than the mean soil water repellency in Site 2 (36%), but not different from that of Sites 3 (54%) and 4 (52%) (Table III). The degree of soil water repellency at Site 3 was less than at other sites. Site 3 had significantly more 'slight' water repellency than Sites 2 and 4, but less 'moderate' water repellency than Site 4 and less 'severe' water repellency than Site 2 (Table III). Although Site 3 did have the lowest mean REW erosion rate, water repellency, like ground cover, did not account for the differences in REW erosion rates (Figure 4).

In most instances, higher rainfall intensities corresponded to greater erosion rates, and at the highest rainfall intensities the influence of other site variables on erosion rates were masked. The variability of erosion rates generated by lower intensity rainfall was likely determined by many site characteristics, some of which may not have been measured in this study. The conflicting effects of these site characteristics make it difficult to determine the relative impact of any single variable on post-fire erosion. Generally, these findings support the study done by Baker (1988), in which extreme rainfall intensities obscured the effects of ground cover and slope steepness on surface erosion.

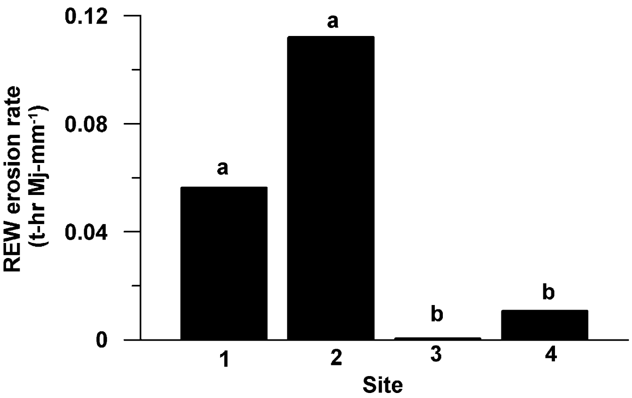

Figure 4. Annual mean rainfall erosivity weighted erosion rates for each site. Values with different letters are significantly different at the $\alpha = 0.01$ level

Organic matter and nutrient content in sediment

The OM analyses showed a significant difference ($\alpha = 0.05$) between Sites 1 and 3 and Sites 2 and 4, with the latter having a greater concentration of post-burn OM in the collected sediment (Table IV). Sites 2 and 4, with 29% and 40% ground cover, had more OM available to be transported in the runoff than Sites 1 and 3 with 16% and 13% ground cover (Table I).

Total N and total C in the sediment were generally proportional to the OM in the sediment, which ranged from 6 to 14% (Table IV). Given the low proportion of organic material in the eroded sediments, total N (the nutrient most closely related to site productivity (DeBano *et al.*, 1998)) was also small (Table IV). For comparison, Robichaud *et al.* (1994) reported 2·8 t ha^{-1} total N in a typical northern Idaho forest soil profile; thus, the amount of total N (0·001–0·1 t ha^{-1}) in the eroded sediments is likely to have minimal impact on site productivity. The

Table IV. Mean organic matter (OM) in the eroded sediments and mean annual nutrient losses through erosion by site for 2001. Different letters within a column indicate significant differences at $\alpha = 0.05$

Site	OM (%)	Total N (t ha^{-1})	Total C (t ha^{-1})	Mg (t ha^{-1})	Ca (t ha^{-1})	K (t ha^{-1})
1	6·6a	0·1	0·9	0·01	0·1	0·03
2	8·1b	0·05	0·9	0·01	0·2	0·03
3	5·5a	0·001	0·01	0·00004	0·002	0·0002
4	14·0b	0·04	0·6	0·005	0·1	0·01

Table III. Water repellent soils detected at each site were classified by degree using the WDPT test: slight (5–60 s); moderate (1–3 min); and severe (3–5 min). The proportion of non-water repellent (less than 5 s) soil and mean depth of the water repellent layer (greatest degree of water repellency) are also indicated. Different letters within a column indicate significant differences at $\alpha = 0.05$

Site	Non-water repellent soil (%)	Water repellent soil (%)	Degree of water repellency			Depth of water repellent layer (mm)
			Slight (%)	Moderate (%)	Severe (%)	
1	42a	58a	47ab	26ab	27ab	12a
2	64b	36b	24b	27ab	50a	9a
3	48ab	52ab	69a	15b	17b	9a
4	46ab	54ab	31b	34a	35ab	13a

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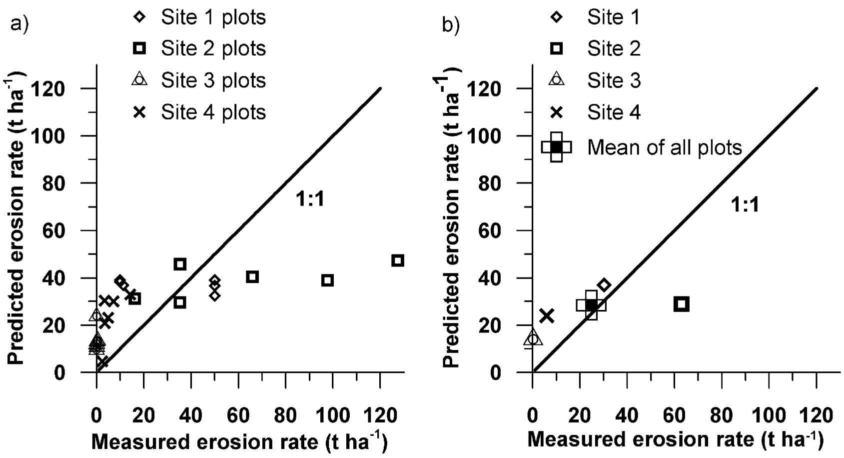

Figure 5. Comparison of disturbed WEPP model predictions and measured annual post-fire erosion rates by (a) individual plots and (b) by site mean, with a 1 : 1 line indicated. Also, the predicted and measured overall (24 plots) mean annual erosion rate is indicated in (b)

losses of major cations (Mg, Ca, and K) in the eroded sediment were negligible (Table IV).

Disturbed WEPP model comparison

Using field data for each site, as well as the soil type and climate data (generated by CLIGEN using historical climate data) from the WEPP model database, the model estimates of mean annual erosion for each plot were compared to the measured annual erosion from each plot (Figure 5a). When each plot was modelled separately, only Site 1 was within the model error range. Disturbed WEPP over-predicts the erosion from low intensity rain events and under-predicts the erosion from high intensity rain events (Figure 5a). Accuracy of model predictions is not improved when combined by site; however, when all 24 plots are combined, the mean annual predicted erosion rate for the study area (28·4 t ha^{-1}) is within 15% of the mean annual measured erosion rate (24·8 t ha^{-1}) (Figure 5b). Spatial variability in site conditions, such as ground cover and water repellency, are not accurately reflected in this model; thus, model predictions compared more closely to measured results when hillslope plots were averaged.

CONCLUSION

On the basis of direct measurements of hillslope erosion, 75% of the variance in first-year post-fire erosion rates was accounted for by I_{10}. When I_{10}'s were greater than 70 mm h^{-1}, the influence of other site characteristics such as ground cover, water repellent soil conditions, and slope steepness were obscured. Although none of these site characteristics were statistically significant, the data suggest that these site variables did influence the observed erosion rates at lower I_{10}'s (near 25 mm h^{-1}). Because site characteristics have a combined effect on erosion rates, it was difficult to identify the individual effect of any single variable. Nonetheless, these results indicate that rainfall intensity is the driving factor for the first-year post-fire erosion.

Nutrient losses through erosion, which were proportional to sediment losses, were small. Even with high intensity rain events that produced substantial erosion, site productivity was not adversely affected by post-fire erosion.

Predicting the spatial and temporal variability of post-fire erosion rates is a complex task. The Disturbed WEPP model provided reasonable first post-fire year annual erosion predictions when the measured results were averaged over a large area, but not at the scale of individual plots. These results reflect the need for an erosion prediction tool that accommodates spatial variability of the factors affecting hillslope erosion.

ACKNOWLEDGEMENTS

The authors wish to thank the following for financial support of this project: USDA Forest Service, Rocky Mountain Research Station; USDI Bureau of Land Management Joint Fire Science Program; Grant-in-Aid of Research from Sigma Xi, The Scientific Research Society; University of Wisconsin-Madison Department of Geography; and Bitterroot National Forest. Also, fieldwork assistance provided by personnel from Rocky Mountain Research Station and Bitterroot National Forest is greatly appreciated. The authors wish to thank Dr William Elliot, Sarah Lewis, Joseph Wagenbrenner, Dr James C. Knox, Louise Ashmun, and three anonymous reviewers for their comments and suggestions on earlier drafts of this manuscript.

REFERENCES

Arkell RE, Richards F. 1986. Short duration rainfall relations for the western United States. *Climate and Water Management-A Critical Era and Conference on the Human Consequences of 1985's Climate*. American Meteorological Society: Asheville, NC, Boston, MA; 136–141, August 1986, 4–7.

Baker M Jr. 1988. Hydrologic and water quality effects of fire. *Conference on Effects of Fire Management of Southwestern Natural Resources*, Krammes JS (Tech coor). November 1988, 15–17, Tucson, AZ. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station: Fort Collins, CO; 31–42.

Barrett ME, Malina JF Jr, Charbeneau RJ. 1998. An evaluation of geotextiles for temporary sediment control. *Water Environment Research* **70**(3): 283–290.

Beschta RL. 1990. Effects of fire on water quantity and quality. In *Natural and Prescribed Fire in Pacific Northwest Forests*, Walstad JD, Radosevich SR, Sandberg DV (eds). Oregon State University Press: Corvallis, OR; 219–232.

Campbell RE, Baker MB Jr, Ffolliott PF. 1977. *Wildfire Effects on a Ponderosa Pine Ecosystem: an Arizona Case Study*, *USDA Forest Service Research Paper RM-191*. Rocky Mountain Forest and Range Experiment Station: Fort Collins, CO; 12.

Chandler C, Cheney P, Thomas P, Trabaud L, Williams D. 1983. *Fire in Forestry: Forest Fire Behavior and Effects, I*. John Wiley and Sons: New York; 450.

Clayton JL. 1976. Nutrient gains to adjacent ecosystems during a forest fire: an evaluation. *Forest Science* **22**: 162–166.

Daly C, Taylor G, Gibson W. 1997. The PRISM approach to mapping precipitation and temperature. *Procedures of 10th Conference on Applied Climatology*. American Meteorological Society: Reno, NV; 10–12.

Das BM. 1985. *Principles of Geotechnical Engineering*. PWS Publishers: Boston, MA; 571.

DeBano LF. 1981. *Water Repellent Soils: A State of the Art*, *USDA Forest Service Research Paper PSW-46*. Pacific Southwest Forest and Range Experiment Station: Berkeley, CA; 21.

DeBano LF. 1990. The effects of fire on soil properties. In *Symposium on Management and Productivity of Western-montane Forest Soils*, Boise, ID; 151–156.

DeBano LF. 2000. The role of fire and soil heating on water repellency in wildland environments: a review. *Journal of Hydrology* **231–232**: 195–206.

DeBano LF, Neary DG, Ffolliott PF. 1998. *Fire's Effects on Ecosystems*. John Wiley and Sons: New York; 333.

DeBell DS, Ralston CW. 1970. Release of nitrogen by burning light forest fuels. *Soil Science Society of America Proceedings* **34**: 936–938.

Dekker LW, Ritsema CJ. 1994. How water moves in a water repellent sandy soil. *Water Resources Research* **30**(9): 2507–2517.

Elliot WJ, Hall DE, Scheele DL. 1999. *Disturbed WEPP: WEPP Interface for Disturbed Forest and Range Runoff, Erosion and Sediment Delivery, [v.99·5 online] USDA Forest Service*. Rocky Mountain Research Station: Moscow; http://forest.moscowfsl.wsu.edu/engr/software.html, [accessed 30 September 2005].

Grier CC. 1975. Wildfire effects on nutrient distribution and leaching in a coniferous ecosystem. *Canadian Journal of Forest Research* **5**: 599–607.

Harvey AE, Jurgensen MF, Graham RT. 1989. Fire-soil interactions governing site productivity in the Northern Rocky Mountains. In *Prescribed fire in the intermountain region: forest site preparation and range improvement*, Baumgartner D (ed.). Washington State University: Pullman, WA; 9–18.

Little SN, Ohmann JL. 1988. Estimating nitrogen lost from forest floor during prescribed fires in Douglas-fir/Western Hemlock clearcuts. *Forest Science* **34**: 152–164.

Maars RH, Roberts RD, Skeffinton RA, Bradshaw AD. 1983. Nitrogen in the development of ecosystems. In *Nitrogen as an Ecological Factor*, Lee JA, McNeill S, Rorison IH (eds). Blackwell Science Publishing: Oxford; 131–137.

McNabb DH, Cromack K Jr. 1990. Effects of prescribed fire on nutrients and soil productivity. In *Natural and Prescribed Fire in Pacific Northwest Forests*, Walstad JD, Radosevich SR, Sandberg DV (eds). Oregon State University Press: Corvallis, OR; 125–142.

McNabb DH, Swanson FJ. 1990. Effects of fire on soil erosion. In *Natural and Prescribed Fire in Pacific Northwest Forests*, Walstad JD, Radosevich SR, Sandberg DV (eds). Oregon State University Press: Corvallis, OR; 159–176.

Megahan WF, Molitor DC. 1975. Erosion effects of wildfire and logging in Idaho. In *Watershed Management Symposium*. Logan, UT., American Society of Civil Engineers Irrigation and Drainage Division: New York; 423–444.

Miller JF, Frederick RH, Tracey RJ. 1973. *Precipitation Frequency Atlas of the Western United States, Volume I, Montana*, *NOAA Atlas 2*. National Weather Service, NOAA, U.S. Dept of Commerce: Silver Springs, MD.

Monnig E, Carlson J, Frament E, Gautreaux R, Johnson P, Johnson S, Johnson W, Krueger J, Leavell D, Kuennen L, Werst K. 2000. *Forest Assessment of Major Fires 2000*. USDA Forest Service, Kootenai National Forest: Libby, MT; 234.

Morris SE, Moses TA. 1987. Forest fire and the natural soil erosion regime in the Colorado Front Range. *Annals of the Association of American Geographers* **77**(2): 245–254.

Newland JA, DeLuca TH. 2000. Influence of fire on native nitrogen-fixing plants and soil nitrogen status in ponderosa pine-Douglas fir forests in western Montana. *Canadian Journal of Forest Research* **30**: 274–282.

Ott RL. 1993. *An Introduction to Statistical Methods and Data Analysis*. Duxbury Press: Belmont, MA; 1081.

Pyne S, Andrews PL, Laven RD. 1996. *Introduction to Wildland Fire*. John Wiley and Sons: New York; 769.

Rich LR. 1962. *Erosion and Sediment Movement Following a Wildfire in a Ponderosa Pine Forest in Central Arizona*, *USDA Forest Service Research Note-76*. Rocky Mountain Forest and Range Experiment Station: Fort Collins, CO; 12.

Richardson R. 2001. *Burned Area Recovery Draft Environmental Impact Statement*. USDA Forest Service, Bitterroot National Forest: Hamilton, MT; 618.

Robichaud PR. 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. *Journal of Hydrology* **231–232**: 220–229.

Robichaud PR, Waldrop TA. 1994. A comparison of surface runoff and sediment yields from low- and high-severity site preparation burns. *Water Resources Bulletin* **30**(1): 27–34.

Robichaud PR, Graham RT, Hungerford RD. 1994. Onsite sediment production and nutrient losses from a low-severity burn in the Interior Northwest. In *Proceedings of Interior Cedar-Hemlock-White Pine Forests: Ecology and Management*. Washington State University: Pullman, WA; 227–232, March 2–4, 1993.

Robichaud PR, Brown RE. 2000. What happened after the smoke cleared: onsite erosion rates after a wildfire in eastern Oregon. In *Proceedings, Wildland Hydrology Conference*, Olsen DS, Potyondy JP (eds). Bozeman, MT. American Water Resource Association: Hernon, VA; 419–426, 1999 June.

Robichaud PR, Hungerford RD. 2000. Water repellency by laboratory burning of four northern Rocky Mountain forest soils. *Journal of Hydrology* **231–232**: 207–219.

Robichaud PR, Brown RE. 2002. *Silt Fences: An Economical Technique for Measuring Hillslope Soil Erosion*, *USDA Forest Service GTR-RMRS-94*. Rocky Mountain Research Station: Ft. Collins, CO; 24.

Robichaud PR, McCool DK, Pannkuk CD, Brown RE, Mutch PW. 2001. Trap efficiency of silt fences used in hillslope erosion studies. In *Soil Erosion Research for 21st Century*, Ascough JC II, Flanagan DC (eds). American Society of Agricultural Engineers: Saint Joseph, MI; 541–543, January 2001, 3–5.

Shakesby RA, Doerr SH, Walsh RPD. 2000. The erosional impact of soil hydrophobicity: current problems and future research directions. *Journal of Hydrology* **231–232**: 178–191.

Smith RT, Atkinson K. 1975. *Techniques in Pedology: A Handbook for Environmental and Resource Studies*. Elek: London; 213.

Soil Survey Staff. 1999. *Soil Taxonomy, Agricultural Handbook #436*, 2nd edn. USDA Natural Resources Conservation Service: Washington, DC.

S-Plus Professional. 1999. *S-plus Professional*. Release 2, MathSoft, Inc.: Cambridge, MA.

Stark N. 1977. Fire and nutrient cycling in a Douglas fir/larch forest. *Ecology* **58**: 16–30.

Sumner ME, Miller WP. 1996. Cation exchange capacity and exchange coefficients. In *Methods of Soil Analysis. Part III. Chemical Methods*. SSSA, Inc. American Society of Agronomy, Inc.: Madison, WI; 1201–1229.

Swanson FJ. 1981. Fire and geomorphic processes. In *Proceedings: Fire Regimes and Ecosystem Properties*, *General Technical Report WO-26*, Mooney HA, Bonnicksen TM, Christensen NL, Lotan JE, Reiners WA (eds). USDA, Forest Service: Washington, DC; 410–420.

USDA Forest Service. 2000. *Bitterroot Fires 2000: An Overview of the Events, Effects on People and Resources, and Post-fire Recovery Priorities*, Unpublished report. USDA Forest Service, Bitterroot National Forest: Hamilton, MT; 108.

Wright AF, Bailey JS. 2001. Organic carbon, total carbon, and total nitrogen determinations in soils of variable calcium carbonate contents using a Leco CN-2000 Dry Combustion Analyzer. *Communications in Soil Science and Plant Analysis* **32**(19 & 20): 3243–3258.