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Rill erosion in natural and disturbed forests:
1. Measurements

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[1] Rill erosion can be a large portion of the total erosion in disturbed forests, but measurements of the runoff and erosion at the rill scale are uncommon. Simulated rill erosion experiments were conducted in two forested areas in the northwestern United States on slopes ranging from 18 to 79%. We compared runoff rates, runoff velocities, and sediment flux rates from natural (undisturbed) forests and in forests either burned at low soil burn severity (10 months or 2 weeks post-fire), high soil burn severity, or subject to skidding of felled logs. The runoff rates and velocities in the natural sites (2.7 L min^{-1} and 0.016 m s^{-1}, respectively) were lower than those in all the disturbed sites (12 to 21 L min^{-1} and 0.19 to 0.31 m s^{-1}, respectively), except for the 10-month old low soil burn severity site where the velocity (0.073 m s^{-1}) was indistinguishable from the natural sites. The mean sediment flux rate in the natural sites also was very small ($1.3 \times 10^{-5} \text{ kg s}^{-1}$) as compared to the rates in the disturbed areas (2.5×10^{-4} to 0.011 kg s^{-1}). The hillslope gradient did not affect the runoff or sediment responses. The sediment flux rates generally were greater in the initial stage of each inflow period than in the steady state condition, but there was no corresponding transient effect in runoff rates. Rill erosion modeling implications based on these data are presented in part 2 of this study.

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1. Introduction

[2] *Lal* [2001] estimated the global land area affected by severe erosion to be nearly 1100 Mha. A large portion of this area is either arable land or land that is desert, and by comparison the forested area affected by water erosion is relatively small. However, much of the world depends on forested areas for clean water for drinking and agricultural use, and forest disturbances that increase erosion have a broad human impact.

[3] Various approaches have been used to measure hillslope erosion with the ultimate goals of improving predictability of erosion or comparing erosion rates from various land uses and disturbances, including various forms of agriculture, timber harvest, wildfire, and construction. Erosion experiments under natural rainfall or snowmelt can provide much insight as to the nature and variability of the driving processes of water driven erosion, but rely on the random effects of climate (e.g., rainfall and air temperature) and so data collection may take many years. More controlled experimental methods include rainfall simulation on field or laboratory plots, flume experiments with artificial rainfall and/or runoff in laboratory settings, and rill experiments with artificial rainfall and/or runoff in field settings. These methods, each with their own respective drawbacks, can provide more timely answers to narrowly focused research questions.

[4] Given the large amount and impacts of erosion from agricultural lands, the vast majority of both natural and simulated rainfall and runoff experiments have been conducted in or to simulate agricultural settings. This focus on agriculture has resulted in sophisticated measurement tools, erosion prediction technology, and erosion mitigation treatment efficacy for these conditions. However, there is a considerable dearth of knowledge concerning erosion rates from undisturbed lands and in soil types not often found in agriculture [*Bryan*, 2000]. This lack of knowledge results in a lack of specificity in erosion and runoff predictions for forest management activities that involve soil disturbance.

[5] As a result of the underlying differences in topography, surficial geology, climate, vegetative cover, and land use, forest soils often have very different properties than those found in agricultural settings. Although forest soils often have a history of disturbance from fire, logging activity, roads or trails, and/or grazing, these disturbances are not as uniformly distributed or as frequently applied as tillage in agricultural land. Hence, forest soils generally have greater cohesion, a more developed structure, and greater aggregate stability [*Burroughs et al.*, 1992] than agricultural soils [*Elliot et al.*, 1989] and as a result are less erodible than agricultural soils. In addition, in undisturbed forest soils, vegetation, litter, duff, and roots increase the surface roughness, thereby reducing the shear stress on the soil particles [*Foster*, 1982], which results in less soil detachment than typically found in agricultural settings. *Patric et al.* [1984] summarized erosion research in the United States and reported mean annual erosion rates of less than

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0.4 Mg ha^{-1} yr^{-1} for undisturbed forested areas in most of the country, with greater values (11 Mg ha^{-1} yr^{-1}) reported along the Pacific coast where mass movements increase sediment delivery to streams.

[6] Forest disturbances can have various negative effects on soils. These include the breakdown of soil aggregates by burning of soil organic matter [*Giovannini and Lucchesi*, 1983], removal of forest duff or litter by fire or mechanical disturbance, compaction by mechanical disturbance [*Steinbrenner and Gessel*, 1955; *Startsev and McNabb*, 2000; *Han et al.*, 2009], creation or augmentation of water repellency by fire [*DeBano*, 2000; *Doerr et al.*, 2006], changes in the occurrence or diversity of soil biota [*Mataix-Solera et al.*, 2009], and sealing of the soil surface by fire [*Doerr et al.*, 2000]. These changes tend to decrease the infiltration rate [*Robichaud*, 2000; *Startsev and McNabb*, 2000], decrease soil productivity [*Harvey et al.*, 1994] and reduce the size of soil aggregates, thereby reducing the median soil particle diameter and making the resultant soil more easily transportable by overland flow. Various soil types may show different relative effects of forest disturbance. For example, researchers in Australia found a similar absolute change in bulk density across six varied soil and forest types that resulted in a greater relative change in bulk density in the wet forests than the coarser soils found in dry forests [*Williamson and Neilsen*, 2000]. It follows that disturbance-driven changes can be highly variable both within a location and also across different ecosystems [*Moody and Martin*, 2009].

[7] Overland flow begins as inter-rill (sheet) flow as a result of exceeding the infiltration rate or saturated water content of the soil. Once overland flow begins, the hydraulic roughness controls the velocity and therefore the erosivity of the flow [*Giménez and Govers*, 2001]. Inter-rill flow can rapidly concentrate into rill flow, depending on topography [*McCool et al.*, 1989; *Zartl et al.*, 2001], soil properties [*Elliot et al.*, 1989; *Govers*, 1991], surface cover [*Pannkuk and Robichaud*, 2003], and infiltration and rainfall rates [*Robichaud*, 2000]. Because of its greater depth, concentrated flow in rills has greater hydraulic power and thereby more erosive energy than inter-rill flow [*Meyer et al.*, 1975; *Pietraszek*, 2006], so rills can cause rapid surface incision [*Gilley et al.*, 1990]. The ability of the concentrated flow in rills to transport sediment is also greater than that of sheet flow, and so up to 80% of the sediment eroded from bare hillslopes is transported in rills [*McCool et al.*, 1989]. Consequently, erosion from steep hillslopes in disturbed forests with exposed mineral soil is likely to be dominated by rill erosion processes [*Slattery and Bryan*, 1992; *Lei et al.*, 1998].

[8] Despite the dominance of rill erosion in the hillslope erosion processes few studies have quantified rill erosion rates from forests or the effect of different types of forest disturbance on rill erosion. Researches using flume or simulated runoff experiments have found runoff and sediment loss were significantly higher on a bare gravelly sand soil than on a bare silt loam soil [*Yanosek et al.*, 2006]; rill erosion was greater on a burned granitic soil than on a burned volcanic soil [*Pannkuk and Robichaud*, 2003]; the rill erodibility was strongly correlated to soil texture, pH, and bulk density [*Sheridan et al.*, 2000a, 2000b]; and erosion immediately after burning was 540 times the value measured two years later [*Sheridan et al.*, 2007].

[9] Results from two simulated runoff experiments suggest that erosion rates are much higher in the early part of a runoff event than in the latter part of the event on forest roads [*Foltz et al.*, 2008] and burned rangeland [*Pierson et al.*, 2008]. These rapid changes in the rill erosion rate on disturbed soils may be caused by the winnowing of fine or easily detached soil particles during the early stages of erosive runoff, thus leaving larger or more embedded particles and/or aggregates which require greater shear stress for detachment.

[10] While few studies specifically address rill erosion in forests, the hillslope or larger scale effects of some forest disturbances on runoff and erosion are fairly well reported, including effects of prescribed fires and wildfires [e.g., *Robichaud et al.*, 2008], logging [*Binkley and Brown*, 1993], and road building, use, and maintenance [*Burroughs et al.*, 1991; *Megahan and King*, 2004].

[11] Many observations of post-fire effects have been conducted over the past half century [*Hendricks and Johnson*, 1944] and there has been an increase in rigorous evaluations in the past 15 years. *Inbar et al.* [1998] reported increases in runoff and erosion of 2 and 6 orders of magnitude, respectively, as compared to unburned areas in Israel. *Robichaud* [2000] conducted rainfall simulations after site preparation (prescribed) burns in the northern Rocky Mountains and found that burned areas with both low and high soil burn severity produced between 1.6 and 3.8 times more runoff than undisturbed plots. A simulated rainfall study in Colorado measured runoff and sediment production rates in unburned forests and in nearby areas with low and high soil burn severity [*Benavides-Solorio and MacDonald*, 2001]. The runoff and sediment production rates in the low soil burn severity sites were no different than in the unburned forest while the rates in the high soil burn severity sites were significantly greater than in the unburned areas [*Benavides-Solorio and MacDonald*, 2001]. All four of these studies recognized the importance of ground cover—vegetation, duff, or litter—for reducing runoff and erosion.

[12] Considerable research has been conducted into the watershed scale effects of timber harvest on runoff [e.g., *Bates and Henry*, 1928; *Troendle and King*, 1985; *Swank et al.*, 1989; *Stott and Mount*, 2004] and erosion [e.g., *Megahan and Kidd*, 1972], and the construction, use, and decommissioning of forest roads [e.g., *Elliot*, 2000; *Megahan and King*, 2004; *Foltz et al.*, 2007]. Work done to evaluate the specific impacts of logging skid trails on runoff and erosion is less prevalent. *Robichaud et al.* [1993] conducted rainfall simulation experiments on logging sites and found that low-use skid trails produced 4 times more sediment and runoff than the undisturbed plots, while high-use skid trails produced 25 times more sediment and 7 times more runoff than the undisturbed plots. *Croke et al.* [1999, 2001] also conducted rainfall simulation experiments on recent (1.5 yr old or less) and 5 yr old skid trails on soils derived from either granitic or meta-sediment parent materials. On the recent skid trails, the sediment yields were 3 to 5 times greater on the granitic sites than on those derived from meta-sediments, while no difference in sediment yield between soil types was measured in the older sites; in all sites, the sediment yields from the skid trails were greater than those in harvested areas without skid trails. A study in the Sierra Nevada of California found that sediment production from skid trails was 100 times the value from

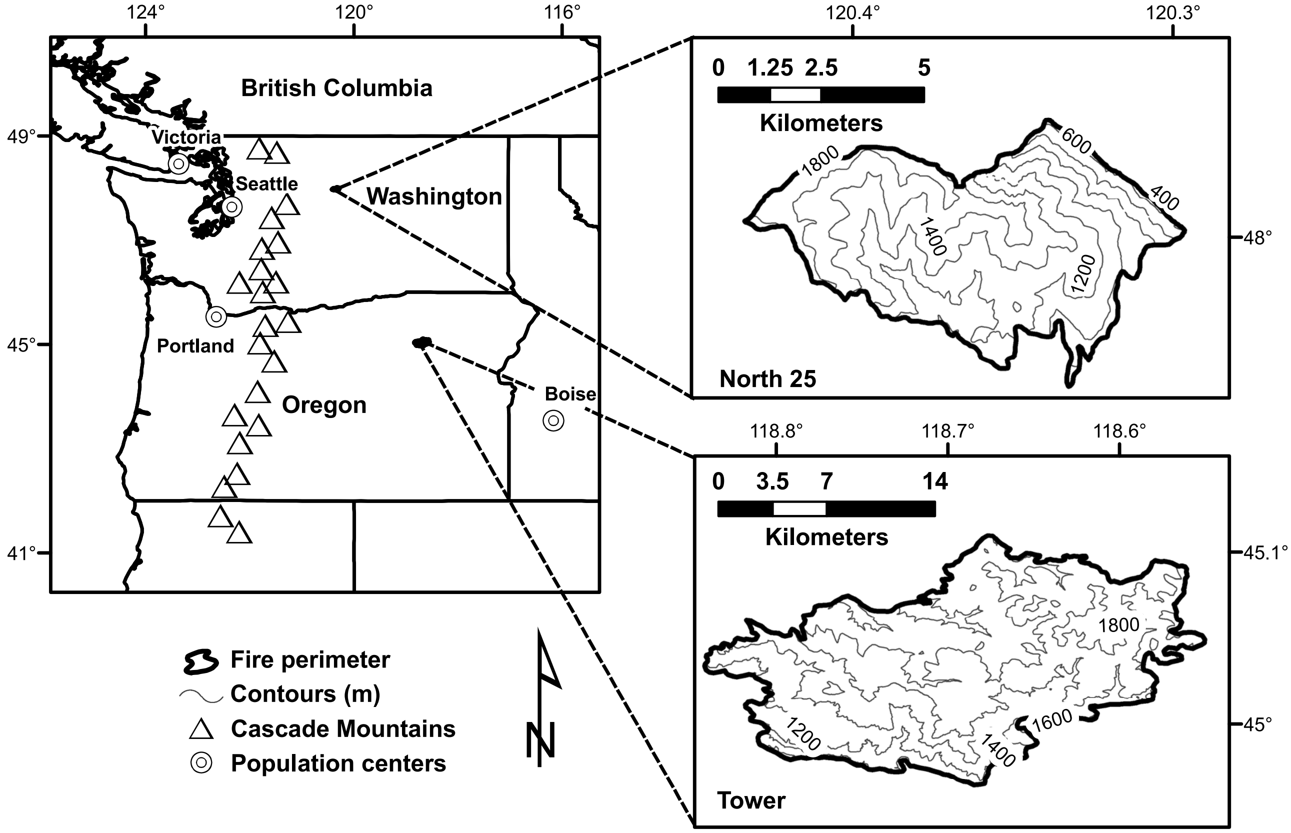

Figure 1. Map of the Tower and North 25 study locations in the northwestern United States.

undisturbed sites (0.001 kg m^{-2}), while sediment production from high severity burned areas was 1000 times the undisturbed value and sediment production rates from prescribed burns were of the same magnitude [*MacDonald et al.*, 2004].

[13] Since the driving force for runoff is gravitational acceleration, and steeper slopes would induce a larger magnitude force in the downslope direction, the erosion rates should thereby increase with increasing rill slope. On stable surfaces the correlation between slope and flow velocity has been shown [*Foster et al.*, 1984; *Abrahams et al.*, 1996], but in more erodible soils this relationship was not significant [*Nearing et al.*, 1999; *Liu et al.*, 2000]. *Takken et al.* [1998] measured the runoff velocity on slopes of between 5% and 21% with varying amounts of rock fragments and vegetative cover and confirmed the runoff velocity was independent of slope and also concluded that increases in rock or vegetative cover reduced the runoff velocity. On eroding surfaces, the steeper rills tended to create rougher surfaces that counteracted the slope effect of velocity [*Govers*, 1992; *Nearing et al.*, 1997, 1999]. In an effort to explain this lack of correlation, *Giménez and Govers* [2001] described the strong feedback loop that exists between flow hydraulics and rill geometry whereby slope has no significant effect on rill flow velocities on mobile beds. The independence of flow velocity and slope was attributed to the changes in rill bed morphology (increased roughness) that occurred in response to flow velocity effects induced by the slope gradient.

[14] The plot length needed to capture rill erosion effects in a natural or disturbed forest environment, as well as the hydrologic factors that might affect this parameter, have not been established. *Huang et al.* [1996] used various plot lengths to evaluate sediment detachment and transport processes in an agricultural setting. The small plots used in many erosion studies often preclude rill development [*Bryan*, 2000].

[15] The goal of the first part of this two-part study was to quantify and compare runoff and erosion rates from concentrated flow experiments in undisturbed and disturbed forests. We conducted simulated rill erosion experiments at two locations in the northwestern United States (Tower and North 25) on steep forested hillslopes. Tests were done on undisturbed (natural) sites as well as sites from areas that had been disturbed by low severity wildfire (both 10 months and 2 weeks after burning), high severity wildfire, and log skidding by ground-based equipment. The specific objectives were to 1) quantify the effects of five forest conditions on rill runoff and erosion rates; 2) determine whether the runoff and sediment production rates in these different conditions changed within the first few minutes of the onset of runoff; and 3) determine if the runoff or sediment responses varied by plot length or slope class. These data are used in part 2 of this study to examine rill erosion mechanics and the parameterization and comparison of rill erosion models [*Wagenbrenner et al.*, 2010].

2. Methods

2.1. Study Sites

[16] Simulated rill experiment sites were selected after the Tower Fire in Oregon and the North 25 Mile Fire in Washington (Figure 1) (Table 1). The mean elevation at both locations was 1200 m and the terrain at both locations was steep and rugged (Table 2). Average annual precipitation near the Tower location was 610 mm, while the North

Table 1. Site Locations, Elevations, Historic Annual Rainfall, Dominant Pre-disturbance Vegetation, and Duff Layer Thickness in the Undisturbed (Natural) Sites

Location	Latitude and Longitude	Elevation (m)	Annual Rainfall (mm)	Dominant Overstory Vegetation	Dominant Understory Vegetation	Duff Thickness (mm)
Tower	45.00° N 118.75° W	1040–1310	610[a]	Lodgepole pine (*Pinus contorta*)	Mallow ninebark (*Physocarpus malvaceus*)	23
North 25	47.99° N 120.34° W	1000–1380	897[b]	Grand fir (*Abies grandis*)	Oceanspray (*Holodiscus discolor*)	47

[a] Period of record was 29 yr.

[b] Period of record was 28 yr.

25 area received 897 mm of precipitation annually (Table 1) (Natural Resources Conservation Service, Snotel site data and information for the County Line site, http://www.wcc.nrcs.usda.gov/snotel/snotel.pl?sitenum=422&state=or, and Snotel site data and information for the Pope Ridge site, http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=699&state=wa). Soils at the Tower location were classified as a complex of the Piutespring and Coyotebluff soil series near granitic outcrops (C. Busskohl, personal communication, 2009). These soils were formed in granitic colluvium; the Piutespring series has a thin layer of volcanic ash and the Coyotebluff series has a mixture of volcanic ash and loess but no distinct ash layer (USDA, NRCS Soil Survey Division, Official soil survey descriptions, http://www2.ftw.nrcs.usda.gov/cgi-bin/osd/osdname.cgi) (Table 2). The soils in the North 25 location were in the Palmich series [*Forest Service*, 1998], which formed in volcanic ash and pumice, and overlies colluvium from granodiorite or rhyolite (http://www2.ftw.nrcs.usda.gov/cgi-bin/osd/osdname.cgi) (Table 2). Soil textures in each location were classified as stony (Tower) or gravelly (North 25) ashy sandy loams. At each of the locations, soil bulk density was measured using a core sampler, and surface soil texture was classified using the particle size distribution [*Gee and Bauder*, 1986].

[17] At the Tower location in the Umatilla National Forest in Oregon, the overstory vegetation consisted of *Pinus contorta* (lodgepole pine) and *Pseudotsuga menziesii* (Douglas-fir) (Table 1). At the North 25 location in the Okanogan-Wenatchee National Forest in Washington the dominant overstory species were *Abies grandis* (grand fir) and *Psuedotsuga menziesii* (Douglas-fir) (Table 1). In unburned and undisturbed (natural) areas at both locations, the forests had a thick understory of grasses, forbs and shrubs, and litter and duff completely covered the soil surface (Table 1) (Figure 2).

Table 2. Soil and Site Characteristics by Location, Disturbance Class, and Slope Class

Soil Series Name[a]	Textural Class[b]	Disturbance Class	Aspect	Bulk Density[c] (kg m^{-3})		Slope Class[d]	Slope (%)	Surface Fraction by Class[e] (%)		
				0–5 cm	5–10 cm			Silt	Sand	>2 mm
			Tower							
Piutespring (*Loamy-skeletal, isotic, frigid Andic Haploxerepts*) and Coyotebluff (*Ashy-skeletal over loamy-skeletal, glassy over isotic, frigid Humic Vitrixerands*)	Stony, ashy sandy loam (granitic with ash mantle)	Natural	S	1.06 (0.12)	1.15 (0.13)	Low	27–33	22	60	17
						Moderate	49–50	11	68	21
						High	72–79	13	66	20
		Low soil burn severity	SE	1.08 (0.12)	1.02 (0.04)	Low	24–29	No data	No data	No data
						Moderate	36–46	No data	No data	No data
						High	48–52	23	67	10
		High soil burn severity	SE	1.01 (0.10)	0.99 (0.09)	Low	23–28	16	67	17
						Moderate	42–49	No data	No data	No data
						High	69–75	15	69	16
		Skid trails	W	1.11 (0.19)	1.01 (0.16)	Low	24–27	31	57	11
						Moderate	46–54	22	64	14
			North 25							
Palmich *Ashy-pumiceous, glassy, frigid Typic Vitrixerands*)	Gravelly, ashy sandy loam (volcanic ash and pumice)	Natural	E	0.89 (0.20)	0.95 (0.19)	Low	25–26	19	64	17
						Moderate	40–44	27	57	17
						High	62–66	22	63	15
		Low soil burn severity	SW or E	0.77 (0.11)	0.77 (0.09)	Low	27–28	20	71	9
						Moderate	43–49	14	70	16
						High	61–64	23	67	10
		High soil burn severity	S	0.75 (0.03)	0.76 (0.03)	Low	25–29	16	64	20
						Moderate	47–47	19	63	19
						High	66–69	15	68	17
		Skid trails	SW	0.99 (0.22)	1.13 (0.22)	Low	18–21	18	68	14
						Moderate	49–51	17	66	17

[a] Taxonomic class is given in parentheses.

[b] Parent material is given in parentheses.

[c] Bulk density standard deviations are in parentheses.

[d] "Low" indicates the low slope class, "Moderate" indicates the moderate slope class, and "High" indicates the high slope class.

[e] All surface composite soil samples had 1% or less clay content.

Figure 2. Photographs of four of the study sites: (a) Tower natural, (b) North 25 low soil burn severity, (c) North 25 high soil burn severity, and (d) North 25 skid trail.

[18] A natural forest condition (no recent disturbances) and three types of disturbance were selected for study in each location: low soil burn severity 10 months or 2 weeks after burning, high soil burn severity, and skid trails. The burned sites were established 10 months after the Tower wildfire and 2 weeks after the North 25 wildfire. The low soil burn severity [*Ryan and Noste*, 1985; *Parsons et al.*, 2010] sites had some charred but recognizable litter and duff remaining (Tower: 11 mm, or 48% of the duff found in the Tower natural sites; North 25: 5 mm, or 11% of the duff

Table 3. Number of Plots by Plot Length for Each Disturbance and Slope Class at the Tower and North 25 Locations

	Natural			Low Soil Burn Severity			High Soil Burn Severity			Skid Trails		
	Low Slope	Moderate Slope	High Slope	Low Slope	Moderate Slope	High Slope	Low Slope	Moderate Slope	High Slope	Low Slope	Moderate Slope	Total
						Tower						
2 m	3	3	3	3	3	3	3	3	3	3	3	33
4 m	3	3	3	3	3	3	3	3	3	3	3	33
9 m	3	3	3	3	3	3	3	3	3	3	3	33
						Noth 25						
4 m	3	3	3	3	3	3	3	3	3	3	3	33
						Combined Total						
2 m	3	3	3	3	3	3	3	3	3	3	3	33
4 m	6	6	6	6	6	6	6	6	6	6	6	66
9 m	3	3	3	3	3	3	3	3	3	3	3	33
Total	12	12	12	12	12	12	12	12	12	12	12	132

found in the North 25 natural sites), and a brown or black and lightly charred ground surface. The high soil burn severity [*Ryan and Noste*, 1985; *Parsons et al.*, 2010] sites had a white or gray ash layer indicating complete consumption of the litter and duff, and no living trees. The skid trails had been created by a metal-tracked log skidder within 12 months prior to the experiments and this resulted in the removal of all vegetation, litter, and duff and complete exposure of the mineral soil (Figure 2).

[19] Four sites—one for each of the four types of disturbance—were located within a 3 km radius at each location. Within each site, plots were established in 3 slope class sub-sites, all having similar disturbance, vegetation, and soils. The three targeted slope classes were 20 to 35% (low), 35 to 55% (moderate), and 55 to 70% (high); however, variation in local topography precluded clear separation of plots into these target classes. The resultant slope classes overlapped slightly: low (18 to 33%), moderate (36 to 54%), and high (48 to 79%) (Table 2). Because logging by ground based mechanical equipment is not typically done on steep slopes, skid trail plots were only established in the low and moderate slope classes. No runoff or erosion mitigation treatments were installed in any of the sites.

[20] In the natural and burned sites, plot locations were selected in locations where no rills were visible and the hillslope was uniform over the entire plot length. In the skid trail sites, the disturbance from the tracked skidder often caused rutting, and the skid trail plots generally were located in the rutted sections. As runoff may have occurred in the ruts before the experiments, some pre-existing rills might have been present in the skid trail plots.

[21] The plots at the Tower location were further split into 2 m, 4 m, and 9 m length sub-plots along the slope gradient to determine the effect of plot length on runoff rates and sediment fluxes (Table 3). All the plots at the North 25 location were 4 m long (Table 3). There were three replicates for each of the disturbance-slope-length class combinations, which resulted in 99 plots at Tower and 33 plots at North 25. After initial plot length analysis, we conducted all other analyses using just the 4 m plots resulting in 33 plots in each location.

2.2. Experimental Procedure

[22] One day prior to the rill experiment, low intensity simulated rainfall was applied to sets of three plots using a CSU-type rainfall simulator [*Holland*, 1969]; rainfall was applied until runoff occurred, and the applied amount varied between a trace and 2.4 cm depending on the distance from the rainfall simulator nozzles. The simulated rainfall increased the surface soil moisture content to between 3 and 34% without rill formation. Sophisticated, highly controlled rainfall simulation experiments were not feasible at these locations; therefore inflow rate was used as a surrogate variable that integrated the effects of upslope accumulation area, rainfall intensity, and infiltration rate.

[23] For each rill experiment, concentrated flow, controlled using a flowmeter, was applied at the top of the plot through an energy dissipater at five sequential inflow rates (4 ± 1 L min^{-1}; 20 ± 2 L min^{-1}; 28 ± 2 L min^{-1}; 14 ± 3 L min^{-1}; and 45 ± 3 L min^{-1}). The 14 L min^{-1} flow rate was placed between the 28 and 45 L min^{-1} flow rates to examine effects of a reduced flow rate on erosion and transport during a flow event. Each inflow rate was applied for 12 min. The 12-min duration was selected based on a test of the experimental procedures and equipment on burned 40% slopes in northern Idaho. During this test, observations of the runoff and sediment concentrations at the various flow rates indicated that flow patterns stabilized after 6 to 8 min. The 12-min duration was therefore selected to ensure steady state conditions could be established for each inflow rate.

[24] The plots were unbounded on the sides, but if needed, Z-shaped sheet metal (10 cm by 70 cm) was used to funnel the flow to the sampling point at the outlet of the plot. Runoff samples were collected at the outlet of each plot, and between 6 (for the 4 and 14 L min^{-1} inflow rates) and 11 (for the 45 L min^{-1} inflow rate) timed samples were taken for each 12-min period. Runoff volume and sediment weight were determined for each sample by weighing the samples before and after drying. Runoff (L min^{-1}) and sediment flux (kg s^{-1}) rates were calculated using the measured sample durations. The procedure was replicated three times for each disturbance-slope class-length combination (Table 3). The runoff velocity was measured using a dyed calcium chloride solution and two conductivity probes [*King and Norton*, 1992]. The transit time of the peak of each saline pulse and the distance between the probes were used to calculate the runoff velocity.

[25] Since the flow often dispersed after exiting the energy dissipater, each rill was identified and each rill's flow depth and width were measured during each inflow

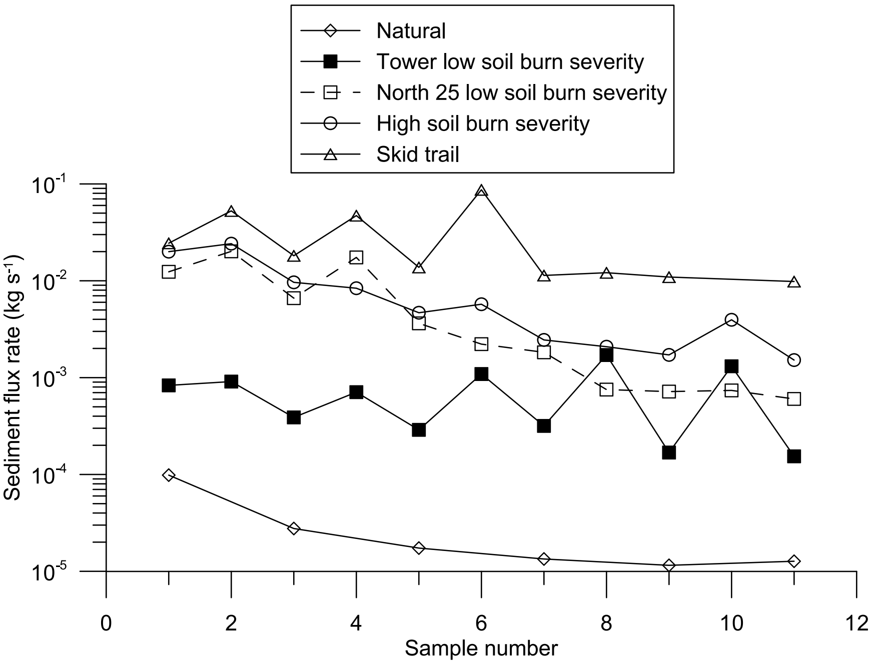

Figure 3. Mean sediment flux rate verses sample for each treatment.

using a ruler. The total flow width and the mean flow depth for each set of rills for each inflow rate were calculated. Any wetted ground surface area surrounding the rills was noted but not used in calculations because flow in these areas, when it occurred, was very shallow and its contribution to total runoff and erosion rates was assumed to be small [*Pierson et al.*, 2008].

2.3. Calculations and Statistical Analysis

[26] All statistical analyses were conducted with the SAS statistical software [*SAS Institute*, 2008a]. Initial analyses indicated that there was a sharp decline in sediment production rates within most of the 12-min inflow periods (Figure 3). Results from sediment sampling during plot experiments were therefore split into two groups. The first group (termed "initial") was samples from the first 4 to 5 min of each 12-min inflow period, and represented the sediment flux rates from an initial phase of runoff and erosion during each inflow rate. The second group began at 4 to 5 min and continued through the end of the 12-min period and represented conditions where loose soil had been removed from the rills. We assumed the second group represented the steady state condition, and refer to it as "steady state" [*Elliot et al.*, 1989; *Nearing et al.*, 1999] and this group was used for all calculations except when the transient nature of runoff or sediment flux specifically was under investigation.

[27] Initial analyses indicated that the responses in runoff, runoff velocity, and sediment flux rates from the two low soil burn severity sites were different. This may have been a result of different pre-fire conditions, different exposure to heat during the fire, or because the time between burning and the experiments was different at the two fire locations. Because of the difference in responses, the two low soil burn severity sites were analyzed as separate disturbance classes. In contrast, no differences in these responses were observed between the two high soil burn severity sites, despite the same potential differences in the site conditions as described for the low soil burn severity sites. Studies have shown that minimal recovery occurs in high soil burn severity areas within a 10 month (or longer) period [*Benavides-Solorio and MacDonald*, 2005; *Wagenbrenner et al.*, 2006; *Robichaud et al.*, 2008]. Considering this information, both high soil burn severity sites were analyzed in the same disturbance class.

[28] The study was analyzed as a split-split plot experiment. The whole plot "treatment" was the fire location, which was also a random variable. Each whole plot was split into four types of disturbance (natural, low soil burn severity, high soil burn severity, and skid trail), and each split plot was split again into the three slope classes (low, moderate, and high). At the Tower site the three plot lengths—2 m, 4 m, and 9 m—were tested in each disturbance-slope class combination. Only the 4 m plot length was established at the North 25 site, and so after initial evaluation of the effects of slope length, the 2 m and 9 m plots were excluded from subsequent analysis. Three of the 4 m natural plots produced no runoff. For these plots, values of zero were assigned to runoff rate, runoff velocity, and sediment flux rate.

[29] General linear mixed effects statistical models [*Littel et al.*, 2006] were developed using the disturbance and slope class as fixed effects while the fire and plot were random effects. The multiple samples for each inflow rate were treated as repeated measures; the midpoint of the sample time was the spacing between measurements [*Littel et al.*, 2006]. Least squares means, with a Tukey-Kramer adjustment, were used to test the significance of differences among disturbances and slope classes [*Ott*, 1993]. The sediment flux rates were log-transformed prior to analysis to improve normality of the residual errors [*Ott*, 1993]; a small quantity (5×10^{-7} kg s^{-1}) was added to zero value data (when no runoff occurred or less than 1×10^{-5} kg of sed-

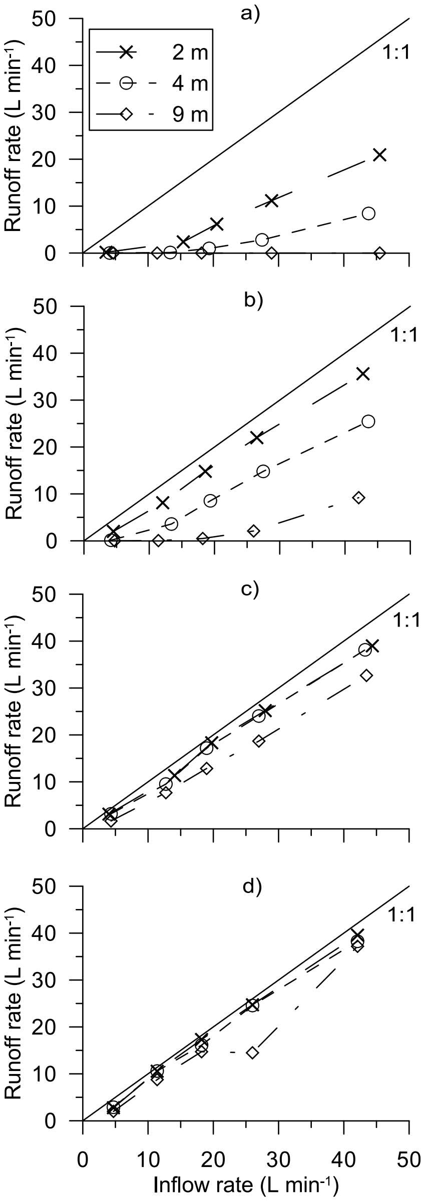

Figure 4. Runoff rate versus inflow rate by plot length for each disturbance class in the Tower location: (a) natural, (b) low soil burn severity, (c) high soil burn severity, and (d) skid trail.

iment was measured in the sample) so this transformation could be conducted. The runoff rates and runoff velocities were modeled using a lognormal distribution [*SAS Institute*, 2008b]. Soil moisture and duff thickness were tested as covariates for sediment flux rate, runoff rate, and runoff velocity; both covariates were non-significant and were not retained in the models. The significance level was 0.05 for all statistical tests.

3. Results

3.1. Slope Length

[30] In the Tower natural and low soil burn severity sites the runoff rate in the 4 m and 9 m plots was much less than the inflow rates (Figure 4), indicating significant infiltration occurred over the 9 m length. Infiltration also occurred in some of the 2 m plots in the natural site. Less infiltration occurred in the longer plots in the high soil burn severity and skid trail sites than in lesser disturbed sites.

[31] The sediment flux rates in the natural and low soil burn severity plots also decreased with increasing plot length (Figure 5). This is a result of the increased infiltration and resultant decrease in runoff rates in these longer plots as described above. In contrast, the more disturbed plots—the high soil burn severity site and the skid trail site—produced

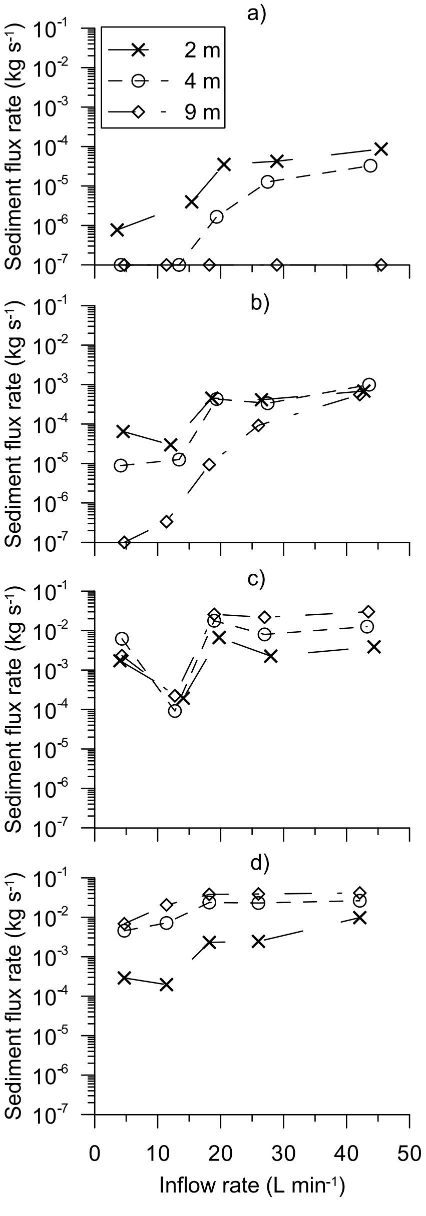

Figure 5. Mean sediment flux rate versus mean inflow rate by plot length for the Tower location: (a) natural, (b) low soil burn severity, (c) high soil burn severity, and (d) skid trail. Eight plots (1 low soil burn severity plot and 6 natural plots with no sediment flux as well as 1 natural plot with a sediment flux rate of 5×10^{-9} kg s^{-1}) were assigned sediment flux rate values of 1.0×10^{-7} kg s^{-1} for graphing purposes only; no other analysis was conducted with the altered data. The sequence of inflow rates was 4, 20, 28, 14, and 45 L min^{-1}.

Table 4. Number of Samples, Slope Range, and Mean and Standard Deviation for the Steady State Runoff Rate, Runoff Velocity, Sediment Flux Rates, Number of Rills, Flow Width, and Flow Depth for Each Disturbance Class[a]

Disturbance	n	Slope (%)	Runoff Rate (L min^{-1})	Runoff Velocity (m s^{-1})	Sediment Flux Rate (kg s^{-1} × 10^{-3})	Number of Rills	Flow Width (mm)	Flow Depth (mm)
Natural	264	25–79	2.7 (5.3) C	0.016 (0.027) C	0.013 (0.036) B	1.7 (0.60)	281 (118)	6.5 (1.4)
Low soil burn severity (Tower)	131	24–52	12 (11) B	0.073 (0.058) C	0.25 (0.64) A,B	1.3 (0.56)	282 (136)	6.3 (2.2)
Low soil burn severity (North 25)	140	27–64	18 (10) A,B	0.24 (0.10) A,B	1.0 (2.2) A,B	2.5 (1.2)	233 (117)	7.1 (2.3)
High soil burn severity	278	23–75	21 (12) A	0.31 (0.12) A	1.9 (3.3) A	2.6 (1.3)	232 (117)	6.5 (2.0)
Skid trails	183	18–54	21 (14) A	0.19 (0.079) B	11 (17) A	1.7 (0.90)	156 (100)	12 (5.8)

[a]The number of samples is shown for the runoff rate and sediment flux rate means; the number of samples for runoff velocity, flow width, and flow depth was one per plot per flow rate (90 for the natural and high soil burn severity, 45 for the low soil burn severity, and 60 for the skid trails). Flow width was the mean of the total width of all rills for each flow rate. Flow depth was the mean depth of all rills for each flow rate. Letters A, B, or C indicate significantly different means within that column (α = 0.05). Sediment fluxes were log-transformed for statistical analysis. Standard deviations are given in parentheses.

greater sediment flux rates in the longer plots, despite some apparent infiltration and reduction in runoff rates. These results indicate that the sediment transport may have been flow limited in the less disturbed sites and source limited in the more disturbed sites, and the additional source material in the longer plots was eroded and transported in the more disturbed sites.

[32] *Huang et al.* [1996] suggested that rill erosion should be measured using flow rates that are high enough so that minimal infiltration occurs. In a natural runoff condition, where rainfall or snowmelt had resulted in increases in soil moisture and occasionally produced overland flow these plots would have had higher antecedent soil moisture contents than in this experiment, and this would have resulted in lower infiltration rates. Although the least amount of infiltration occurred in the 2 m plots, we believe the 2 m length was too short to allow development of a stable flow path. In the combined interest of optimizing flow condition and minimizing the infiltration only the 4 m plot length data were used in subsequent analyses.

3.2. Disturbance Effects

[33] The natural sites produced runoff in 15 of the 18 plots. The mean runoff rate for the natural plots over all the inflows and plots was 2.7 L min^{-1}. Each of the disturbances had mean runoff rates that were significantly greater than this value, and the runoff rates generally increased with increasing level of disturbance (Table 4). The greatest mean runoff rate occurred in the high soil burn severity and the skid trail plots (21 L min^{-1}), while the runoff rates in North 25's low soil burn severity plots were close to this value (Table 4). The mean runoff rate from the Tower low soil burn severity plots (12 L min^{-1}) was between the values for the natural and skid trail sites, and this value was statistically distinct from the two endpoints.

[34] The natural plots also had the lowest mean runoff velocity (0.016 m s^{-1}) although the mean velocity from the Tower low soil burn severity plots (0.073 m s^{-1}) was not statistically different from this value. In contrast, the runoff velocity in the North 25 low soil burn severity site was 0.24 m s^{-1}, and this result was no different than the runoff velocity in the high soil burn severity sites (0.31 m s^{-1}), which was the maximum value. The mean velocity in the skid trail plots (0.19 m s^{-1}) was significantly different than both the natural and the high soil burn severity means (Table 4). The relatively low velocity in the skid trail sites—despite their having the greatest runoff rate—was at least partly due to the much greater relative roughness of the skid trails as compared to the other disturbed plots. Skid trail surface roughness was increased by depressions from the metal cleats on the tracked skidder and embedded slash that was pressed into the soil during the skidding operation.

[35] The sediment flux rates ranged from 1.3 × 10^{-5} kg s^{-1} in the natural plots to 0.011 kg s^{-1} in the skid trail plots (Table 4). Within this range, the mean sediment flux rates in the Tower and North 25 low soil burn severity plots (2.5 × 10^{-4} and 1.0 × 10^{-3} kg s^{-1}, respectively) were no different than the mean from the natural plots. The sediment flux rates from the high soil burn severity (1.9 × 10^{-3} kg s^{-1}) and skid trail plots were both significantly greater than the mean from the natural plots, but not different from the means of the low soil burn severity plots (Table 4). The log-transformed sediment flux rates increased with increasing runoff rates (Figure 6).

3.3. Transiency of Runoff and Sediment Production

[36] There was no difference in runoff rate between the initial and steady state sample groups for any of the disturbance classes (Table 5). The lack of difference in runoff rate between the initial and steady state groups suggests that the infiltration rate within the rill did not change throughout the experiment. In contrast, differences in sediment flux rate between the initial and steady state groups were significant for all the disturbance classes except the Tower low soil burn severity site (Table 5). The initial sample groups produced sediment flux rates that were between 1.9 times (skid trail sites) and 8.1 times (North 25 low soil burn severity) greater than the steady state sample groups. In each disturbance class, the relatively large quantity of available sediment was transported in the first few minutes of each flow rate, leaving a more armored condition for the flow in the assumed steady state portion of each inflow step.

[37] The results from the 14 L min^{-1} flow rate, sequenced between the 28 L min^{-1} and 45 L min^{-1} flow rates, also suggest an armoring effect. While the runoff rates roughly followed the inflow rates during the inflow sequence (Figure 7), the sediment flux rates often peaked at one of the early, lower flow rates, and only in the natural and Tower low soil burn severity sites did the peak sediment flux occur during the 45 L min^{-1} flow rate.

3.4. Slope Effect

[38] There were no significant differences in runoff rate, runoff velocity, or log-transformed sediment flux rate

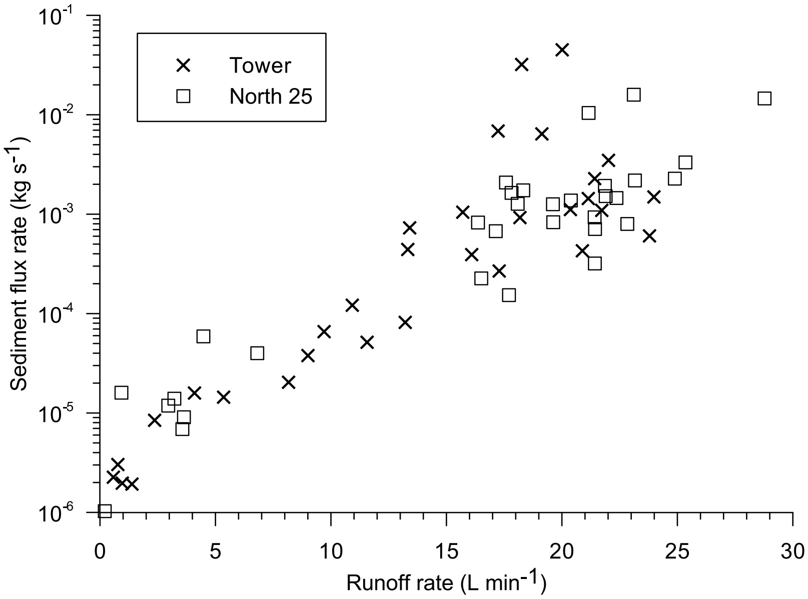

Figure 6. Mean sediment flux rate versus mean runoff rate for each plot. The figure excludes three natural plots with no runoff.

among the slope classes in any of the disturbance classes (Table 6). These results are similar to earlier studies [*Govers*, 1992; *Nearing et al.*, 1997, 1999; *Giménez and Govers*, 2001] that found the flow velocity was strongly correlated to discharge rate but was independent of slope.

[39] Despite the lack of statistical differences among the slope classes, the skid trail results require further investigation. The sediment flux rate from the moderate slope plots (0.020 kg s^{-1}) was more than 12 times that of the low slope plots (1.6×10^{-3} kg s^{-1}), despite nearly the same runoff rates and runoff velocities. During the log skidding process we observed more slipping of the skidder's track cleats on the moderate slope plots than on the low slope plots (skidders were not used on high slopes), resulting in greater disturbance of the organic matter and soil in the moderate slope plots. This slippage and resultant churning effect made more sediment available for transport.

4. Discussion

4.1. Disturbance Effects

[40] Although soil physical and chemical properties were not measured at the plot scale, the differences in runoff and sediment flux rates among the natural and disturbed sites were probably at least partly a result of changes in soil structure—as a result of soil crusting, sealing, water repellency, and breakdown of aggregates—for the burned soils [*Doerr et al.*, 2000] and of compaction and break down of aggregates for the skid trails [*Lal*, 2001]. However, the aim of this study was to discern aggregate effects of disturbance on runoff and sediment production, and not specific effects to the mineral soil, litter, duff, or vegetation. Hence, the measured effects represent the cumulative effect of the changes in the soil physical and chemical properties and the changes to the protective ground cover, and therefore reveal more about the measurable effects at the outlet of the plots and at the hillslope scale as a result of the disturbance.

[41] Sediment flux rates ranged from 0 to 0.23 kg s^{-1} across 33 soils in a series of rill experiments in agricultural plots [*Elliot et al.*, 1989]. In contrast, the sediment flux rates in the current study ranged from 0 to 5.7×10^{-3} kg s^{-1} in the natural sites and 0 to 9.6×10^{-3} kg s^{-1} in the Tower low soil burn severity site. The more disturbed high soil burn severity and skid trail sites, however, had maximum single sample sediment flux rates of 0.33 and 0.17 kg s^{-1}, respectively, and these rates were of the same order of magnitude as the rates from recently tilled agricultural fields. These results help justify the use of post-fire rehabilitation treatments in high soil burn severity areas to protect downstream values [*Robichaud et al.*, 2000] and also the use of

Table 5. Mean Inflow, Runoff, and Sediment Flux Rates for the Initial and Steady State Sample Groups by Disturbance Class[a]

Disturbance Class	Inflow Rate (L min^{-1})	Runoff Rate (L min^{-1})		Sediment Flux (kg $s^{-1} \times 10^{-3}$)	
		Initial	Steady State	Initial	Steady State
Natural	23 (264)	2.8	2.7	0.048 A	0.013 B
Low soil burn severity (Tower)	22 (131)	11	12	0.52 A	0.25 A
Low soil burn severity (North 25)	27 (140)	20	18	8.1 A	1.0 B
High soil burn severity	25 (278)	22	21	12 A	1.9 B
Skid trails	24 (183)	22	21	21 A	11 B

[a] The minimum sample size for each disturbance is shown in parentheses. Different letters A or B in the sediment flux column indicate significantly different means between groups for each disturbance ($\alpha = 0.05$). There were no significant differences in runoff rate between the groups.

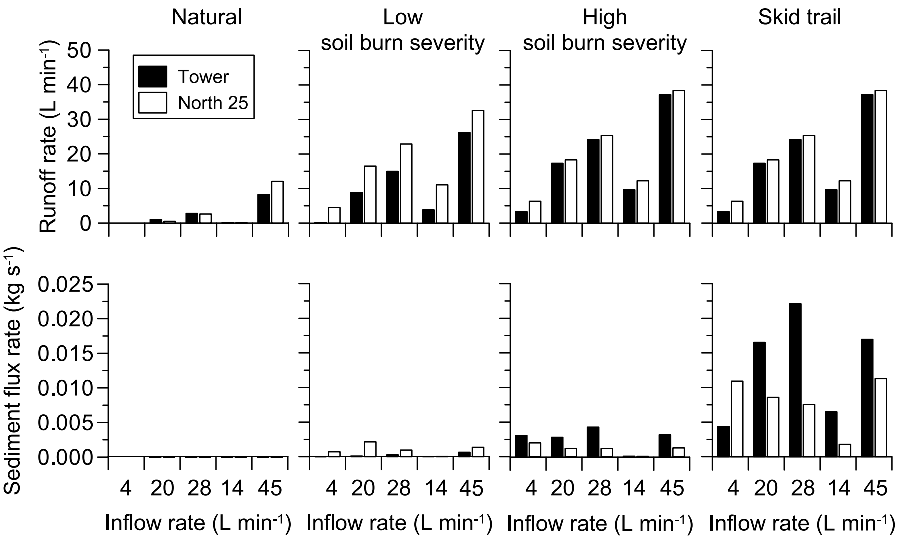

Figure 7. Steady state runoff and sediment flux rates by inflow rate for the natural, low soil burn severity, high soil burn severity, and skid trail sites. Dark bars represent the Tower location and unfilled bars represent the North 25 location. The inflow rates shown on the x axis are the nominal rates in the sequence of the experiment.

best management practices in logging areas to minimize soil erosion from skid trails.

[42] Though not all the differences were significant, the runoff rate, runoff velocity, and log-transformed sediment flux rates were all greater in the North 25 low soil burn severity site than in the Tower low soil burn severity site (Table 4). Since there was not much difference in these responses between the two natural sites we attribute these differences between the two low soil burn severity sites to the shorter time since burning in the North 25 site (2 weeks) as compared to the Tower site (10 months). A previous study compared ground cover and erosion rates from simulated rainfall in areas burned at moderate soil burn severity; this study showed differences in time since burning can affect ground cover and sediment delivery rates [*Benavides-Solorio and MacDonald*, 2001]. It follows that the greater time since burning would allow greater vegetative and soil recovery rates in the Tower site. The responses in the Tower low soil burn severity site were more similar to the responses in the natural plots than the other disturbed plots, especially with respect to runoff velocity. We attribute this to an increase in vegetative or litter cover resulting from regrowth or deposition of needles, respectively, during the 10 months since burning at this site. The increased ground cover resulted in greater roughness at the scale of the runoff depth, and this resulted in greater resistance to flow and lower runoff velocities than in the other burned sites.

Table 6. Number of Samples, Slope Range, and Mean and Standard Deviation for Steady State Runoff Rate, Runoff Velocity, Sediment Flux Rate, Flow Width, and Flow Depth for Each Disturbance and Slope Class[a]

Disturbance	Slope Class	Number of Samples	Slope (%)	Runoff Rate ($L\ m^{-1}$)	Runoff Velocity ($m\ s^{-1}$)	Sediment Flux Rate ($kg\ s^{-1} \times 10^{-3}$)	Flow Width (mm)	Flow Depth (mm)
Natural	Low	87	25–33	3.6 (5.9) B, C, D	0.022 (0.030) D	0.010 (0.019) D	292 (128)	6.3 (1.1)
	Moderate	87	40–50	2.0 (3.8) D	0.015 (0.026) D	0.009 (0.021) D	243 (68)	6.0 (2.2)
	High	90	62–79	2.5 (5.8) C, D	0.011 (0.022) D	0.019 (0.054) D	250 (88)	9.0 (0)[b]
Low soil burn severity (Tower)	Low	40	24–29	9.8 (9.9) A, B, C, D	0.061 (0.039) B, C, D	0.073 (0.11) B, C, D	No data	No data
	Moderate	47	36–46	8.8 (10) A, B, C, D	0.038 (0.035) C, D	0.047 (0.10) C, D	220 (136)	7.6 (2.0)
	High	44	48–52	17 (13) A, B, C	0.12 (0.061) A, B, C, D	0.64 (1.0) A, B, C, D	343 (89)	6.0 (1.4)
Low soil burn severity (North 25)	Low	46	27–28	19 (10) A, B, C	0.29 (0.089) A, B, C	1.8 (3.6) A, B, C	185 (79)	8.8 (2.7)
	Moderate	45	43–49	18 (9.3) A, B, C	0.27 (0.058) A, B, C	0.80 (0.80) A, B, C	212 (81)	6.6 (1.2)
	High	49	61–64	18 (11) A, B, C, D	0.15 (0.097) A, B, C, D	0.54 (0.84) A, B, C, D	303 (145)	5.9 (1.4)
High soil burn severity	Low	91	23–29	22 (13) A	0.33 (0.12) A	0.97 (1.0) A, B, C	256 (129)	6.2 (2.0)
	Moderate	93	42–49	21 (12) A	0.32 (0.091) A	2.9 (3.9) A, B	197 (83)	6.9 (1.7)
	High	94	66–75	19 (12) A, B	0.28 (0.13) A, B	2.0 (4.0) A, B, C	243 (126)	6.3 (2.3)
Skid trails	Low	90	18–27	22 (14) A	0.21 (0.086) A, B, C	1.6 (2.0) A, B, C	147 (55)	11 (3.9)
	Moderate	93	46–54	21 (14) A	0.18 (0.068) A, B, C	20 (20) A	165 (129)	14 (7.0)

[a] Abbreviations in the slope class column are the same as in Table 2. The number of samples is shown for the runoff rate and sediment flux rate means. The number of samples for the runoff velocity was one per plot per flow rate (15 for each location-disturbance-slope class combination). Different letters A, B, C, or D indicate significantly different means within that column ($\alpha = 0.05$). Sediment flux rates were log-transformed for statistical analysis. Flow width is the mean of the total width of all rills for each flow rate. Flow depth is the mean depth of all rills for each flow rate. Standard deviations are given in parentheses.

[b] For this depth measurement, n was 3.

[43] Forest floor or duff thickness often is used to indicate the degree of forest disturbance [e.g., *Huisinga et al.*, 2005]. The duff may absorb large quantities of water; one estimate of the water holding capacity of the duff layer in a forest in the northwestern United States was 25 mm [*Isaac and Hopkins*, 1937]. The duff therefore has the capacity to substantially reduce runoff rates as well as increase roughness and thereby reduce the runoff velocity. One indicator of the differences in fire effects between the two locations in the current study was the amount of duff material remaining above the mineral soil surface. Despite less duff in the Tower natural site as compared to the North 25 natural site (Table 1), the Tower low soil burn severity site had twice as much duff (11 mm) as the North 25 low soil burn severity site (5.2 mm). This greater reduction in duff in the North 25 low soil burn severity site suggests that the soil burn severity, within the class of low soil burn severity [*Parsons et al.*, 2010; *Ryan and Noste*, 1985], may have been greater in the North 25 location.

[44] The mechanical disturbance in the skid trail plots caused the surface to become loose and more erodible than in the fire disturbed sites, and this combined with the relatively high surface roughness caused by the tracks' cleats produced low runoff velocity and high sediment flux rates. One implication of these results is that forest best management practices should focus on maintaining soil roughness to minimize runoff velocity and sediment detachment rates.

4.2. Transient Nature of Rill Erosion

[45] During this experiment we applied simulated runoff to areas of the hillslopes that were not necessarily convergent. It is possible that concentrated flow may not have naturally occurred on these slope positions. If that was the case, these non-convergent areas would only have experienced sheet flow and inter-rill erosion, and therefore the amount of soil available for detachment in the experiment may have been greater and it may have had a different particle size distribution than in a naturally occurring convergent area that had recently experienced rill erosion. This leads to the conclusion that our erosion rates may have been high, especially in the disturbed plots where minimal ground cover was available to reduce the erosive energy.

[46] The difference in sediment flux rates between the initial and steady state samples taken during each 12-min inflow rate suggests that there is a large decrease in the sediment flux rate between the initiation of runoff and the steady state condition. With more available sediment, as at the beginning of a runoff event or in a highly disturbed site, the sediment flux rates were relatively high. As finer soil particles were removed, larger particles were exposed and these larger particles required a larger force for initiation of motion. As the depth of flow and therefore the applied force was relatively constant throughout each inflow rate, this resulted in lower sediment fluxes. This trend was more obvious in the disturbed sites than in the natural sites, where the data were sparse and much lower sediment flux rates were measured (Table 5). These transient effects generally are not represented in current erosion prediction models [*Bryan*, 2000; *Foltz et al.*, 2008], and are further explored in part 2 of this study [*Wagenbrenner et al.*, 2010].

[47] The results above suggest that the rill erosion process can change rapidly—on the order of minutes—once flow concentrates, especially for the initiation of rill erosion on a hillslope with no pre-existing rills. In the skid trail sites, which may have experienced concentrated flow prior to this experiment, the difference in sediment flux rates between the initial and the steady state periods was notably lower; this indicates that sediment availability in existing rills may be lower than the availability in incipient rills.

[48] The results from the step-down of the inflow to the 14 L min^{-1} rate indicate that available sediment was transported during the antecedent, increasing sequence of flow rates, simulating the onset of a runoff event. The energy of the 14 L min^{-1} inflow rate was not sufficient to detach additional soil from the perimeter of the rill, but when the inflow rate was increased to 45 L min^{-1}, more detachment occurred. The sediment delivery rate in the 14 L min^{-1} flow rate appears to be limited by the available sediment.

[49] While the data indicate that sediment availability changes rapidly with the application of concentrated flow, and that within a simulated runoff event the armoring effect is evident at the highest flow rate, the results raise the question of whether the reduced sediment availability is a transient or permanent feature when time scales are increased beyond the experimental duration. Observations of existing rills in disturbed forests suggest that rills can be filled in by sediment deposited by fluvial, biotic, freeze-thaw, colluvial, or aeolian processes. It is not clear from the current study how the detachment of soil in the eroding rill will change over longer time periods or during intermittent flows where the sediment availability in the rill has had an opportunity to recover. As this process is beyond the scope of the current study, the degree and extent of this in-filling, as well as its effect on subsequent rill erosion rates requires further analysis.

5. Conclusions

[50] Simulated rill experiments were used at two locations in the northwestern United States (Tower and North 25) to compare runoff and sediment fluxes among natural forests and three types of forest disturbance—low soil burn severity, high soil burn severity, and skid trails. The natural sites had very low runoff rates (2.7 L min^{-1}), runoff velocities (0.016 m s^{-1}) and sediment flux rates (1.3×10^{-5} kg s^{-1}). Each type of disturbance produced greater runoff rates than the natural sites and these responses increased with increasing degree of disturbance (10-month old low soil burn severity, 2-week old low soil burn severity, high soil burn severity, and skid trail). The maximum runoff rate (21 L min^{-1}) was in the high soil burn severity and skid trail sites whereas the high soil burn severity sites produced the greatest runoff velocities (0.31 m s^{-1}). The skid trail sites produced the greatest sediment flux rates (0.011 kg s^{-1}) and this rate was more than 800 times the rate measured in the natural plots. Sediment flux rates in the natural and lesser disturbed sites were much lower than values previously reported for tilled agricultural soils, whereas maximum sediment flux rates in the high soil burn severity and skid trail sites were of the same order of magnitude as those reported for agricultural soils.

[51] While there was no difference in the runoff rates between the initial and steady state sample groups, the sediment flux rates were significantly lower in the steady state group for all the disturbance classes except the Tower

low soil burn severity site. These results suggest that erosion rates and sediment loads during the initial minutes of a single runoff event, or subject to initial runoff and erosion, would be much greater than those only a few minutes later.

[52] The slope class did not affect the runoff rate, runoff velocity, or sediment flux rate for any of the disturbance classes. At the Tower location, more infiltration occurred in the longer (4 m and 9 m) plots than in the shorter (2 m) plots, but the increased infiltration in the longer plots in the natural and low soil burn severity sites resulted in lower sediment flux rates.

[53] These results confirm that runoff and sediment production rates in natural forest areas are low and that disturbance of the forest floor and soil causes significant increases in the runoff rate, runoff velocity, and sediment flux rate.

[54] **Acknowledgments.** Funding for this project was provided by the U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Additional support was provided by the U.S. Department of Agriculture, Forest Service and U.S. Department of Interior Joint Fire Science Program. We are grateful for the assistance provided by the Umatilla and Okanogan-Wenatchee National Forests and by the field crews from the Moscow Forestry Sciences Laboratory. William Elliot, Richard Woodsmith, Craig Busskohl, Chi-hua Huang, Mark Nearing, Dave Turner, and Louise Ashmun provided insightful advice and comments. Comments from three anonymous reviewers, the editor, and the assistant editor also greatly improved this manuscript.

References

Abrahams, A. D., G. Li, and A. J. Parsons (1996), Rill hydraulics on a semiarid hillslope, southern Arizona, *Earth Surf. Processes Landforms*, *21*, 35–47, doi:10.1002/(SICI)1096-9837(199601)21:1<35::AID-ESP539>3.0.CO;2-T.

Bates, C. G., and A. J. Henry (1928), Forest and stream-flow experiment at Wagon Wheel Gap, Colorado, final report, *Weather Bur. Mon. Weather Rev. Suppl. 30*, U.S. Dep. of Agric., Washington, D. C.

Benavides-Solorio, J., and L. H. MacDonald (2001), Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range, *Hydrol. Processes*, *15*, 2931–2952, doi:10.1002/hyp.383. (Correction, Hydrol. Processes, 16, 1131–1133, doi:10.1002/hyp.5017, 2002.)

Benavides-Solorio, J., and L. H. MacDonald (2005), Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range, *Int. J. Wildland Fire*, *14*, 457–474, doi:10.1071/WF05042.

Binkley, D., and T. C. Brown (1993), Forest practices as nonpoint sources of pollution in North America, *Water Resour. Bull.*, *29*(5), 729–740.

Bryan, R. (2000), Soil erodibility and processes of water erosion on hillslope, *Geomorphology*, *32*, 385–415, doi:10.1016/S0169-555X(99)00105-1.

Burroughs, E. R., Jr., R. B. Foltz, and P. R. Robichaud (1991), Sediment production from forest roads and timber harvest areas, *Our Calif. Environ.*, *1*(4), 4–6.

Burroughs, E. R., Jr., C. H. Luce, and F. Phillips (1992), Estimating interrill erodibility of forest soils, *Trans. ASAE*, *35*(5), 1489–1495.

Croke, J. P., P. B. Hairsine, and P. Fogarty (1999), Sediment transport, redistribution and storage on logged forest hillslopes in south-eastern Australia, *Hydrol. Processes*, *13*, 2705–2720, doi:10.1002/(SICI)1099-1085(19991215)13:17<2705::AID-HYP843>3.0.CO;2-Y.

Croke, J. P., P. B. Hairsine, and P. Fogarty (2001), Soil recovery from track construction and harvesting changes in surface infiltration, erosion, and delivery rates with time, *For. Ecol. Manage.*, *143*, 3–12, doi:10.1016/S0378-1127(00)00500-4.

DeBano, L. F. (2000), The role of fire and soil heating on water repellency in wildland environments: A review, *J. Hydrol.*, *231–232*, 195–206, doi:10.1016/S0022-1694(00)00194-3.

Doerr, S. H., R. A. Shakesby, and R. P. D. Walsh (2000), Soil water repellency: Its causes, characteristics and hydro-geomorphological significance, *Earth Sci. Rev.*, *51*, 33–65, doi:10.1016/S0012-8252(00)00011-8.

Doerr, S. H., R. A. Shakesby, W. H. Blake, C. J. Chafer, G. S. Humphreys, and P. J. Wallbrink (2006), Effects of differing wildfire severities on soil wettability and implications for hydrological response, *J. Hydrol.*, *319*, 295–311, doi:10.1016/j.jhydrol.2005.06.038.

Elliot, W. J. (2000), Impact of roads and other corridors, in *Drinking Water From Forests and Grasslands—A Synthesis of the Scientific Literature*, *Gen. Tech. Rep. SRS-39*, edited by G. Dissmeyer, pp. 85–100, South. Res. Stn., For. Serv., U.S. Dep. of Agric., Asheville, N. C.

Elliot, W. J., A. M. Liebenow, J. M. Laflen, and K. D. Kohl (1989), A compendium of soil erodibility data from WEPP cropland soil field erodibility experiments 1987 & 1988, *Rep. 3*, Natl. Soil Erosion Res. Lab., West Lafayette, Indiana.

Foltz, R. B., H. Rhee, and K. A. Yanosek (2007), Infiltration, erosion, and vegetation recovery following road obliteration, *Trans. ASABE*, *50*(6), 1937–1943.

Foltz, R. B., H. Rhee, and W. J. Elliot (2008), Modeling changes in rill erodibility and critical shear stress on native surface roads, *Hydrol. Processes*, *22*, 4783–4788, doi:10.1002/hyp.7092.

Forest Service (1998), North 25 fire burned area report, Okanogan-Wenatchee National Forest, U.S Dep. of Agric., Wenatchee, Wash.

Foster, G. R. (1982), Modeling the erosion process, in *Hydrologic Modeling of Small Watersheds*, *Am. Soc. Agric. Eng. Monogr.*, vol. 5, edited by C. T. Haan, H. P. Johnson, and D. L. Brakensiek, pp. 297–380, Am. Soc. Agric. Eng., St. Joseph, Mich.

Foster, G. R., L. F. Huggins, and L. D. Meyer (1984), Laboratory study of rill hydraulics: I Velocity relationships, *Trans. ASAE*, *27*(3), 790–796.

Gee, G. W., and J. W. Bauder (1986), Particle-size analysis, in *Methods of Soil Analysis: Part 1*, edited by A. Klute, pp. 383–411, Am. Soc. of Agron., Madison, Wis.

Gilley, J., E. Kottwitz, and J. Simanton (1990), Hydraulic characteristics of rills, *Trans. ASAE*, *33*(6), 1900–1906.

Giménez, R., and G. Govers (2001), Interaction between bed roughness and flow hydraulics in eroding rills, *Water Resour. Res.*, *37*(3), 791–799, doi:10.1029/2000WR900252.

Giovannini, G., and S. Lucchesi (1983), Effect of fire on hydrophobic and cementing substances of soil aggregates, *Soil Sci.*, *136*(4), 231–236, doi:10.1097/00010694-198310000-00006.

Govers, G. (1991), Rill erosion on arable land in central Belgium: Rates, controls and predictability, *Catena*, *18*, 133–155, doi:10.1016/0341-8162(91)90013-N.

Govers, G. (1992), Relationship between discharge, velocity and flow area for rills eroding loose, non-layered materials, *Earth Surf. Processes Landforms*, *17*, 515–528, doi:10.1002/esp.3290170510.

Han, S. K., H. S. Han, D. S. Page-Dumroese, and L. R. Johnson (2009), Soil compaction associated with cut-to-length and whole-tree harvesting of a coniferous forest, *Can. J. For. Res.*, *39*, 976–989, doi:10.1139/X09-027.

Harvey, A. E., J. M. Geist, G. L. McDonald, M. F. Jurgensen, P. H. Cochran, D. Zabowski, and R. T. Meurisse (1994), Biotic and abiotic processes in eastside ecosystems: The effects of management on soil properties, processes, and productivity, *Gen. Tech. Rep. PNW-GTR-323*, 71 pp., Pac. Northwest Res. Stn., For. Serv., U.S. Dep. of Agric., Portland, Oreg.

Hendricks, B. A., and J. M. Johnson (1944), Effects of fire on steep mountain slopes in central Arizona, *J. For.*, *42*, 568–571.

Holland, M. E. (1969), Design and testing of rainfall systems, *Ser. Rep. 69-70*, Colo. State Exp. Stn., Fort Collins.

Huang, C., J. M. Bradford, and J. M. Laflen (1996), Evaluation of the detachment-transport coupling concept in the WEPP rill erosion equation, *Soil Sci. Soc. Am. J.*, *60*, 734–739.

Huisinga, K. D., D. C. Laughlin, P. Z. Fulé, J. D. Springer, and C. M. McGlone (2005), Effects of an intense prescribed fire on understory vegetation in a mixed conifer forest, *J. Torrey Bot. Soc.*, *132*(4), 590–601, doi:10.3159/1095-5674(2005)132[590:EOAIPF]2.0.CO;2.

Inbar, M., M. Tamir, and L. Wittenberg (1998), Runoff and erosion processes after a forest fire in Mount Carmel, a Mediterranean area, *Geomorphology*, *24*, 17–33, doi:10.1016/S0169-555X(97)00098-6.

Isaac, L. A., and H. G. Hopkins (1937), The forest soil of the Douglas-fir region, and changes wrought upon it by logging and slash burning, *Ecology*, *18*(2), 264–279, doi:10.2307/1930465.

King, K. W., and L. D. Norton (1992), Methods of rill flow velocity dynamics, paper presented at International Winter Meeting, Am. Soc. of Agric. Eng., Nashville, Tenn., 15–18 Dec.

Lal, R. (2001), Soil degradation by erosion, *Land Degrad. Dev.*, *12*, 519–539, doi:10.1002/ldr.472.

Lei, T., M. Nearing, K. Haghighi, and V. Bralts (1998), Rill erosion and morphological evolution: A simulation model, *Water Resour. Res.*, *34*(11), 3157–3168, doi:10.1029/98WR02162.

Littel, R. C., G. A. Milliken, W. W. Stroup, R. D. Wolfinger, and O. Schabenberger (2006), *SAS® for Mixed Models*, 2nd ed., SAS Inst., Cary, N. C.

Liu, B., M. Nearing, P. Shi, and J. Jia (2000), Slope length effects on soil loss for steep slopes, *Soil Sci. Soc. Am. J.*, *64*, 1759–1763.

MacDonald, L. H., D. Coe, and S. Litschert (2004), Assessing cumulative watershed effects in the central Sierra Nevada: Hillslope measurements and catchment-scale modeling, in *Proceedings of the Sierra Nevada Science Symposium*, *Gen. Tech. Rep. PSW-GTR-193*, edited by D. D. Murphy and P. A. Stine, pp. 149–157, Pac. Southwest Res. Stn., For. Serv., U.S. Dep. of Agric., Albany, Calif.

Mataix-Solera, J., C. Guerrero, F. García-Orenes, G. M. Bárcenas, and M. P. P. Torres (2009), Forest fire effects on soil microbiology, in *Fire Effects on Soils and Restoration Strategies*, edited by A. Cerdá and P. R. Robichaud, pp. 134–175, Sci. Publ., Enfield, N. H.

McCool, D., G. Foster, C. Mutchler, and L. Meyer (1989), Revised slope length factor for the universal soil loss equation, *Trans. ASAE*, *32*(5), 1571–1576.

Megahan, W. F., and W. J. Kidd (1972), Effects of logging and logging roads on erosion and sediment deposition from steep terrain, *J. For.*, *70*, 136–141.

Megahan, W. F., and J. G. King (2004), Erosion, sedimentation, and cumulative effects in the northern Rocky Mountains, in *A Century of Forest and Wildland Watershed Lessons*, edited by G. G. Ice and J. D. Stednick, pp. 201–222, Soc. of Am. For., Bethesda, Md.

Meyer, L. D., G. R. Foster, and S. Nikolov (1975), Effect of flow rate and canopy on rill erosion, *Trans. ASAE*, *8*, 905–911.

Moody, J. A., and D. A. Martin (2009), Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States, *Int. J. Wildland Fire*, *18*, 96–115, doi:10.1071/WF07162.

Nearing, M., L. Norton, D. Bulgakove, G. Larionov, L. West, and K. Dontsova (1997), Hydraulics and erosion in eroding rills, *Water Resour. Res.*, *33*(4), 865–876, doi:10.1029/97WR00013.

Nearing, M. A., J. R. Simanton, L. D. Norton, S. J. Bulygin, and J. Stone (1999), Soil erosion by surface water flow on a stony, semiarid hillslope, *Earth Surf. Processes Landforms*, *24*, 677–686, doi:10.1002/(SICI)1096-9837(199908)24:8<677::AID-ESP981>3.0.CO;2-1.

Ott, L. (1993), *An Introduction to Statistical Methods and Data Analysis*, 4th ed., Wadsworth, Belmont, Calif.

Pannkuk, C. D., and P. R. Robichaud (2003), Effectiveness of needle cast at reducing erosion after forest fires, *Water Resour. Res.*, *39*(12), 1333, doi:10.1029/2003WR002318.

Parsons, A., P. R. Robichaud, S. A. Lewis, C. Napper, and J. Clark (2010), Field guide for mapping post-fire soil burn severity, *Gen. Tech. Rep. RMRS-243*, Rocky Mt. Res. Station, For. Serv., U.S. Dep. of Agric., Ft. Collins, Colo.

Patric, J. H., J. O. Evans, and J. D. Helvey (1984), Summary of sediment yield data from forested land in the United States, *J. For.*, *82*, 101–104.

Pierson, F. B., P. R. Robichaud, C. A. Moffet, K. E. Spaeth, S. P. Hardegree, P. E. Clark, and C. J. Williams (2008), Fire effects on rangeland hydrology and erosion in a steep sagebrush-dominated landscape, *Hydrol. Processes*, *22*, 2916–2929, doi:10.1002/hyp.6904.

Pietraszek, J. H. (2006), Controls on post-fire erosion at the hillslope scale, Colorado Front Range, M.S. thesis, 124 pp., Colo. State Univ., Fort Collins.

Robichaud, P. R. (2000), Fire effects on infiltration rates after prescribed fire in northern Rocky Mountain forests, USA, *J. Hydrol.*, *231–232*, 220–229, doi:10.1016/S0022-1694(00)00196-7.

Robichaud, P. R., C. H. Luce, and R. E. Brown (1993), Variation among different surface conditions in timber harvest sites in the southern Appalachians, in *The International Workshop on Soil Erosion*, edited by G. A. Larionov and M. A. Nearing, pp. 231–241, Cent. for Technol. Transfer and Pollut. Prev., Purdue Univ., West Lafayette, Indiana.

Robichaud, P. R., J. L. Beyers, and D. G. Neary (2000), Evaluating the effectiveness of postfire rehabilitation treatments, *Gen. Tech. Rep. RMRS-GTR-63*, Rocky Mt. Res. Station, For. Serv., U.S. Dep. of Agric., Fort Collins, Colo.

Robichaud, P. R., J. W. Wagenbrenner, R. E. Brown, P. M. Wohlgemuth, and J. L. Beyers (2008), Evaluating the effectiveness of contour-felled log erosion barriers as a post-fire runoff and erosion mitigation treatment in the western United States, *Int. J. Wildland Fire*, *17*, 255–273, doi:10.1071/WF07032.

Ryan, K. C., and N. V. Noste (1985), Evaluating prescribed fires, *Gen. Tech. Rep. INT-182*, pp. 230–238, Intermt. Res. Stn., For. Serv., U.S. Dep. of Agric., Ogden, Utah.

SAS Institute (2008a), *SAS® for Windows 9.2*, SAS Inst., Cary, N. C.

SAS Institute (2008b), *SAS/STAT 9.2 User's Guide*, SAS Inst., Cary, N. C.

Sheridan, G. J., H. B. So, R. J. Loch, and C. M. Walker (2000a), Estimation of erosion model erodibility parameters from media properties, *Aust. J. Soil Res.*, *38*, 265–284, doi:10.1071/SR99041.

Sheridan, G. J., H. B. So, R. J. Loch, C. Pocknee, and C. M. Walker (2000b), Use of laboratory-scale rill and interill erodibility measurements for the prediction of hillslope-scale erosion on rehabilitated coal mine soils and overburdens, *Aust. J. Soil Res.*, *38*, 285–297, doi:10.1071/SR99039.

Sheridan, G. J., P. N. J. Lane, and P. J. Noske (2007), Quantification of hillslope runoff and erosion processes before and after wildfire in a wet Eucalyptus forest, *J. Hydrol.*, *343*, 12–28, doi:10.1016/j.jhydrol.2007.06.005.

Slattery, M., and R. Bryan (1992), Hydraulic conditions for rill incision under simulated rainfall: A laboratory experiment, *Earth Surf. Processes Landforms*, *17*, 127–146, doi:10.1002/esp.3290170203.

Startsev, A. D., and D. H. McNabb (2000), Effects of skidding on forest soil infiltration in west-central Alberta, *Can. J. Soil Sci.*, *80*, 617–624.

Steinbrenner, E. C., and S. P. Gessel (1955), The effect of tractor logging on physical properties of some forest soils in southwestern Washington, *Soil Sci. Soc. Proc.*, *19*, 372–376.

Stott, T., and N. Mount (2004), Plantation forestry impacts on sediment yields and downstream channel dynamics in the U.K.: A review, *Prog. Phys. Geogr.*, *28*, 197–240, doi:10.1191/0309133304pp410ra.

Swank, W. T., L. F. DeBano, and D. Nelson (1989), Effects of timber management practices on soil and water, in *The Scientific Basis for Silvicultural and Management Decisions in the National Forest System*, *Gen. Tech. Rep. WO-55*, edited by R. L. Burns, pp. 79–106, For. Serv., U.S. Dep. of Agric., Washington, D. C.

Takken, I., G. Govers, C. A. A. Ciesiolka, D. M. Silburn, and R. J. Loch (1998), Factors influencing the velocity-discharge relationship, in *Modeling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes*, edited by W. Summer, E. Klaghofer, and W. Zhang, *IAHS Publ.*, 249, 63–69.

Troendle, C. A., and R. M. King (1985), Effect of timber harvest on the Fool Creek Watershed, 30 years later, *Water Resour. Res.*, *21*(12), 1915–1922, doi:10.1029/WR021i012p01915.

Wagenbrenner, J. W., L. H. MacDonald, and D. Rough (2006), Effectiveness of three post-fire rehabilitation treatments in the Colorado Front Range, *Hydrol. Processes*, *20*, 2989–3006, doi:10.1002/hyp.6146.

Wagenbrenner, J. W., P. R. Robichaud, and W. J. Elliot (2010), Rill erosion in natural and disturbed forests: 2. Modeling approaches, *Water Resour. Res.*, *46*, W10507, doi:10.1029/2009WR008315.

Williamson, J. R., and W. A. Neilsen (2000), The influence of forest site on rate and extent of soil compaction and profile disturbance of skid trails during ground-based harvesting, *Can. J. For. Res.*, *30*, 1196–1205, doi:10.1139/cjfr-30-8-1196.

Yanosek, K. A., R. B. Foltz, and J. H. Dooley (2006), Performance assessment of wood strand erosion control materials among varying slopes, soil textures, and cover amounts, *J. Soil Water Conserv.*, *61*(2), 45–51.

Zartl, A., A. Klik, and C. Huang (2001), Soil detachment and transport processes from inter-rill and rill areas, *Phys. Chem. Earth*, *26*(1), 25–26.

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