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Wildfire effects on road surface erosion, deposition, and road–stream connectivity

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ABSTRACT: High and moderate severity wildfires should increase sediment production from unpaved roads due to the increased surface runoff from upslope, and increase road–stream connectivity due to the decrease in downslope surface roughness as well as the increase in surface runoff and erosion. Because no study has documented these effects, we surveyed road surface erosion features and quantified road–stream connectivity as a function of fire severity and road segment characteristics. The data were collected one year after the High Park wildfire from 141 hydrologically distinct road segments along 6.8 km of an unpaved road west of Fort Collins, Colorado. Road segments below areas burned at high and moderate severity had significantly more rills than road segments below areas that burned at low severity. Road segment slope was an important control on the proportion of segment length with rills, and the strength of the relationship between road segment slope and the amount of rilling increased with burn severity. Flatter road segments tended to capture the sediment eroded from upslope burned areas. In areas burned at high and moderate severity all of the road segments had drainage features extending to a stream, and 78% of the segments in areas burned at low severity also were connected. These exceptionally high rates of road–stream connectivity are attributed to the increased runoff from upslope, the segment-scale collection and funneling of hillslope and road surface runoff to a single drainage point, and the reduced infiltration and trapping capacity of the burned area below the road. The results show the need to either outslope the roads or increase the frequency of constructed drainage features after wildfires, particularly for steeper road segments in areas burned at high or moderate severity.
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KEYWORDS: wildfire; runoff; road surface erosion; road–stream connectivity; disturbance cascades

Introduction

Both unpaved roads and severe wildfires can reduce infiltration rates to less than 10 mm h^{-1} and increase surface erosion rates by several orders of magnitude (Ziegler and Giambelluca, 1997; Shakesby and Doerr, 2006; MacDonald and Larsen, 2009; Moody and Martin, 2009; Robichaud *et al*., 2016). It follows that roads in areas burned at high and moderate severity will produce even more runoff and erosion, and the resultant effects on flooding, water quality, aquatic habitat, and sedimentation rates are a major concern for the public and resource managers (Neary *et al*., 2005). Resource managers typically upgrade or remove road crossings and may increase the number and size of waterbars to accommodate the increased runoff and sediment loads after wildfires. However, to the best of our knowledge, there have been no studies that have directly examined how wildfires affect road surface rilling and deposition as a result of the increased runoff and sediment from upslope, or how the combination of fires and roads alters road–stream connectivity.

The goal of this study was to evaluate how the interactions between fire severity and road segment characteristics affect road erosion features, sediment deposition, road drainage features, and road–stream connectivity. The study was conducted along 6.8 km of an unpaved road that passed through areas burned at varying severity by the 2012 High Park fire west of Fort Collins, Colorado.

Background and Objectives

Roads are essential for many forest management activities, as they provide access for timber harvest, fire management, insect and disease control, and recreation. The problem is that unpaved forest roads significantly alter hillslope hydrology by increasing and concentrating surface runoff and erosion (Jones and Grant, 1996; Fu *et al*., 2010; Sidle and Ziegler, 2012; van Meerveld *et al*., 2014). Actively-used unpaved road surfaces are severely compacted, and saturated hydraulic conductivity values for unpaved roads have been reported as 0.2 mm h^{-1} to 5.1 mm h^{-1} (Ziegler and Giambelluca, 1997), 5 mm h^{-1} (Ramos-Scharrón and LaFevor, 2016), <8.8 mm h^{-1} (Foltz *et al*., 2007), and 0 to 12 mm h^{-1} (Luce, 1997). These low values mean that even low or moderate intensity rains can generate infiltration-excess overland flow (Ziegler and Giambelluca, 1997; Ramos-Scharrón and MacDonald, 2007).

In sloped areas road cuts can further increase the amount of surface runoff by intercepting downslope subsurface flow

(Megahan, 1972; Wemple and Jones, 2003; Negishi *et al.*, 2008). Road cuts that intersect the entire soil profile are more likely to intercept subsurface flow than road segments whose road cuts intersect only part of the soil profile (Wemple and Jones, 2003).

The total amount and energy of overland flow on the road surface is important because this determines both the erosive force and sediment transport capacity (Luce and Black, 1999). Since road surfaces have minimal detention storage, the amount of runoff from a road segment (Q in l^3[volume] T^{-1}) is:

$$Q = (P - I)\,A + \mathrm{SSSF} + \mathrm{HOF}_{\mathrm{upslope}} \quad (1)$$

where P is the rainfall or snowmelt intensity (in l T^{-1}), I is the infiltration rate (l T^{-1}), A is the road surface area (l^2), SSSF is the intercepted subsurface stormflow ($l^3\,T^{-1}$), and HOF ($l^3\,T^{-1}$) is the overland flow from upslope. The energy of the road surface runoff depends on the amount of road surface runoff (Equation (1)) and the road segment slope (MacDonald and Coe, 2008). Thus the product of road surface area times road segment slope, or segment area times segment slope squared, is often used to predict road surface erosion because this captures both the amount and the energy of the road surface runoff (e.g. MacDonald *et al.*, 1997; Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2005).

Unpaved roads also can concentrate surface runoff depending on the road drainage design and hillslope characteristics. Road segments with an insloped design concentrate the surface runoff into an inside ditch that is then drained by a culvert or cross-drain (Moll *et al.*, 1997). On crowned roads half of the road surface drains to an inside ditch while the outer half drains to the outside edge (Moll *et al.*, 1997). Planar roads do not have any cross-slope, so the runoff flows along the road surface until a dip or waterbar diverts it, usually to the outside edge. Outsloped roads direct the runoff across the road so the water is dispersed along the outside edge. Hence the road drainage design affects the extent to which the road surface runoff is concentrated or dispersed, which then affects the potential for road surface rilling, rilling on the fillslope and hillslope where the water drains off the roadbed, and the potential delivery of runoff and sediment (Takken *et al.*, 2008).

Road surface erosion rates are typically orders of magnitude higher than the erosion rates from adjacent undisturbed areas (Dubé *et al.*, 2004; Fu *et al.*, 2010), but these high rates are generally only a concern for resource managers if: (1) the runoff and sediment are delivered to a stream, wetland, or lake where it can adversely affect water quality and aquatic habitat; or (2) the road becomes difficult to travel because of rilling and gullying. The delivery of road sediment depends on the hydrologic connectivity, where connectivity refers to the linkage or connection between a runoff source and the receiving water(s) (Croke and Mockler, 2001). The hydrologic connectivity of a given road can be highly variable according to both the segment and site characteristics (Takken *et al.*, 2008). Key factors that affect road–stream connectivity include the amount of runoff from the road segment, placement and type of road drainage structures such as waterbars, distance from the drainage outlets to streams, hillslope gradient, downslope infiltration capacity, and the trapping efficiency of obstructions (Megahan and Ketcheson, 1996; Croke and Hairsine, 2006).

For analysis purposes unpaved roads are commonly divided into hydrologically distinct segments (Luce and Black, 1999; Wemple and Jones, 2003). A road segment is typically defined by the road prism, which includes the road surface plus the cutslope and fillslope if present) and the inside ditch if the road is crowned or insloped (Dubé *et al.*, 2004). From a hydrologic perspective, the road segment also should include the hillslope draining onto the road, but in forested areas the high infiltration rates means that this source of runoff is commonly ignored. However, in recently burned forested areas infiltration rates can be less than 10 mm h^{-1}, and this plus other changes in soil and vegetative cover can increase surface runoff and erosion rates by one or more orders of magnitude (Martin and Moody, 2001; Neary *et al.*, 2005; Foltz *et al.*, 2009). Areas burned at high and moderate severity are generally of much greater concern than areas burned at low severity (Benavides-Solorio and MacDonald, 2001; Larsen *et al.*, 2009). Wildfires are also a concern because the downslope reduction in infiltration, surface roughness, and associated trapping capacity can greatly increase the likelihood for water and sediment to be delivered from burned hillslopes to a stream or other water body (Robichaud, 2005; Wagenbrenner *et al.*, 2006).

After wildfires resource managers often try to protect forest roads, primarily by increasing the capacity of culverts and drainage structures to handle the increased runoff, sediment, and woody debris (Robichaud *et al.*, 2000; Foltz *et al.*, 2009). However, no studies have documented how road erosion features and road–stream connectivity change after wildfires.

Hence the specific objectives of this study were to evaluate how: (1) the frequency and size of road surface erosion features vary with upslope fire severity and road segment characteristics; and (2) road drainage features and road–stream connectivity vary with fire severity. Process-based models helped compare the relative amounts of runoff and sediment from a typical road segment and hillslopes under unburned and burned conditions. The results should help forest managers assess and potentially minimize both post-fire road surface erosion and the downslope delivery of water and sediment to streams or other aquatic features.

Study Area

The study was conducted along the Old Flowers Road (US Forest Service Road 152), which is a poorly-maintained, unpaved 19-km long road in the Colorado Front Range approximately 40 km west of Fort Collins, Colorado (Figure 1). It runs primarily through forested land managed by the Arapaho-Roosevelt National Forest (ARNF). The road climbs from 2230 m at the eastern end to a maximum elevation of 2560 m, and then drops sharply to 2400 m at the western end where it terminates at the intersection with Pingree Park Road (Figure 1).

The area surrounding the road was burned in June 2012 by the 350 km^2 High Park Fire. Within the fire perimeter, 41% of the area was classified as high vegetation burn severity, 19% as moderate severity, 27% as low severity, and 13% as unburned (Stone, 2015). Most of the Old Flowers Road is on sideslopes with only a few sections on a ridgetop or in a valley bottom. It is closed during the winter due to snow and had relatively low traffic during the summer because some sections were severely rutted, making it only passable for high-clearance four-wheel drive vehicles. Off-highway and all-terrain vehicles are prohibited.

Different sections of the road were selected for detailed surveys according to the upslope burn severity; sections of the road that were in the valley bottom, in unburned areas, or immediately adjacent to stream crossings were excluded to maximize comparability among the surveyed sections. The mean hillslope gradient above and below the road was 18% so the surveyed road segments generally had a

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Figure 1. Location of Old Flowers Road and the High Park Fire, Colorado. Orange areas were burned, and gray areas were unburned. [Colour figure can be viewed at wileyonlinelibrary.com]

cut-and-fill profile, but the cutslopes intersected only a thin layer of the soil profile so there was little evidence of subsurface flow interception. Road design was primarily planar and there were no insloped segments with inside ditches, so waterbars were the primary structures for draining water off the road surface.

Mean annual precipitation at the Buckhorn Mountain 1 E weather station (Figure 1) is approximately 550 mm (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?cobuck). This falls as snow from about November through April, and predominantly as rain from May through October. Both post-fire and road erosion are driven almost entirely by the convective storms that occur from about 1 June through 30 September (Benavides-Solorio and MacDonald, 2005; Welsh, 2008).

The bedrock is metamorphic, igneous, and sedimentary, with metamorphic biotitic and felsic gneiss covering approximately 79% of the burned area. Approximately 20% of the burned area is granitic, while sedimentary formations cover only about 1% of the area (BAER, 2012). The three dominant soil types are Haploborolls-Rock outcrop complex, Wetmore-Boyle-Rock outcrop complex, and Redfeather sandy loam. These three soils generally have from 10% to 60% rock fragments by volume in the surface horizons and 35% to 80% rock fragments in the subsoil (Moreland, 1980). Surface textures are primarily sandy loam. Rock outcrops are common (BAER, 2012) but generally were not present upslope of our surveyed road sections. The main tree species along Old Flowers Road prior to the fire were ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), and aspen (*Populus tremuloides*).

Methods

Delineation of study segments and hillslope characterization

The detailed road survey was conducted in July–August 2013, which was just over one year after burning. This identified 141 hydrologically distinct road segments, with most segments being defined by waterbars at each end. A global positioning system (GPS) with a resolution of 3 m was used to register the beginning and end of each road segment. For each segment we characterized the road prism, the hillslope draining onto the road segment, and the drainage feature(s) (rill or sediment plume) emanating from that segment.

Burn severity was classified as high, moderate, or low following Parsons *et al.* (2010) for a 50-m wide strip upslope of each segment. High soil burn severity was defined by the complete consumption of surface organic layer and at least some of the organic matter in the uppermost portion of the mineral soil. Moderate soil burn severity was defined by complete charring or consumption of the organic layer with no alteration of the organic matter, shallow roots, or rhizomes in the underlying mineral soil. Low soil burn severity was defined by some charring of the surface organic layer but the original form of some leaves and needles were still intact and there was only limited exposure of the mineral soil.

Hillslope gradients above and below the road were measured with a clinometer. Percent bare soil, rock, and vegetation (including litter) cover were visually estimated for a 20-m zone above each segment. Some short sections had been treated with straw mulch immediately after the fire, but this was lumped with vegetation and litter because it provides similar protection against post-fire soil sealing and erosion (Larsen *et al.*, 2009). Wood cover was not estimated because there were very few residual logs.

Erosion features coming from the hillslope were classified as none, sheetwash, or rills. Sheetwash was identified by the absence of ash and loss of surface fines as indicated by protruding rock fragments together with evidence of overland flow such as small debris dams, pockets of deposition behind obstructions, and wide shallow channels. Rills were defined as channelized erosional features at least 5 cm deep. For the purposes of this paper gullies, which are channels at least 0.5 m deep (Soil Science Society of America [SSSA], 2001) or with a cross-sectional area of 0.09 m^2 (Poesen *et al.*, 2003), were lumped with rills because there was no need to separate these and the channels on the hillslopes and roads shifted back and forth between rills and gullies as they coalesced, diverged, or became shallower or deeper due to the presence of rocks, roots, or bedrock. The width and depth of a representative rill draining onto a segment was measured to the extent that these could be identified.

A 1-m digital elevation model (DEM) derived from July 2013 aerial LiDAR (light detection and ranging) data was used with the ArcHydro extension of ArcGIS 10.2 and a minimum threshold drainage area of 5000 m^2 to delineate the channel network. This threshold is more than the minimum drainage area of 100 to 3000 m^2 reported for channel initiation after the High Park fire (Wohl, 2013) but less than the threshold of ~10 000 m^2 for unburned areas (Henkle *et al.*, 2011), and it provided the most realistic results based on our field observations. The DEM also was used to calculate the contributing area above each road segment, and to determine the horizontal distance between the drainage point(s) for each segment and the nearest channel as identified by ArcHydro.

Road segment characterization

The drainage design for each segment was classified as planar or outloped. Segment length was measured along the centerline of the road with a measuring wheel. Total width (the width of the road surface) and active width (the actively used road tread) were measured at a minimum of three locations in each segment to determine a mean value. There was relatively little variation in these widths as the overall mean standard deviation (s.d.) for the active and total widths was 0.3 m. Segment slope was measured with a clinometer, and a distance-weighted mean slope was calculated if the slope varied over the length of the segment. Road segment area was calculated as segment length times active width, and this was used to calculate the additional independent variables of segment area times segment slope, and segment area times segment slope squared.

Percent surface cover was visually estimated for each road segment using the same classes of bare soil, rock, and vegetation plus litter. These visual estimates had been trained by comparisons with quantitative data collected from 29 road segments in a separate study (Sosa-Pérez, 2016). The percent of the road surface with recent sediment deposits from the hillslope also was estimated, as the sediment deposited from upslope was very distinct due to its darker color from ash and charred organic matter. The total length of all rills on each segment was measured, and for each rill a representative width and depth was measured. The length of the longest rill was used to calculate the proportion of segment length with a rill. The percent of the segment area with rills was calculated by multiplying the length of each rill by its representative width, summing these areas, and dividing this by the road segment area. Rill volumes were calculated for the road segments with slopes of at least 5% in order to help determine how much the fire had increased rill volumes in areas burned at high and moderate severity as opposed to low severity.

Drainage features

The drainage feature(s) coming from each segment were classified as a rill or a sediment plume, where a sediment plume was defined by a trail of deposited sediment. Gullies were again lumped with rills, and the number of drainage rills was counted for each segment. The widths and depths of these rills were measured at the outer edge of the road if they were well defined. The cross-sectional area of each rill was calculated by assuming a triangular shape, and these values were summed to obtain a total cross-sectional drainage area for the segment. In many cases, however, the width and depth could not be reliably determined because the drainage features were a broken and highly variable mixture of rills and sediment plumes due to large rocks at the edge of the road. Many other road segments had waterbars or a short low-gradient section at the lower end that led to diffuse outflow, and in these cases the depth of the drainage rill was either less than 5 cm or too variable to measure. Hillslope roughness below each road segment was classified into four qualitative classes, where class 1 was mostly smooth with little potential for trapping water and sediment; class 2 was mostly litter and perhaps some small woody debris so there was only limited trapping capacity; class 3 had some obstructions such as woody debris or small logs; and class 4 – which we did not observe in this study – would have multiple large obstructions (logs, rocks) with very high sediment trapping capacity.

A road segment was assumed to be connected if the drainage feature extended to within 5 m of a channel. In many cases, however, it was not possible to track the road drainage features because these merged with the sheetwash and rills originating on the burned hillslope below the road to form a complex set of new and often larger rills. For 56% of the segments the stream was sufficiently close so that we could directly determine if a segment was connected to the stream, while for the other 44% the combined road drainage and hillslope rills were so long – in some cases more than 100 m – that it was not practical to trace every drainage feature. For these segments we assumed the road drainage feature was connected to the stream when there was low roughness on the hillslopes below the road, and the rills increased in size or frequency in the downslope direction. In most cases the channels below the road were small, confined ephemeral tributaries with little or no riparian zone or valley bottom, so there was little or no potential for the observed flowpaths to be interrupted before reaching a channel.

Statistical analysis

The first step was to determine if any of the independent and dependent variables varied significantly with burn severity using either analysis of variance (ANOVA) or non-parametric methods. The independent variables were the hillslope and road surface characteristics, while the dependent variables were the proportion of road segment length with rills, the percent of road segment area covered by rills or sediment deposits, and the cross-sectional area of the drainage features. Most of the variables were normally distributed, and if there was a significant difference at $p < 0.05$, multiple comparisons (LSMeans) were used to determinate which means were significantly different (SAS Institute, Inc., 2002–2010) and Tukey's method was used for all pairwise comparisons (Ott

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and Longnecker, 2008). If the data were not normally distributed, non-parametric Kruskal–Wallis tests were used to determine whether there were significant differences among burn severities as standard transformations were not able to successfully normalize the data. If significant differences were detected we used the Nemenyi pairwise test for multiple comparisons of mean rank sums using the PMCMR package in R (R Core Team, 2015).

The relationships between the independent and dependent variables were initially assessed with scatterplots and simple linear regression. Multiple linear regression with stepwise model selection (SAS Institute, Inc., 2002–2010) was used to develop predictive models for each dependent variable for all of the data, and then for each subset of data after stratifying by burn severity class. Variables were only included if they were significant at $p \leq 0.05$.

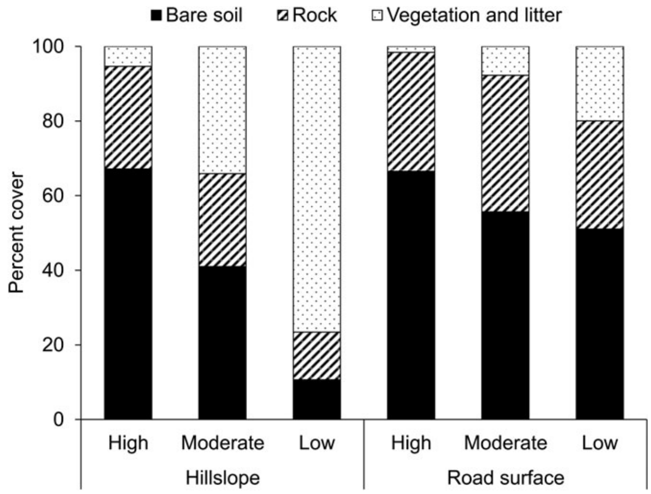

Figure 2. Mean surface cover by burn severity for the upper hillslope and the active road surface.

Results

Hillslope and road segment characteristics

The number of road segments were relatively similar when stratified by burn severity, with 37%, 27%, and 36% of the 141 road segments below areas burned at high, moderate, and low severity, respectively. No segments were sampled in unburned areas. The overall mean contributing area of the hillslopes above the road was 0.82 ha, and this did not vary significantly with burn severity (Table I). Four road segments with contributing areas of 10 to 49 ha were excluded from some of the data analyses because the size of these contributing areas as delineated by ArcGIS were unrealistically large and inconsistent with our field observations.

The mean gradient for the hillslopes above the road was 18% (s.d. = 8%) with no significantly differences by burn severity (Table I). Hillslope gradients below the road were generally very similar to the gradients above the road, but the hillslopes below the road in areas burned at high severity averaged only 15% slope, which was significantly less than the mean value of 21% for areas burned at low severity (Table I).

Percent bare soil on the hillslope above the road decreased significantly with decreasing burn severity, as the mean values were 67%, 41%, and 11% for areas burned at high, moderate, and low severity, respectively (Figure 2). Similarly, the mean vegetation and litter cover on the upper hillslope significantly increased from 5% in the areas burned at high severity to 34% and 77% for the areas burned at moderate and low severity, respectively. These values are consistent with other studies in the Colorado Front Range (e.g. Benavides-Solorio and MacDonald, 2005).

Eighty-six percent or 121 of the 141 road segments had a planar design while the other 20 road segments were outsloped, with the outsloped segments being relatively evenly distributed by burn severity. Mean segment length was 49 m (s.d. = 18 m), and the minimum and maximum segment lengths were 18 and 122 m, respectively (Table I). Both the mean active width of 2.4 m (s.d. = 0.3 m) and the mean total width of 2.9 m (s.d. = 0.3 m) were relatively consistent, and neither segment length nor width varied significantly with burn severity. Mean segment slope was 8% with a range of 1% to 19%; the 6% mean slope of the road segments below areas burned at high severity was significantly less than the mean segment slopes of 9% and 10% for the roads below areas burned at moderate and low severity, respectively (Table I).

The overall road surface cover averaged 58% bare soil (s.d. = 27%) and 32% rock (s.d. = 26%) (Figure 2). The segments in areas burned at high severity did have significantly more bare soil than the segments in areas burned at low severity, with mean values of 67% (s.d. = 29%) and 51% (s.d. = 24%), respectively. The mean vegetation and litter cover of 20% (s.d. = 26%) for the segments burned at low severity also was significantly higher than the segments burned at high and moderate severity (Figure 2). The high percent rock cover is

Table I. Mean, standard deviation (s.d.), and range of the hillslope and road segment characteristics by burn severity

	Burn severity					
	High ($n = 54$)		Moderate ($n = 37$)		Low ($n = 50$)	
Hillslope and segment characteristic	Mean ± s.d.	Range	Mean ± s.d.	Range	Mean ± s.d.	Range
Contributing area (ha)[1]	0.86 ± 1.1	0.03–5.9	0.73 ± 0.85	0.10–4.9	0.85 ± 1.3	0.04–8.8
Upper hillslope gradient (%)	16 ± 9	5–35	19 ± 7	5–36	19 ± 8	2–36
Lower hillslope gradient (%)	$15^{a} \pm 9$	2–35	$17^{ab} \pm 8$	3–37	$21^{b} \pm 9$	3–50
Road segment length (m)	47 ± 20	21–122	50 ± 16	20–83	49 ± 18	18–97
Road active width (m)	2.4 ± 0.3	1.9–3.3	2.3 ± 0.3	1.8–2.8	2.4 ± 0.2	2.2–3.1
Road segment slope (%)	$6^{a} \pm 4$	1–15	$9^{b} \pm 5$	1–19	$10^{b} \pm 5$	1–19

Note: The numbers in parentheses at the top of each column are the number of segments. Different letters indicate significant differences among burn severities, and the absence of letters indicates no significant differences.

[1]These values do not include the four segments with exceptionally large contributing areas of 10 to 49 ha as delineated from the digital elevation model (DEM). These four segments included one each in areas burned at high and moderate severity, and two segments in areas burned at low severity.

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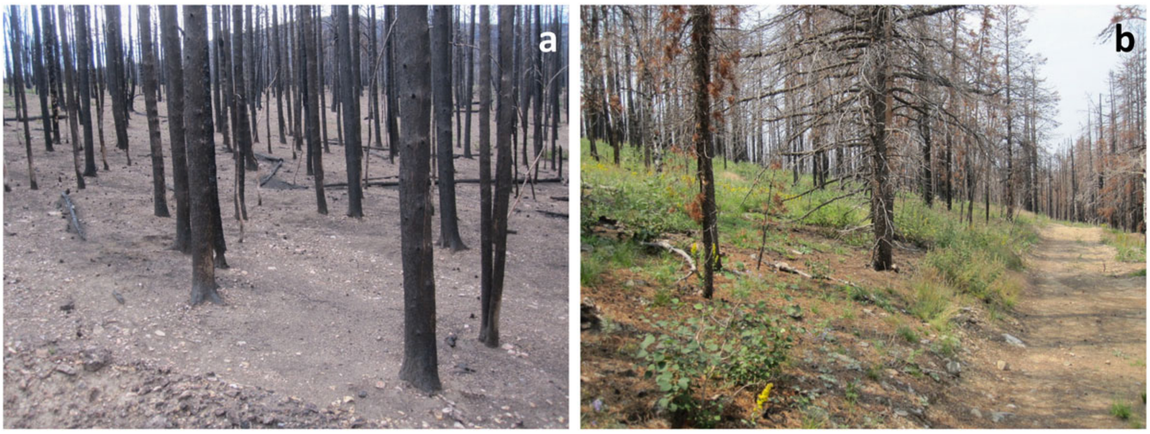

Figure 3. (a) Representative hillslope from an area burned at high severity that experienced extensive rainsplash and sheetwash erosion. (b) Representative hillslope burned at low severity showing much more live vegetation, some residual charred litter, and minimal surface erosion. [Colour figure can be viewed at wileyonlinelibrary.com]

consistent with the high rock content of the soils and the extensive road surface rilling, but percent rock cover did not vary significantly by burn severity (Figure 2).

Erosion features on the upper hillslope

The amount and type of erosion features on the upper hillslope varied with burn severity, but quantitative measurements and comparisons were hindered by the large numbers of rills and their small-scale variations in size and depth. This variability often made it difficult to distinguish between rills and deep sheetwash, particularly in areas burned at high severity (Figure 3a). Hence representative rills draining onto a road segment could only be identified and measured for 16 of the 54 road segments below hillslopes burned at high severity. For these segments the mean rill width was 0.30 m and the mean depth was 0.07 m. Qualitatively, the hillslopes burned at moderate severity had fewer rills and much less deeply incised sheetwash than the hillslopes burned at high severity, but there

Figure 4. Representative road segments along Old Flowers Road. (a) Road segment with 10% slope and road surface rilling below an area that burned at high severity. (b) Road segment with 2% slope below an area burned at high severity with no rills due to deposited sediment. (c) Road segment below an area that burned at moderate severity showing how the one rill in the wheel track closest to the upper side of the road captures all of the runoff from the burned hillslope above the road. (d) An unusually large incised gully draining a 51-m long road segment in an area burned at high severity. This gully drained directly to the ephemeral stream at the base of the slope, and its large size can be attributed to the combination of runoff from the severely burned hillslope and the 15% slope of the road segment. [Colour figure can be viewed at wileyonlinelibrary.com]

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was no difference in the mean width and depth of the measured rills. In contrast, only 46% of the road segments in areas burned at low severity had rills coming from the upper hillslope (Figure 3b). Representative rills could only be identified and measured for seven segments, and these rills also had a very similar width and depth as the rills on the more severely burned hillslopes. These results indicate that the amount of deep sheetwash and rilling greatly increased with burn severity, but these differences were expressed primarily by a difference in frequency than in the width and depth of the rills that were present.

Effects of burn severity and road segment characteristics on road segment rilling and deposition

The percent of segments with rills in areas burned at high severity was slightly less than the percent of segments in areas burned at moderate severity (70% versus 89%), but this is almost certainly due to the significantly lower mean slope of the segments in areas burned at high severity (Table I; Figures 4a and 4b). Rills were only present on 54% of the segments in areas burned at low severity. In contrast, the number of rills on the road surface did not vary with burn severity because the wheel track on the cutslope or upper side of the road generally captured the runoff from both the upper hillslope and the road surface, resulting in just one rill (Figure 4c). Only 15% of the segments with rills had two or more rills.

The mean percent of segment length with rills and the mean segment area covered by rills varied significantly with fire severity (Figure 5). On average the segments in areas burned at high severity had rills for 55% of their length as compared to 76% for the segments in areas burned at moderate severity and 38% for the segments in areas burned at low severity. The lower amount of rilling for segments in areas burned at high severity versus moderate severity can be attributed to their significantly lower mean slopes, as segment slope was the strongest control on the proportion of segment length with rills when all the data were pooled ($R^2 = 0.24$; $p < 0.0001$) (Table II). Surprisingly, upslope contributing area, percent bare soil on the hillslope above the road, and road surface cover did not significantly affect either the proportion of segment length with rills or percent rill area ($R^2 < 0.01$).

When stratified by burn severity, the road segments in areas burned at high severity had the strongest relationship between segment slope and the proportion of segment length with rills ($R^2 = 0.75$; Figure 6). For the segments in areas burned at low severity segment slope only explained 15% of the variation in the proportion of segment length with rills. The results for rill area were very similar because rill area was closely related to the proportion of segment length with rills ($R^2 = 0.59$).

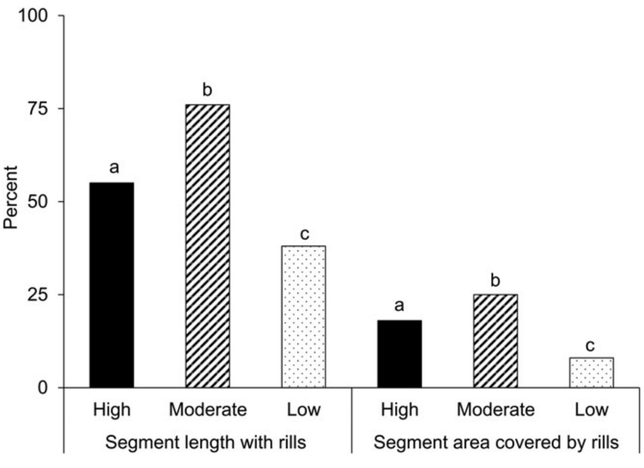

Figure 5. Mean percent of segment length with rills and mean percent of segment area covered by rills by burn severity. Different letters indicate significant differences.

Table II. Multiple linear regression models to predict the proportion of segment length with rills for all segments, and for the segments stratified by high, moderate, and low burn severity, respectively. Intercept values that are not significant are shown in italics, and n/a means that a variable was not significant

Model characteristics	All data	Burn severity High	Burn severity Moderate	Burn severity Low
Model R^2	0.38	0.76	0.38	0.23
Number of independent variables	3	3	1	1
Intercept				
Parameter estimate	0.230	*−0.093*	0.402	*0.111*
p-value	0.0002	*0.14*	<0.0001	*0.21*
Road segment slope (%)				
Partial R^2	0.24	0.70	0.38	
Parameter estimate	0.040	0.099	0.040	n/a
p-value	<0.0001	<0.0001	<0.0001	
Road surface rock (%)				
Partial R^2	0.11	0.04		
Parameter estimate	0.003	0.003	n/a	n/a
p-value	0.005	0.01		
Hillslope vegetation (%)				
Partial R^2	0.03			
Parameter estimate	−0.003	n/a	n/a	n/a
p-value	0.0001			
Length × slope squared				
Partial R^2		0.02		
Parameter estimate	n/a	0.00003	n/a	n/a
p-value		0.04		
Segment area × slope				
Partial R^2				0.23
Parameter estimate	n/a	n/a	n/a	0.0002
p-value				0.0004

In contrast to rill length and rill area, rill widths and depths tended to increase with burn severity, but rill size did not significantly vary between segments in areas burned at high severity versus moderate severity (Figure 7). The mean rill width of 0.47 m (s.d. = 0.18 m) and mean rill depth of 0.11 m (s.d. = 0.07 m) for the segments in areas burned at low severity generally were significantly lower than the mean values for road segments in areas burned at high and moderate severity (Figure 7). The larger road surface rills below areas burned at high and moderate severity is consistent with greater amounts of surface runoff.

Mean rill volumes for the road segments with a slope of at least 5% were 2.9 m^3 (s.d. = 3.2 m^3) and 2.6 m^3 (s.d. = 2.4 m^3) in areas burned at high and moderate severity, respectively. The road segments in areas burned at low severity had a significantly smaller mean rill volume of 0.9 m^3 (s.d. = 1.2 m^3) despite their slightly steeper mean slope and nearly identical mean segment area ($p < 0.0001$). Since the post-fire increase in hillslope runoff would be much smaller in areas burned at low severity, the much lower mean rill volume can be considered as the maximum value prior to burning, and the three-fold increase in rill volumes in areas burned at high and moderate severity can be attributed to the greater increase in hillslope runoff after burning. This inference is further supported by the fact that most of the road surface rills in areas

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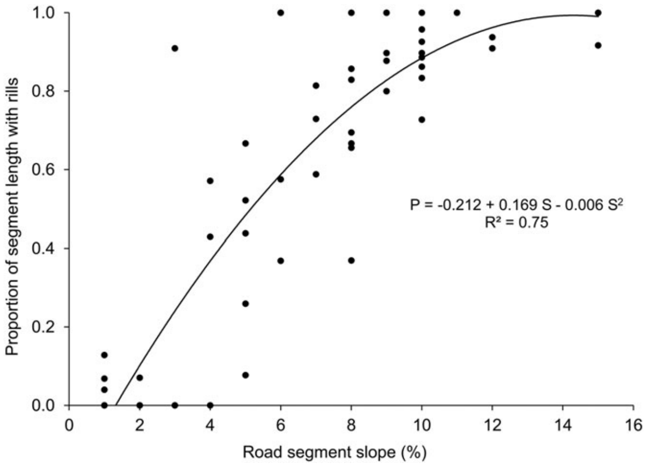

Figure 6. Proportion of road segment length with rills (*P*) versus segment slope (*S*) for the segments in areas burned at high severity. The polynomial regression equation is only valid up to its maximum value at 15%.

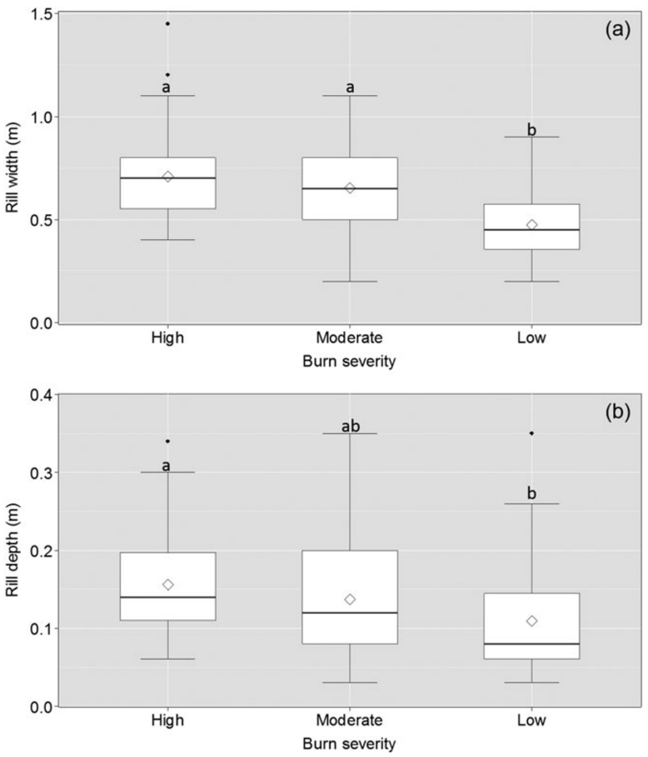

Figure 7. Mean rill width (a), and mean rill depth (b) by burn severity. Different letters indicate significant differences. The line in the box represents the median, the diamond is the mean, and the boxes represent the 25th to 75th percentiles. The upper and lower whiskers extend from the box to the highest or lowest value that is within 1.5*IQR of the box, where IQR is the distance between the 25th and 75th percentiles. Data beyond the end of the whiskers are outliers and plotted as points.

burned at high and moderate severity were freshly incised and enlarged, whereas the rills in areas burned at low severity showed much less evidence of recent erosion.

Multivariate linear regression indicated that segment slope was the strongest control on the proportion of segment length with rills when all the data were pooled (Table II). The proportion of segment length with rills also increased with the amount of rock cover and a decrease in the amount of hillslope vegetation (Table II), but the relationship with rock cover is most likely a result of the post-fire road surface rilling rather than a cause.

The interactions between the different controlling factors are more clear when the data were stratified by burn severity. In areas burned at high severity road segment slope was the dominant control on the proportion of the road segment with rills, and this was followed by the amount of rock cover on the road segment and road segment length times segment slope squared ($R^2 = 0.76$; Table II). Road segment slope was the only significant variable for the segments in areas burned at moderate severity, but the relationship was much weaker than for the segments burned at high severity ($R^2 = 0.38$). In areas burned at low severity road segment area times slope was the only variable that was significantly related to the proportion of road length with rills ($R^2 = 0.23$).

These results indicate that when there is much less surface runoff from upslope, such as from unburned areas or areas burned at low severity, road surface area is an important source of overland flow and a significant control on road surface rilling. In areas burned at high or moderate severity road segment slope is the primary control on road surface rilling and road surface area is relatively unimportant as there is so much more runoff from upslope.

An unexpected result was the extent to which the flatter road segments tended to capture and store the sediment coming from the upper hillslope (Figure 4b). The percent of road segments with sediment deposits increased with increasing burn severity from 14% in areas burned at low severity to 24% and 37% for the road segments in areas burned at moderate and high severity, respectively. This increase in the percent of the segments with sediment deposits is due to both the increasing amounts of sediment being produced from upslope and the differences in road segment slopes with burn severity. Segment slope explained 34% of the variation in the percent of the road surface with sediment deposits, and the scatterplot suggests a threshold effect as no segment with a slope of more than 5% had more than 25% of its area covered by sediment deposits (Figure 8).

Effect of the road on flow paths, drainage feature characteristics, and road–stream connectivity

The presence of Old Flowers Road had a major effect on the post-fire hillslope flow paths (Figure 9). The hillslopes burned at high and moderate severity generated large amounts of surface runoff, and this led to extensive sheetwash and numerous

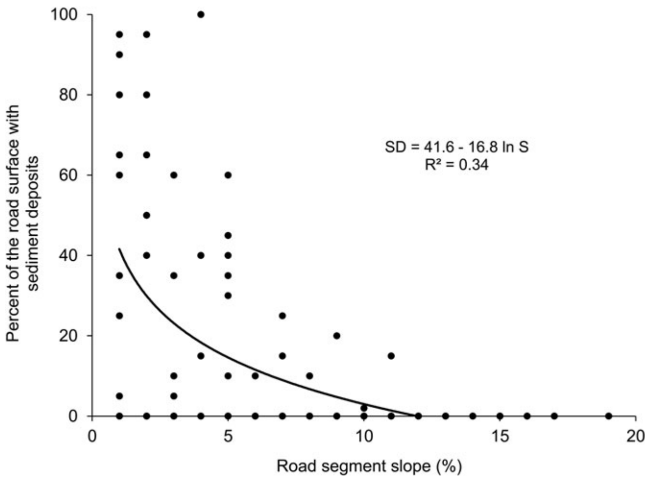

Figure 8. Percent of the road surface with sediment deposits (SD) versus road segment slope (*S*). Many points represent multiple segments, especially those on the *x* axis.

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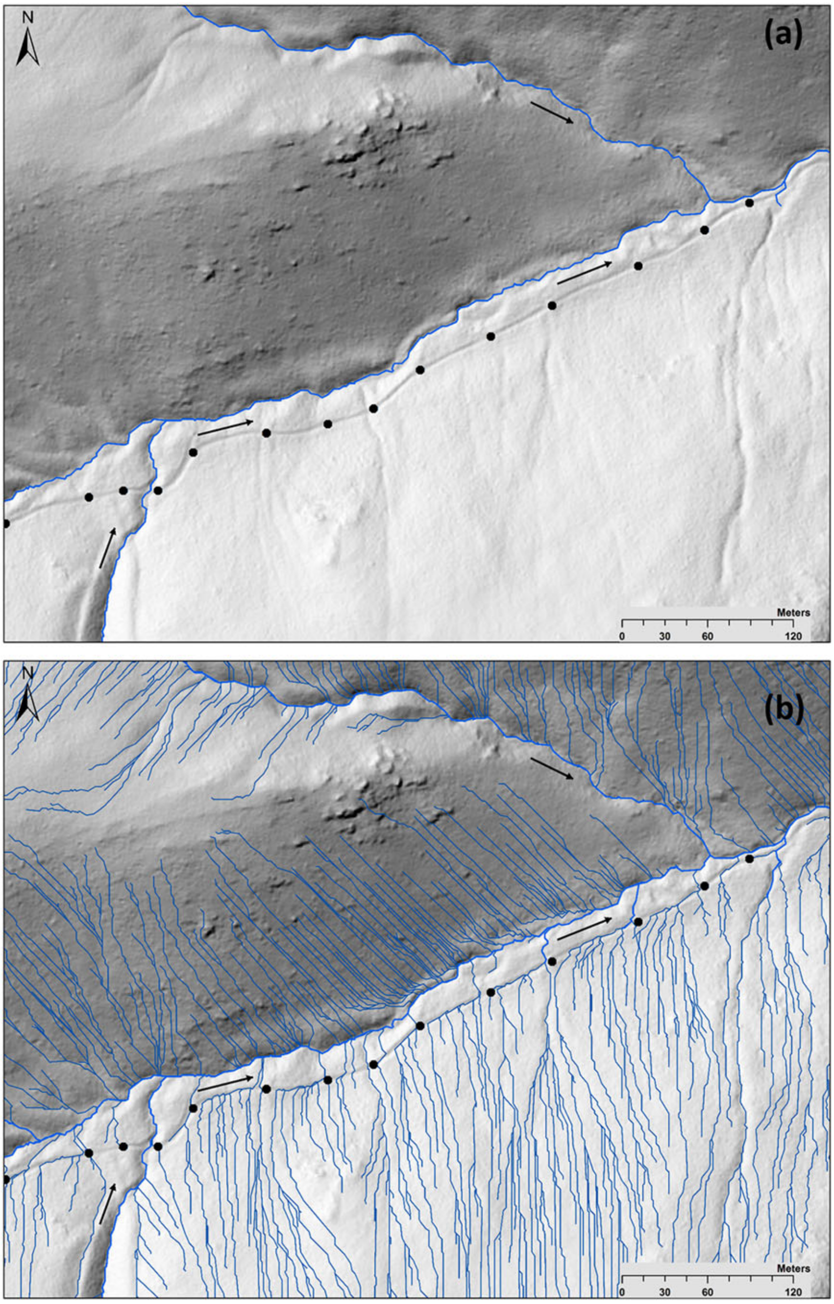

Figure 9. (a) Enlarged view of a typical section of Old Flowers Road running parallel to a seasonal stream in an area burned at moderate severity. Black dots show the beginning and end of each road segment as identified by the field survey, and the arrows indicate the flow direction. (b) The same road section showing how the road segments collected the dispersed runoff from the upper hillslope and then funneled this to a single drainage point. The hillslope flow paths were generated from the LiDAR-derived DEM using a threshold drainage area of 200 m^2. [Colour figure can be viewed at wileyonlinelibrary.com]

parallel rills that flowed down onto the road (Figure 9b). The road typically collected all of this runoff and diverted it down the road, usually in a single, deeply incised rill or gully (Figures 4c and 9b). For 74% of the 141 segments the hillslope and road surface runoff was collected over the entire length of the segment and discharged at a single drainage point (Figure 10). Sixteen percent of the segments had from two to nine drainage points, while 4% of the segments were outsloped with either dispersed runoff or at least 10 small drainage features. The remaining 6% of the road segments had no distinct drainage feature, and all of these segments were in areas burned at low severity and therefore had substantially less surface runoff from upslope (Figure 10).

The section of road in Figure 9b clearly shows how Old Flowers Road disrupted the LiDAR-derived hillslope flow paths in an area burned at moderate severity. The field survey confirmed that nearly all of the runoff from upslope was

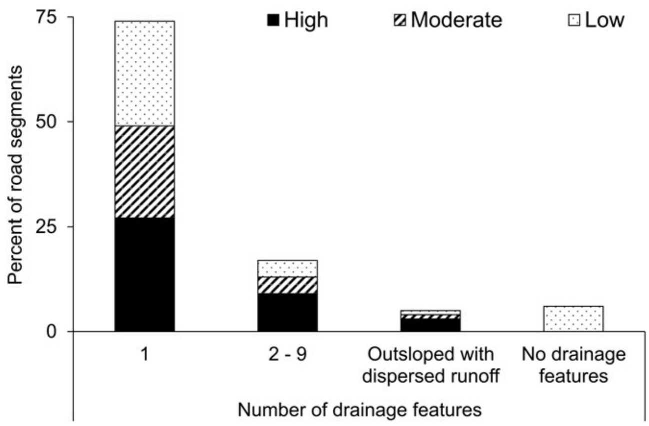

Figure 10. Percent of all road segments by number of drainage features and burn severity.

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collected by the road and generally discharged at a single location, and this concentration of flow helped ensure that each of the road segments was directly connected to the stream. This concentration of runoff by Old Flowers Road is very different to the multiple flowpaths on the burned but unroaded hillslope on the opposite side of the stream (Figure 9b).

The mean cross-sectional area of the incised drainage rills leaving the road was 0.1 m^2 in areas burned at high and moderate severity, with virtually no difference between high and moderate severity (Figure 11). Some of these drainage rills were quite large, as the maximum width was 1.70 m and the maximum depth was 0.48 m. The drainage rills from the road segments in areas burned at low severity were significantly smaller ($p = 0.02$) (Figure 11).

The high-resolution DEM data indicated that the mean horizontal distance between the road drainage points and the nearest modeled stream channel was nearly 70 m (s.d. = 53 m), and this did not significantly vary by burn severity. Twenty percent of the segments were more than 100 m from the stream, and three segments were more than 200 m from the stream. The field survey showed that all of the 91 segments in areas burned at high and moderate burn severity were connected to the stream, and this included 25 segments that were more than 100 m from a stream. Seventy-eight percent of the road segments in areas burned at low severity were connected to the stream.

These very high rates of road–stream connectivity can be attributed in large part to the increased runoff from the upslope burned areas and the reduced roughness of the burned hillslopes below the road. The hillslopes below 96% of the segments in areas burned at high severity and 67% of the segments burned at moderate severity were classified as roughness class 1, meaning that they were mostly smooth with little potential for trapping water and sediment. In the areas burned at low severity only 38% of the hillslopes below the road had a roughness class of one, while 59% had a roughness class of two. Even though the hillslopes below the road in areas burned at low burn severity tended to be steeper (Table I), this did not fully compensate for the lower amounts of hillslope runoff and higher downslope roughness as 22% of the segments in areas burned at low severity were still not connected to the stream. Each of these 11 segments were below hillslopes with at least 80% vegetation cover and no erosion features, indicating that relatively little surface runoff and erosion was coming from the hillslope onto the road. These 11 segments also did not have any road surface rilling, further confirming the relative lack of overland flow.

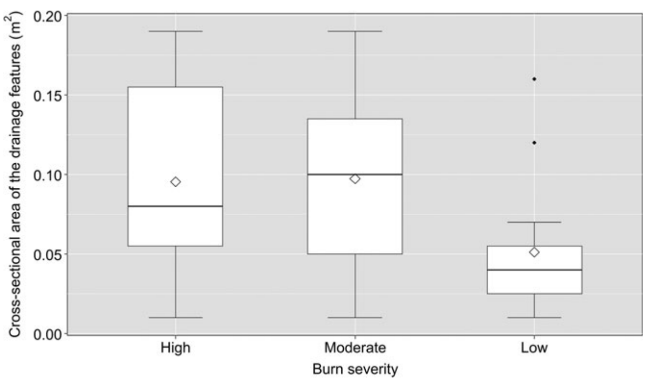

Figure 11. Boxplots of the cross-sectional areas of the representative drainage features by burn severity. The format of the boxplots is identical to those in Figure 7.

Discussion

Relative importance of hillslope and road segment characteristics for road surface runoff and erosion

Both severely burned hillslopes and unpaved roads have very low infiltration and high surface erosion rates (Robichaud, 2000; Fu *et al.*, 2010). Since a road surface and its contributing hillslope are subject to the same rainfall, burned hillslopes above a road should be the dominant source of road surface runoff and erosion because of their much greater contributing area. In this study the average upslope contributing area was 0.82 ha compared to just 0.012 ha for the average road segment, or a 70-fold difference. This large difference means that, at least for unpaved roads in mid-slope or downslope positions in a burned area, the amount of road surface runoff and associated rilling should be strongly related to the hillslope contributing area and the amount of bare soil on the hillslope, as these are primary controls on sediment production and presumably surface runoff (Larsen *et al.*, 2009; Robichaud, 2005; Wagenbrenner *et al.*, 2015). However, our results showed that the length and area of rills on the road surface were primarily controlled by road segment slope rather than the contributing area or percent bare soil of the burned hillslope above the road (Table II).

The primary importance of road segment slope as a control on rill length and rill area should not be surprising because slope controls the potential energy of flowing water. Road segment slope is typically a key factor in both empirical and process-based road surface erosion models; in some empirical models percent slope is even more dominant because it is raised to a power of 1.5 to 2 (Luce and Black, 1999; Ramos-Scharrón and MacDonald 2005). Road segment slope was an increasingly important control on the extent of road segment rilling with increasing burn severity (Table II), and this indicates how burn severity and segment slope work together to increase rill lengths and areas on the road surface. Conversely, the overland flow often could not transport all of the sediment that was being delivered onto, and generated from, road segments with slopes ≤5%, resulting in deposition (Figure 8).

In areas burned at low severity the compound variable of road segment area times slope was the only significant control on road surface rilling. The inclusion of road segment area in areas burned at low severity is logical because these hillslopes typically generate much less surface runoff than hillslopes burned at high or moderate severity (e.g. Robichaud, 2000; Benavides-Solorio and MacDonald, 2001). If a hillslope produces less surface runoff, road segment area becomes a relatively more important source of the surface runoff that induces road surface rilling.

In areas burned at high and moderate severity the combined variable of road segment area times slope was either insignificant or of minor importance compared to road segment slope. This indicates that in more severely burned areas the amount of hillslope runoff is more important for generating rills on the road surface than the infiltration-excess overland flow from the road surface. The analogous situation for unburned hillslopes is when the cutslope intercepts large amounts of subsurface flow (Equation (1)), as this additional surface runoff can greatly increase road surface erosion rates compared to segments without this additional source of runoff (e.g. Wemple and Jones, 2003; Coe, 2006).

The relative importance of road segments and hillslopes was further explored by comparing predicted average annual runoff and erosion for road segments using WEPP:Road (Elliot *et al.*, 1999) and hillslopes using Disturbed WEPP (Elliot and Hall, 2010). These process-based models use the same underlying model structure and stochastic climates, which maximizes the comparability of their results, and Disturbed WEPP has been validated for burned hillslopes similar to the study area (Larsen and MacDonald, 2007).

We used our field-measured average values for the modeled road segment, so this was 50 m long with a slope of 8%, a sandy loam soil with 32% rock fragments, planar but rutted, and with low traffic. Runoff and erosion also were predicted for an unburned, low severity, and high severity hillslope using our average contributing hillslope that was 170 m long with a slope of 18% and a sandy loam soil with 22% rock content. Surface cover was assumed to be 100% under unburned conditions, 80% for low severity, and 30% for high severity. Both models were run using a 30-year average climate adjusted to the study area using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly *et al.*, 1997).

Predicted road surface runoff was only $0.23\,m^3\,yr^{-1}$ (Figure 12a), or just 0.4% of the annual precipitation. The unburned hillslope generated $5\,m^3\,yr^{-1}$ of runoff, while the predicted runoff from the hillslopes burned at low and high severity were approximately four and nearly 10 times larger than the unburned hillslope (Figure 12a). The much larger volumes of hillslope runoff are primarily due to its much larger area relative to the road segment.

Predicted sediment yields had a quite different pattern, as the road segment generated $33\,kg\,yr^{-1}$ while the unburned hillslope produced no sediment and the hillslope burned at low severity generated just half of the predicted sediment from the much smaller road segment (Figure 12b). Predicted sediment production from the severely burned hillslope was much larger at $230\,kg\,yr^{-1}$ or seven times the predicted value from the road segment (Figure 12b).

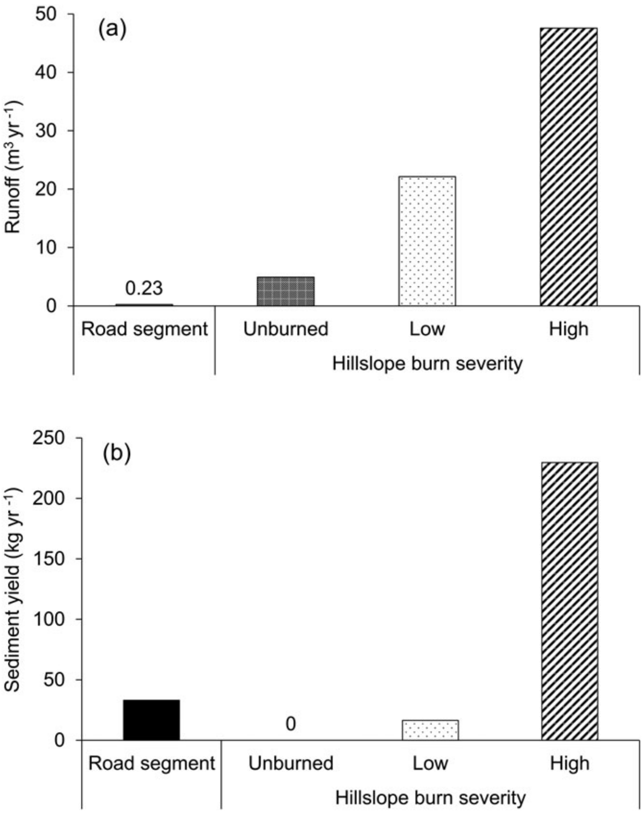

Figure 12. (a) Predicted surface runoff (in $m^3\,yr^{-1}$) and (b) predicted sediment yields ($kg\,yr^{-1}$) from a road segment using WEPP:Road and an unburned, low severity, and high severity hillslope above the road using Disturbed WEPP. The modeled road segment and hillslope both used mean values from our field survey.

When these model predictions are combined with road and post-fire erosion data from the Colorado Front Range (MacDonald and Stednick, 2003; Libohova, 2004; Benavides-Solorio and MacDonald, 2005; Welsh, 2008), we can generalize that road segment characteristics control road sediment production in unburned areas, with unburned hillslopes potentially contributing some runoff (SSSF in Equation (1)) but no sediment. After a fire the hillslopes are a progressively more important source of sediment with increasing burn severity, with hillslopes burned at high severity producing far more sediment than the road segment. The data in the present study show that under burned conditions road segment slope is critical for determining the amount of road surface rilling and whether the sediment is deposited or transported to the drainage outlet. These combined results show how fires alter the controls, complexity, and magnitudes of road surface erosion and deposition compared to road erosion studies in unburned areas (e.g. Dubé *et al.*, 2004; Fu *et al.*, 2010).

A more complete evaluation of the interactions between hillslopes and roads is not possible because the predicted hillslope runoff and sediment from Disturbed WEPP cannot be directly used as an additional input into WEPP:Road. Similarly, the user interface in Road:WEPP does not readily allow one to modify a downslope buffer area to reflect the reduced infiltration and roughness following fires. Hence we cannot readily compare our field data to model predictions, and the linking of process-based road and hillslope models is an important management need.

It should be emphasized that the additive effects of burned hillslopes on road surface erosion and road–stream connectivity are primarily a short-term problem. Typically the runoff and erosion from burned hillslopes sharply decreases within three to firve years as they revegetate and infiltration rates recover (Larsen *et al.*, 2009; Wagenbrenner *et al.*, 2015). In areas very similar to the High Park fire hillslope sediment yields typically decline to very low values by the third summer after burning (Benavides-Solorio and MacDonald, 2005; Wagenbrenner *et al.*, 2006).

In contrast, infiltration and sediment production from actively-used roads do not recover over time, so roads are chronic sources of overland flow and sediment. After a wildfire the pulse of sediment inputs from burned hillslopes is initially much larger than the sediment inputs from roads simply because roads occupy only 1% or so of the watershed area. But at the watershed scale and over longer time periods the chronic delivery of sediment from unpaved roads can be roughly similar to the much larger but less frequent pulses of sediment from wildfires (MacDonald and Larsen, 2009). This means that the land managers have to decide whether to focus their mitigation and restoration efforts on the road segments that are producing much more sediment per unit area over time, or on the spatially more extensive burned hillslopes that produce a shorter-term but much more dramatic impact on water quality and sediment yields.

Road–stream connectivity

This study found that 92% of the 141 road segments were connected to the stream despite a mean distance of 70 m between the road and the channel network. These exceptionally high connectivity rates and distances for road–stream connectivity are in marked contrast to nearly all other studies of road–stream connectivity for unburned conditions. Road–stream connectivity from other studies in the

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Colorado Front Range with similar precipitation were only 14% (Welsh, 2008) and 15% (Libohova, 2004). Studies in the Sierra Nevada of California reported road–stream connectivity values of only 25% for a wetter area with a mixture and rain and snow (Coe, 2006) and 30% for a lower elevation rain-dominated area (Stafford, 2011). A study in Oregon reported that 34% of the roads were connected to a stream (Wemple *et al.*, 1996), while in southeastern Australia 25% of the surveyed road drains were connected to the stream (Croke *et al.*, 2005).

These much lower rates of road–stream connectivity from unburned areas can be largely explained by the relatively short length of the road drainage features. For example, the mean length of road drainage rills and sediment plumes was less than 20 m in a highly erosive granitic terrain in the central Colorado Front Range (Libohova, 2004), and only 12 m for drainage features from waterbars and rolling dips in a relatively wet area of weathered granitics in California's Sierra Nevada (Coe, 2006). Newly-constructed road segments in the Idaho batholith had a mean sediment plume length of just 12 m for segments with rock drains (Megahan and Ketcheson, 1996). These short distances can be attributed to the typically high infiltration rates and roughness in forested areas. The length of rills and sediment plumes from relief culverts are generally longer as these typically collect the runoff from much longer segments, but the mean length was still only 37 m in the Sierra Nevada (Coe, 2006) and 53 m for newly-constructed roads in Idaho (Megahan and Ketcheson, 1996).

Our data show that after high and moderate severity fires the rills and gullies emanating from the road extend for many tens or even hundreds of meters. The much longer lengths of these drainage features are due to the increased amounts of runoff and sediment from upslope, the accumulation and discharge of this runoff at a single location due to the road segment, and the reduced infiltration and roughness of the burned hillslopes below the road. This means that after wildfires the distance from a road to a stream becomes a much less important control on road–stream connectivity. A high post-fire rate of road–stream connectivity also is due to the tremendous headward extension of the channel network after high and moderate severity wildfires (Eccleston, 2008; Wohl, 2013). The much greater drainage density, when combined with the reduction in infiltration and surface roughness, has led to the assertion that nearly all of the post-fire hillslope runoff and sediment is delivered to the stream network (Pietraszek, 2006). Given these changes, it should not be surprising that road–stream connectivity values can approach 100% in sloped areas that have recently burned at high and moderate severity. It is somewhat more surprising that 78% of the road segments in areas burned at low severity were connected to the stream, but we would expect this high connectivity to rapidly decline with vegetative regrowth and the accompanying increases in infiltration and surface roughness.

The combined discharge from burned hillslopes and roads also is more likely to trigger debris flows or landslides as part of a disturbance cascade (Montgomery, 1994; Nakamura *et al.*, 2000). Similarly, the more concentrated delivery of runoff and sediment from a road will initiate larger and longer drainage rills or gullies, and the delivery of large amounts of runoff and sediment to the stream channels can trigger additional downstream disturbances such as flooding, bank erosion, and streamside landslides (Nakamura *et al.*, 2000). Each of these cascading processes can leave a distinctive disturbance signature on stream and riparian biota and habitat.

Management Implications

After high and moderate severity wildland fires resource managers can use various treatments to increase the capacity of drainage structures and road crossings to convey runoff, sediment, and woody debris. The specific road treatments depend on the local climate, burn severity, resources at risk, cost, and other factors, but the most commonly used road treatments include: (1) rolling dips, waterbars, and/or cross drains to improve road surface drainage; (2) increasing culvert size and adding metal end sections; (3) ditch cleaning and armoring; and (4) culvert removal (Foltz *et al.*, 2009). In this study 70 of the 141 road segments were defined by older waterbars that existed before the High Park fire. Surprisingly, none of these waterbars failed despite the increased runoff and erosion after burning.

The increased hillslope runoff after fires, particularly in areas burned at high and moderate severity, indicates that land managers need to greatly increase the amount of road surface drainage after wildfires, and this is especially critical for road segments with more than 5% slope. Any increase in drainage frequency should reduce the amount of localized surface runoff and rilling, and reduce the volume of concentrated outflow at any given drainage point. For planar roads this increased drainage can be accomplished either by adding waterbars or rolling dips, but the optimal waterbar spacing after fires is a topic that needs further investigation.

Our results do provide some guidance for waterbar spacing as a function of segment slope, as rills occupied only 28% of the segment length on segments with less than 6% slope in areas burned at high and moderate severity. This means that 72% of the road segment length was unrilled, which would imply that, at least for our study area, segments could be up to 37 m long with relatively little rilling, and the spacing of water bars or other drainage structures could be set accordingly. Road segments with a slope of 6 to 10% had rills for 80% or their length, and this increased to 94% for segments with more than 10% slope. These data suggest that it is extremely difficult to stop road surface rilling on moderately or steeply sloped road segments after a high or moderate severity wildfire, but frequent waterbars should reduce road surface erosion and hence the need for post-fire regrading to maintain driveability. An increased frequency of waterbars may not, however, greatly reduce road–stream connectivity in areas burned at high and moderate severity given the low hillslope infiltration rates and surface roughness. It should be self-evident that any effort to increase road surface drainage needs to be done as soon as possible after burning, and the potential benefits need to be weighed against the costs.

Outsloping is another but substantially more expensive treatment as it requires a regrading of the road surface. This should greatly reduce concentrated outflows, but in the absence of rocking it is only likely to be effective if traffic is completely prohibited under wet weather conditions since a single vehicle can create a small depression that captures some surface runoff. The concentrated flow in such a depression can progressively incise and capture more surface runoff and divert this down the road until it reaches a waterbar, stream crossing, or low gradient section. Hence outsloped roads in hilly terrain should either be closed to all traffic for the first two or so years after burning, or have some waterbars or other drainage structures to insure that the road is properly drained. In summary, the combined effects of fires and roads pose a very difficult challenge for land managers, but any effort to reduce the adverse effects of roads after a fire will continue to be beneficial after the hillslopes recover.

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Conclusions

The objectives of this study were to evaluate how fire severity and road segment characteristics interact to affect the frequency and size of road surface erosion features and road–stream connectivity. High and moderate severity wildfires greatly increase surface runoff and erosion rates, and the road segments below hillslopes burned at high and moderate severity had significantly more rilling than road segments below hillslopes burned at low severity. Road segment slope was a very important control on the percent of segment length with rills, and by implication the amount of sediment eroded from the road surface. Conversely, the flatter road segments (≤ 5% slope) tended to capture the sediment eroded from upslope burned areas. Road surface area did not affect the amount of rilling on the road surface except in areas burned at low severity, and this shows the increasing importance of hillslope runoff and the decreasing importance of road surface runoff with increasing burn severity. The modeled erosion from hillslopes and a typical road segment confirmed the increasing dominance of hillslope runoff and sediment production with increasing burn severity.

The majority of the road segments collected all of the dispersed runoff and sediment from the burned hillslopes and discharged it at a single drainage point. All of the road segments in areas burned at high and moderate severity were connected to the stream, despite a mean distance to the stream of nearly 70 m, and 78% of the road segments in areas burned at low severity also were connected. These extremely high rates of road–stream connectivity can be attributed to the increased runoff from upslope, the effectiveness of the road in capturing and funneling the hillslope and road surface runoff to a single point, and the reduced infiltration and trapping capacity of the burned hillslopes below the road. The results show the need for an increased frequency of drainage structures immediately after wildfires, particularly for steeper road segments in areas burned at high or moderate severity. A key need is to couple existing process-based road and hillslope models to better understand and predict road surface runoff, sediment production and deposition, and road–stream connectivity resulting from the synergistic interactions between burned hillslopes and road segments.

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