DISSERTATION

ROAD SEDIMENT PRODUCTION AND DELIVERY:

EFFECTS OF FIRES, TRAFFIC, AND ROAD DECOMMISSIONING

Submitted by

Gabriel Sosa Pérez

Department of Geosciences

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Doctoral Committee:

Advisor: Lee H. MacDonald

Stephanie Kampf
Michael Lefsky
Gregory Butters

ABSTRACT

ROAD SEDIMENT PRODUCTION AND DELIVERY:

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Unpaved roads often are a major source of sediment to streams in forested watersheds, and an increase in sediment production and delivery can adversely degrade water quality and aquatic habitat. The first part of this study quantifies the effects of wildfires on road erosion and road-stream connectivity as a function of fire severity and road segment characteristics. The data were collected along 6.8 km of an unpaved road after the High Park wildfire in Colorado. The second and third parts of this dissertation investigate how traffic and two road decommissioning treatments affect road sediment production and road-stream connectivity through the use of rainfall simulations, sediment production measurements at the road segment scale, and repeated surveys of 12.3 km of decommissioned roads. The segment-scale and road survey data were collected over a three-year period that included one summer prior to decommissioning and the first two years after decommissioning.

The road-wildfire study indicated that road surface rill erosion increased with hillslope burn severity due to the increasing amounts of runoff, but the length and area of rilling also increased with road segment slope. Segments with a slope ≤5% tended to capture sediment from the hillslope. Road segment area was only important for roads in areas burned at low severity, indicating that hillslopes become a progressively less important source of runoff as burn severity decreases. All of the road segments in areas

burned at moderate and high severity and 78% of the segments in areas burned at low severity were connected to the stream due to the increased runoff from upslope, the concentration of hillslope and road surface runoff to a single drainage point, and the reduced infiltration and trapping capacity of the hillslopes below the road. After wildfires land managers need to increase the frequency of drainage structures, and a more integrated modeling approach is needed to further our understanding of the complex interactions between burned hillslope and roads.

The rainfall simulations showed that the infiltration capacity for the decommissioning treatment of only ripping had little effect on infiltration and significantly increased sediment yields compared to closed roads. Mulching after ripping doubled the final infiltration rate and decreased sediment yields by nearly a factor of five compared to only ripping. Eighty passes of an all-terrain vehicle on two closed roads had no effect on infiltration capacity, but increased sediment yields by a factor of three.

The results at the road segment-scale showed that traffic was the dominant control on sediment production, and both decommissioning treatments greatly reduced road sediment production as nearly all of the eroded sediment was trapped in the furrows. Decommissioning reduced road-stream connectivity from 12% of the total length to only 2%, with most of the connected segments being immediately adjacent to a stream. These results can help calibrate and validate road erosion models, and guide the design of future road decommissioning treatments.

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1. OVERALL INTRODUCTION

The quality of water draining forested watersheds is typically very high (Binkley and Brown, 1993). For this reason the effects of forestry activities on water quality have been widely studied (e.g. Riekerk, 1983; Brown and Binkley, 1994; MacDonald and Stednick, 2003). Forest roads are essential for timber harvest and other forest management activities, and also provide access for fire management, insect and disease control, and recreation. However, it is increasingly recognized that unpaved roads can cause changes in flow and be a major source of sediment in forested catchments (Fulton and West, 2002). The construction and use of roads greatly modifies hydrologic and erosion processes at the hillslope and watershed scale, especially in steep terrain (Megahan, 1983; Ziegler and Giambelluca, 1997).

To understand the effects of forest roads it is necessary to collect data at the road segment scale, and then aggregate the results from many segments to understand the effects of roads at the watershed or landscape scale. The road segment is a common unit of study because each segment of a forest road acts as a subcatchment that includes the hillslope above the road, the road surface, and the drainage point to the hillslope below the road (Reid and Dunne, 1984; Ziegler and Giambelluca, 1997; MacDonald *et al*. 2001). This means that runoff and erosion are not only generated from the compacted road surface, but each segment traversing a hillslope also can intercept subsurface flow and transform this into overland flow (Wemple and Jones, 2003; Negishi *et al*., 2008).

The amount of runoff and sediment generated from a given road segment is most closely related to segment length and segment slope (Luce and Black, 1999), and to rainfall characteristics such as rainfall intensity (MacDonald *et al*. 2001). The amount and type of traffic is another important factor that has not been extensively studied because it is so difficult to quantify and control. The importance of traffic stems from its effect on sediment availability, as the passage of vehicles abrades and crushes particles on the road surface, which increases the mass of fine, easily transported particles (Sheridan *et al*., 2006). The type of traffic also can be important, as off-highway vehicles and heavy trucks can have different effects than standard cars and pickup trucks as a result of driving behavior, the weight of the vehicles, and the design of the tires (Meadows *et al*., 2008).

Numerous other factors can greatly affect runoff and surface erosion, including geology, road design, time since construction, and maintenance practices (Dubé *et al*., 2004). This results in highly variable erosion rates over space and time, and reported erosion rates range from nearly zero to more than 100 kg m^{-2} yr^{-1} (1000 metric tons per hectare) (MacDonald and Coe, 2008). Annual road erosion rates per unit rainfall range from 0.2 g m^{-2} mm^{-1} yr^{-1} to 10 g m^{-2} mm^{-1} yr^{-1} (Fu *et al*., 2010). These type of road erosion rates are primarily a concern if the runoff and sediment are delivered to a stream, wetland, or lake where they can adversely affect water quality and aquatic habitat.

Hence the adverse effects of roads depends first on the amount of runoff and erosion, and then whether the road segments are hydrologically connected (Grayson et al. 1993). Hydrologically connected road segments are those that have a continuous surface flow path to a natural stream or other water body during a runoff event (Croke and Mockler, 2001). The factors affecting road-stream connectivity include the spacing and type of drainage structures, the distance of the road to the stream, hillslope gradient, and the trapping efficiency of obstructions (Megahan and Ketcheson, 1996).

Runoff and sediment from roads is a key environmental concern due to the potential effects on stream channels and the physical characteristics of water, particularly turbidity and total suspended solids (MacDonald and Stednick, 2003). Changes in these parameters can adversely affect the beneficial uses of domestic water supply and recreation. An increase in turbidity and sediment loads also can adversely impact aquatic ecosystems, particularly cold water fisheries (Wood and Armitage, 1997), by filling pools, reducing sight feeding, reducing subsurface dissolved oxygen, and covering salmonid nests (National Council for Air and Stream Improvement 1994; Waters 1995). Large increases in sediment loads will also accelerate the rate of reservoir sedimentation (MacDonald and Stednick, 2003). The documented impacts of roads are a direct result of the very large changes in runoff and erosion, even though roads typically represent a small area of most forested and rural landscapes (Ziegler and Giambelluca, 1997; Ramos- Scharrón and LaFevor, 2016).

Wildland fires also can cause major hydrologic changes in forested areas that can drastically increase surface runoff, erosion, and sediment transport to streams (Robichaud, 2005; Foltz *et al*., 2009). High- and moderate-severity fires are of particular concern as they can reduce ground cover to less than 30%, which can increase runoff rates and peak flows by an order of magnitude and increase surface erosion by up to three orders of magnitude (DeBano, 2000; Robichaud, 2005). Conceptually, road segments below a burned area collect all of the fire-induced increases in hillslope runoff and sediment, and this should increase road surface runoff and erosion at the segment scale. The greater amounts of runoff and sediment draining from individual segments will in turn increase the potential for this material to be delivered to a stream or other water body. Fires can have an even greater effect on the delivery of road runoff and sediment by decreasing infiltration and reducing surface roughness on the burned hillslopes below a road. The problem is that there have been no studies that have examined how wildfires affects 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.

Land management agencies are also increasingly trying to reduce or eliminate the adverse effects of roads by closing or decommissioning roads that are no longer needed or known to be delivering water and sediment to streams. Few studies have rigorously measured the effectiveness of these techniques, and the studies that have been done are from areas with high precipitation, highly erodible soils, and/or steep topography (Switalski, 2004). Additionally, most of these studies were short-term so they do not directly compare pre- and post-treatment conditions or account for long-term variability (Switalski, 2004).

This dissertation addresses these issues through three field studies in the northern Colorado Front Range. Part I is a case study of the effects of a wildfire on road surface erosion and road-stream connectivity as a function of fire severity and road segment characteristics. This study focused on Old Flowers Road, which is an unpaved U.S. Forest Service road that passes through areas burned by the 2012 High Park Fire.

Part II evaluates the effects of traffic, road closures, and two road decommissioning techniques on runoff and sediment production at the plot scale using replicated rainfall simulations. Four simulations in an undisturbed lodgepole pine forest served as the control for the simulations on closed roads, while the simulations on closed roads served as the control for the simulations on roads with traffic and the simulations conducted after two different decommissioning treatments (ripping, and ripping plus mulching). The road closures and decommissioning was done by the USDA Forest Service in the Red Feather lakes area of the Arapaho-Roosevelt National Forest in Colorado.

Part III of this dissertation shows how traffic, road closures, and the two road decommissioning techniques affected sediment production at the road segment scale for one year prior to and two years after decommissioning. The effects of the decommissioning treatments on road-stream connectivity were evaluated over the same period by repeat surveys of 12.3 km of roads that were decommissioned in fall 2013.

The results should help forest managers assess and reduce post-fire road surface erosion and the downslope delivery of water and sediment to streams. The results of the rainfall simulation and segment-scale studies can be used for calibrating and validating road erosion models, and quantifying the effects of road closure and decommissioning treatments. The road survey data provide data on how different road decommissioning treatments affect road-stream connectivity. Taken together, these results will help land managers determine when road treatment costs justify the benefits, and help guide the design of both post-fire and road decommissioning treatments.

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PART I: WILDFIRE EFFECTS ON ROAD SURFACE EROSION AND ROAD-STREAM CONNECTIVITY

1. INTRODUCTION

Both unpaved roads and severe wildfires can reduce infiltration rates to less than 10 mm hr^{-1}, increase surface erosion rates by several orders of magnitude, and degrade water quality and aquatic habitat (Ziegler and Giambelluca, 1997; Shakesby and Doerr, 2006; Moody and Martin, 2009; MacDonald and Larsen, 2009). It follows that roads in areas burned at high and moderate severity will produce even more runoff and erosion, and resource managers typically upgrade or remove road crossings to accommodate the increase in runoff and sediment loads. To the best of our knowledge, however, there have been no studies that have examined how wildfires affects 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.

1.1 Background and objectives

Roads are essential for many forest management activities, as they provide access for timber harvest operations, 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 have correspondingly low infiltration rates (Reid and Dunne, 1984; Luce, 1997; Ziegler *et al*., 2007; Foltz *et al*., 2009) and high rates of infiltration-excess (Horton) overland flow (Ziegler and Giambelluca, 1997). Saturated hydraulic conductivity values for unpaved roads have been reported as 0.2 mm hr^{-1} to 5.1 mm hr^{-1} (Ziegler and Giambelluca, 1997), 5 mm hr^{-1} (Ramos-Scharrón and LaFevor, 2016), <8.8 mm hr^{-1} (Foltz *et al*., 2007), and 0 to 12 mm hr^{-1} (Luce, 1997). These low values mean that even low or moderate intensity rains can generate infiltration-excess overland flow (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).

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 off 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 from concentrated outflows (Takken *et al*., 2008).

For analysis purposes unpaved roads are commonly divided into hydrologically distinct segments. A road segment is typically defined by the road prism (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. In recently burned forested areas, however, the contributions of runoff and sediment from upslope can be substantial.

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). Given the relatively bare surface of most unpaved roads, the amount of runoff from a road segment (Q in $L^3 T^{-1}$) is:

$$Q = (P - I) A + SSSF + HOF_{upslope} \quad (1)$$

where P is the rainfall or snowmelt intensity ($L T^{-1}$), 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 HOFupslope ($L^3 T^{-1}$) is the overland flow from upslope. The energy of the road surface runoff depends on the amount of runoff from equation 1 and the road segment slope (MacDonald and Coe, 2008). Thus the product of road surface area times road segment slope, or segment slope squared, is often used to predict road surface erosion because this captures both the amount and energy of the road surface runoff (e.g., MacDonald *et al*., 1997; Luce and Black, 1999; Ramos-Scharron and MacDonald, 2005).

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 is 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 drainage structures, 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).

Like unpaved roads, wildfires in forests and shrublands can greatly reduce infiltration and increase surface runoff and erosion (Martin and Moody, 2001; Benavides-Solorio and MacDonald, 2001; Foltz *et al*., 2009). High- and moderate-severity wildfires are of particular concern because of the potentially large increases in surface runoff and erosion (Larsen *et al*., 2009), but also the much greater potential delivery of water and sediment to the stream due to the downslope reduction in surface roughness. The resultant effects of fires on flooding, water quality, aquatic habitat, and sedimentation rates are a major concern for the public and resource managers (Neary *et al*., 2005).

After a wildfire resource managers try to protect forest roads and minimize potential road damage, 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). Specific treatments include culvert removal, culvert upgrading, armoring stream crossings, adding diversion potential dips if a crossing were to fail, and installing additional drainage structures such as rolling dips and water bars.

Conceptually, the increased runoff and sediment delivered onto a road from upslope after a fire (Foltz *et al*., 2009) should increase road surface erosion and sediment delivery to the stream network. 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 were then used to compare the amounts of runoff and sediment production from an average road segment with our average hillslope when unburned, burned at low severity, and burned at high severity. The results should help forest managers assess and potentially minimize post-fire road surface erosion and the downslope delivery of water and sediment to streams or other aquatic features.

2. METHODS

2.1 Study area

The study was conducted along the Old Flowers Road (U.S. 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 1.1). It runs primarily through forested land managed by the Arapaho-Roosevelt National Forest (ARNF). The road climbs from 2230 m at Stove Prairie Road at its eastern end to a maximum elevation of 2560 m, and then drops sharply to 2410 m at the western end where it intersects the Pingree Park Road (Figure 1.1).

The area surrounding the road was burned in June 2012 by the 350 km^2 High Park Fire. Within the fire perimeter, 41% 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 has 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 not allowed because it is open only to highway legal vehicles.

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 cut-and-fill profile, but the cut slopes 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 drainage structures for diverting water off the road surface.

Mean annual precipitation at Buckhorn Mountain 1 E weather station (Figure 1.1) 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. Nearly 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 most common soil units generally have between 10% and 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 throughout the burned area, especially on steep slopes with gradients greater than 60% (BAER, 2012), but these were generally 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*).

2.2 Delineation of study segments and hillslope characterization

The detailed road survey was conducted in July-August 2013, or just over one year after the High Park Fire. We identified 141 hydrologically distinct road segments in our road survey, with most of these segments being defined by waterbars at each end. A GPS with a resolution of three meters was used to register the beginning and end of each road segment. For this study each segment included not only the road prism, but also 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, at least some of the organic matter in the uppermost portion of the mineral soil has been burned, and there may also be an associated change in color. Moderate soil burn severity was defined by complete charring or consumption of the organic layer with no alteration of the underlying mineral soil and shallow roots or rhizomes. Low soil burn severity was defined by some charring of the surface organic layer but the original form of some of the leaves or needles were still intact.

Hillslope gradient above and below the road was measured with a clinometer. Percent surface cover of bare soil, rock, and vegetation (including litter) were visually estimated for a 20-m zone above each segment. Some short sections had been treated with straw mulch, but this was lumped with vegetation and litter because these all provide similar protection against post-fire 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 shallow wide channels less than five cm deep. Rills were defined as channelized erosional features at least five cm deep. For the purposes of this paper gullies, which are typically at least 0.5 m deep (SSSA, 2001) or with a cross-sectional area of 0.09 m^2 (Poesen, 2003), were lumped with rills because we were only calculating cross-sectional areas rather than volumes, and many of the channels shifted back and forth between rills and gullies as the channels coalesced, diverged, or became shallower or deeper due to the presence of rocks, roots, or bedrock. For each segment we counted the number of rills draining onto the road from the upper hillslope and measured the width and depth of a representative rill.

A 1-m DEM derived from July 2013 aerial LiDAR data was used with the Arc Hydro extension of ArcGIS 10.2 to delineate flow paths above and below the road. This 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 stream channel. Streams were delineated using the DEM and a minimum threshold drainage area of 5000 m^2, which is more than the minimum drainage area of 100-3000 m^2 reported for channel initiation after the High Park fire, but less than the threshold of ~10,000 m^2 for unburned areas (Wohl, 2013).

2.3 Road segment characterization

The drainage design for each segment was classified as planar or outloped. Segment length was measured along the center line of the road with a measuring wheel. The total width was defined as the width of the road surface, while the active width was defined as the actively used road tread. Both widths were measured at a minimum of three locations to determine a mean value, and there was relatively little variation in these widths as the overall mean standard deviation for the active and total width 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 the segment length times the 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 (Table 1.1).

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 part II of this dissertation. 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. We calculated the percent of the segment area with rills by multiplying the length of each rill by its representative width, summing these areas, and dividing this by the road segment area.

2.4 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. If there was one or more well-defined rills draining the road segment, the widths and depths were measured at the outer edge of the road. The cross-sectional areas were 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 of the drainage rills 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 road segments also 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 five centimeters 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 had multiple large obstructions (logs, rocks) or a deep layer of wood chip mulch with very high sediment trapping capacity.

A segment was assumed to be connected to the channel network if the drainage feature extended to within five meters of a stream. In many cases, however, it was not possible to track each drainage feature because the drainage from the road merged with the sheetwash and rills originating on the burned hillslope below the road to form a complex set of new and 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. Most of the streams were ephemeral and confined with little or no riparian zone or valley bottom, so there was little or no potential that the observed flowpaths would be interrupted before reaching the stream.

2.5 Statistical analysis

The first step was to determine if any of the independent and dependent variables varied significantly with burn severity, and this was done by a combination of analysis of variance (ANOVA) and non-parametric methods. The independent and dependent variables of the survey are listed in Table 1.1. If the criteria for ANOVA were met and 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 and Longnecker, 2008). If the assumptions for ANOVA were not met, non-parametric Kruskal-Wallis tests were used to determine whether there were significant differences among burn severities. 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 when stratified by burn severity class. Variables were only included if they were significant at $p \leq 0.05$.

3. RESULTS

3.1 Hillslope and road segments 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 1.2). Four segments had exceptionally large contributing areas of 10 to 49 ha that were excluded from some of the data analyses because these large areas delineated by ArcGIS were unrealistic and not consistent with our field observations.

The mean gradient for the hillslopes above the road was 18% (s.d.= 8%), and this did not significantly differ by burn severity. 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 of 21% for areas burned at low severity (Table 1.2).

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 1.2). Similarly, the mean vegetation and litter cover on the upper hillslope significantly increased from just 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, and the outsloped segments were 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. 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%, and 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 1.2).

Road surface cover in the areas burned at high severity averaged 67% (s.d.=29%) bare soil, and this was significantly higher than the mean value of 51% (s.d.=24%) in areas burned at low severity (Figure 1.2). Similarly, the mean vegetation cover of less than 8% for the road segments in areas burned at high and moderate severity were significantly lower than the 20% (s.d.=26%) mean vegetation cover for the road segments in areas burned at low severity (Figure 1.2). The road segments had a relatively high mean rock cover of 32% (s.d.=26%), and this is consistent with the high rock content of the soils. Percent rock cover did not vary significantly with burn severity.

3.2 Erosion features on the upper hillslope

The amount and type of erosion features coming from 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, particularly in the areas burned at high severity. This made it difficult to distinguish between rills and deep sheetwash (e.g., Figure 1.3a). The high variability meant that we could only confidently identify and measure representative rills draining onto a road segment for 16 of the 54 segments below hillslopes that burned at high severity. For these segments the mean rill width was 0.30 m and the mean depth was 0.07 m. We qualitatively observed much less deeply incised sheetwash on the hillslopes burned at moderate severity and relatively more rills, but the mean width and depth of the measured rills were similar to the rills draining areas burned at high severity. In contrast, only 46% of the upper hillslopes that burned at low severity had rills (Figure 1.3b). Representative rills could only be identified and measured for seven segments, and these rills had a very similar width and depth as the rills on the more severely burned hillslopes. These results indicate that the more severely burned hillslopes had much more evidence of rill and deep sheetwash erosion, but this difference was expressed more by a greater frequency of these features than a greater width and depth of the rills that were present.

3.3 Road segment rilling and deposition

The number of rills on the road surface did not vary with burn severity as 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 1.4c). Only 15% of the segments had two or more rills. The segments in areas burned at high severity were slightly less likely to be rilled than the segments in areas burned at moderate severity (70% vs. 89%), but this is almost certainly due to the significantly lower mean slope of the segments in areas burned at high severity (Table 1.2; Figures

1.4a and 1.4b). Rilling was only present on 54% of the segments in areas burned at low severity.

The mean percent of segment length with rills and the mean segment area covered by rills varied significantly with fire severity (Figure 1.5). 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 (R^2=0.24; $p<0.0001$). Surprisingly, neither upslope contributing area nor percent bare soil on the contributing hillslope had any significant effect on the proportion of segment length with rills or the percent rill area ($R^2<0.01$).

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 1.6). In contrast, segment slope only explained 15% of the variation in the proportion of segment length with rills for the segments in areas burned at low severity. The results for rill area were very similar as this was very closely correlated with the proportion of segment length with rills (R^2=0.59).

In contrast to rill length and rill area, rill widths and depths tended to increase with burn severity (Figure 1.7). The mean rill widths and depths for the segments below areas burned at high severity were larger than for the rills on the segments burned at moderate severity, but this difference was not significant. 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 areas burned at high and moderate severity (Figure 1.7). The greater size of the road surface rills below areas burned at high and moderate severity is consistent with the greater amounts of surface runoff, sheetwash and rilling.

The flatter road segments tended to capture and store the sediment coming from the upper hillslope (Figure 1.4b), and the amount of deposition varied with both burn severity and road segment slope. In areas burned at high severity 37% of the road segments had sediment deposits, and this decreased to 24% and 14% for the road segments in areas burned at moderate and low severity, respectively. Road segment slope was the dominant controlling factor as this explained 34% of the variation in the percent of the road surface with sediment deposits. There also seemed to be 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 1.8).

3.4 Relative effects of burn severity, segment slope, and segment area on road surface rilling

Multivariate linear regression was used to evaluate the relative importance of burn severity, road segment slope, and road segment area on the proportion of segment length with rills (Table 1.3). Segment slope was the strongest variable when all the data were pooled as indicated by the partial R^2, but the proportion of segment length with rills also significantly increased as the amount of hillslope vegetation decreased and the amount of road segment rock cover increased (Table 1.3). The greater proportion of rill length with decreasing hillslope vegetation indicates how the increasing hillslope runoff with increasing burn severity can increase road surface rilling.

The interactions between the different controlling factors become more clear when the data are stratified by burn severity. For the road segments 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 1.3). 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). For the segments 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).

The implication of these results is that road surface area is not an important control on road surface rilling when there is a proportionally larger contribution of upslope runoff from areas burned at high or moderate severity. When there is much less surface runoff from upslope, such as from unburned areas or areas burned at low severity, road surface area becomes a relatively more important source of overland flow. Hence road surface area is more closely related to the proportion of a road segment with rills in areas burned at low severity, while in areas burned at high severity road segment slope is the primary control.

3.5 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. The hillslopes burned at high and moderate severity generated large amounts of surface runoff, and this led to extensive sheetwash and numerous parallel rills that flowed down onto the road as shown in Figure 1.9a and b. The road typically collected all of this runoff and diverted it down the road, usually in a single, deeply incised rill or gully (Figure 1.4d). The detailed view provided in Figure 1.9a and b shows how the lidar-derived flow paths in an area burned at moderate severity were interrupted by different road segments along Old Flowers Road. The field survey confirmed that for all but one of these segments all of the runoff from upslope was collected by the road and directed down the road segment. This combined runoff and sediment from the hillslope and road surface was then discharged at a single location, and the volume and concentration of this flow and sediment helped ensure that all of the road segments were directly connected to the stream. This concentration of runoff by Old Flowers Road is very different to the flowpaths on the burned but unroaded hillslope on the opposite side of the stream (Figure 1.9b).

For 74% of the 141 segments the hillslope and road surface runoff was collected over the entire length of the segment and then discharged at a single drainage point (Figure 1.10). Of the other 26%, two-thirds or 16% had from two to nine drainage points, and 4% of the 141 segments were outsloped with either dispersed runoff or at least ten small drainage features. Six percent of the road segments had no distinct drainage feature, and each of these segments was in an area that burned at low severity and therefore had substantially less surface runoff from upslope (Figure 1.10).

The size of the drainage channels leaving the road should be a function of burn severity and road segment characteristics, but we could only reliably measure these on 64 of the 141 road segments because they often were a complex mix of incised channels and sediment plumes with no representative cross-section. Again we are using to the term rills to also include gullies, and the median cross-sectional area of the drainage rills in areas burned at high and moderate severity was 0.1 m^2, with virtually no difference between high and moderate severity (Figure 1.11). Some of these drainage features 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 than the road drainage rills in areas burned at high and moderate severity (p=0.98) (Figure 1.11).

The high-resolution DEM data indicated that the mean horizontal distance between the road drainage points and the stream was nearly 70±53 m, and there were no significant differences in this distance with 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 each of the 91 segments in areas burned at high and moderate burn severity was connected to the stream, and this included 25 segments that were more than 100 m from the 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 23% of the hillslopes below the road had a roughness class of one, and the mean value on a scale of one to four was 1.8. It is of interest that the lower hillslopes in areas burned at low burn severity tended to be steeper (Table 1.2), but this did not fully compensate for the lower amounts of hillslope runoff and higher downslope roughness, as 22% or 11 of the segments in low severity areas were not connected to the stream. These 11 segments were all below hillslopes with at least 80% vegetation cover and no erosion features. These 11 segments also did not have any road surface rilling, further confirming the relative lack of overland flow.

4. DISCUSSION

4.1 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 the road surface and adjacent hillslope are subject to the same rainfall, one could expect the burned hillslope to be the dominant control on road surface runoff and erosion because its contributing area is typically so much greater than the road segment 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- or down-slope positions in a burned area, the amount of road surface runoff and associated rilling should be closely 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 upslope contributing area or percent bare soil on the burned hillslope above the road (Table 1.3).

The primary role of road segment slope as a control on rill length and area should not be surprising because this 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 road segment slope is dominant because it is raised to a power of 1.5 to 2 (Elliot *et al*., 1999; Luce and Black, 1999; Ramos-Scharrón and MacDonald 2005). Our results showed that the relative importance of road segment slope on the proportion of rilled segment length increased with burn severity (Table 1.3), and this suggests that high burn severity and high road segment slope combined to create longer rills on the road surface. Conversely, for segments with a slope of less than 5% the overland flow often could not transport all of the sediment that was being delivered onto the road segment, resulting in deposition (Figure 1.8).

For segments with a slope of at least 5% we estimated the rill volume on the road surface and stratified these results by burn severity. For each burn severity the mean segment length was nearly identical at 50-51 m, and the mean segment slopes were relatively similar at 9% for high severity, 11% for moderate severity, and 12% for low severity. For these steeper segments in areas burned at high and moderate severity the mean rill volumes were very similar at 2.9 m^3 (s.d.= 3.2 m^3) and 2.6 m^3 (s.d.= 2.4 m^3), respectively, while the mean rill volume of 0.9 m^3 (s.d.=1.2 m^3) in areas burned at low severity was very significantly less ($p<0.0001$) despite their slightly steeper mean slope. While we do not know the volume of rills prior to the fire, this difference in mean rill volumes helps confirm the importance of road surface slope in determining whether a given road will be subject to rilling or sediment deposition after burning. For steeper roads burn severity becomes the first-order control on the size of rills and presumably the amount of road surface erosion.

In areas burned at low severity road segment area times slope was an important control on road surface rilling. The inclusion of road segment area for predicting rill formation in areas burned at low severity is logical because hillslopes burned at low severity typically have much higher infiltration rates and generate much less surface runoff than hillslopes areas burned at high or moderate severity (e.g., Robichaud, 2000; Benavides-Solorio and MacDonald, 2001). If a hillslope is not producing as much surface runoff, road surface area becomes relatively more important for generating surface runoff and inducing road surface rilling, particularly for steeper segments.

The multivariate modeling to predict the amount of road segment rilling showed that the combined variable of road segment area times slope was less significant than road segment slope in areas burned at high and moderate severity. 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 is when the cutslope below an unburned hillslope intercepts large amounts of subsurface flow, and this additional surface runoff can then greatly increase road erosion rates compared to segments without this additional source of runoff (e.g., Coe, 2006; Wemple and Jones, 2003). These results show how fires can substantially alter the controls, complexity, and magnitudes of road surface erosion and deposition compared to unburned areas (Dube *et al*., 2004; Fu *et al*., 2010).

The relative importance of road segments versus hillslopes can be further explored by comparing the modeled runoff and erosion from road segments versus hillslopes burned at different severities. Models for predicting road surface erosion include the empirical SEDMODL2 (NCASI, 2002), process-based WEPP:Road (Elliot *et al*., 1999), and GIS-based models such as the Geomorphic Road Analysis and Inventory Package (GRAIP) (Black *et al*., 2012). However, only WEPP:Road predicts segment-scale surface runoff. For burned hillslopes Disturbed WEPP is most commonly used to predict runoff and erosion rates (Elliot *et al.*, 2010), and this has been validated for areas similar to the High Park Fire (Larsen and MacDonald, 2007). Both WEPP:Road and Disturbed WEPP use the same underlying model structure and stochastic climates, which should increase the comparability of their results, and they both have a relatively simple user interface (Elliot *et al*.,2010).

We predicted road surface runoff and erosion using WEPP:Road for our average road segment that was 50 m long with a slope of 8%, a sandy loam soil with 32% rock fragments, planar but rutted, and with low traffic. Similarly, runoff and erosion was predicted for unburned, low severity, and high severity hillslopes using our average contributing hillslope that was 170 m long with a slope of 18%, a sandy loam soil with 22% rock content, 80% surface cover for low severity, 30% cover for high severity, and an assumed cover of 100% for unburned. Both models were run using a 30-year average climate based on Fort Collins, Colorado, that was adjusted to the latitude, longitude and elevation of the study area using the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) (Daly *et al*., 1997).

The road segment was predicted to generate 0.12 m^3 of surface runoff and 33 kg yr^{-1} of erosion (Figure 1.12), and these relatively low values can be attributed to the preponderance of precipitation falling as snow. The unburned hillslope was predicted to generate 5 m^3 of runoff (0.2% of precipitation) and no sediment (Figure 1.12). The hillslope burned at low severity was predicted to generate 22 m^3 of runoff and 16 kg yr^{-1} of sediment, or just half of the predicted sediment from the much smaller area of the road segment. The severely burned hillslope was predicted to generate 48 m^3 of runoff

(1.1% of the precipitation) and 230 kg yr^{-1} of sediment, which is seven times the amount of sediment from the road segment (Figure 1.12).

When these results are combined with previous work, we can generalize that road segment characteristics are the primary control on road runoff and sediment production in unburned areas. As burn severity increases the hillslopes become a progressively more important source of runoff, and this decreases the relative importance of road segment area for generating road segment runoff. Similarly, with increasing burn severity the sediment inputs from upslope dominate the amounts of sediment being generated from the road segment, but road segment slope is still critical for determining the amount of sediment produced by the road surface and whether the sediment is deposited or transported to the drainage outlet. The problem is that the predicted hillslope runoff and sediment from Disturbed WEPP cannot be used as an additional input into WEPP:Road, so we cannot more rigorously evaluate the interactions between burned hillslopes and roads, and thereby test or compare our field results against model predictions.

The relative importance of the road segments for generating runoff and erosion also will increase as the burned hillslopes revegetate over time and the infiltration rates recover. Studies in severely burned areas very similar to the High Park fire show that hillslope sediment yields and presumably surface runoff typically decline to very low values by the third summer after burning (Benavides-Solorio and MacDonald, 2005; Wagenbrenner *et al*., 2006). In contrast, active roads do not recover over time so they are chronic sources of overland flow and sediment. At the watershed scale and over longer time periods the chronic delivery of sediment from unpaved roads is roughly similar to the pulsed sediment inputs from high-severity fires (MacDonald and Larsen, 2009). Yet there are far fewer studies of road sediment production and delivery than post-fire sediment production and delivery.

4.2 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 stream. 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. In areas of the Colorado Front Range with similar precipitation road-stream connectivity rates 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 by either gullies or sediment plumes (Croke *et al*., 2005).

These much lower rates of road-stream connectivity are all from unburned areas, and they 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 terrane 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). The length of rills and sediment plumes from relief culverts also averaged just 37 m in the Sierra Nevada (Coe, 2006) and 53 m from newly-constructed roads in Idaho (Megahan and Ketcheson, 1996).

After high and moderate severity forest fires there is a dramatic increase in hillslope-stream connectivity due to the sharp decline in infiltration rates and resultant increase in overland flow. Recent studies in the Colorado Front Range have documented an order of magnitude change in the drainage area and slope needed to initiate a channel (Eccleston, 2008; Wohl, 2013) and a resultant order of magnitude increase in drainage density. The increased drainage density, when combined with the reduction in infiltration and surface roughness, has led to the assertion that nearly all of the post-fire runoff and sediment from hillslopes is delivered to the stream network (Pietraszek, 2006). Given these changes, the distance from the road to the stream is much less important for controlling road-stream connectivity after wildfires than in unburned areas, and road-stream connectivity values can approach 100% in sloped areas that 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 this high connectivity would be expected to rapidly decline with vegetative regrowth and the accompanying increase in infiltration and surface roughness.

4.3 Management implications

Resource managers have been applying various treatments after high and moderate severity wildland fires to increase the capacity of drainage structures and road crossings to transmit flow, 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 are: (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). Our field survey showed that 70 of the 141 road segments were defined by pre-existing waterbars. Perhaps 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. An increase in drainage frequency would reduce the amount of surface runoff and road surface 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, rolling dips, or outsloping, with the latter being a substantially more expensive treatment. The frequency of waterbar spacing after fires is a topic that needs further investigation. In our study the percent of segment length with rills averaged only 28% or 13 m for 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 drainage features could be set accordingly. Road segments with a slope of 6-10% 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 a relatively high frequency of waterbars could greatly reduce road surface erosion and hence the need for post-fire regrading to maintain driveability. On the other hand, an increased frequency of waterbars may not greatly reduce road stream-connectivity in areas burned at high and moderate severity given that the hillslopes have very low 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.

The data above indicate that outsloping is the only means for reducing or eliminating road surface rilling after wildfires. Outsloping also can help to reduce concentrated outflows, but outsloping will not necessarily reduce or eliminate road-stream connectivity for the first one or two years after burning given the very limited assimilative capacity of the hillslopes. Outsloping also is only likely to be effective if traffic is completely prohibited, as a single vehicle can create a small depression that captures some surface runoff. Once concentrated flow begins this can rapidly incise into a rill or gully that captures and conveys nearly all of the surface runoff and sediment along the road surface until it reaches a waterbar, stream crossing, or other drainage structure. The combination of fires and roads pose a particularly difficult challenge for land managers, but efforts to reduce the effects of roads after a fire will also be beneficial as the hillslopes recover and the roads become a major source of anthropogenic runoff and sediment.

5. CONCLUSIONS

The goal of this study was to evaluate how fire severity and road segment characteristics affect both the frequency and size of road surface erosion features, and road-stream connectivity. Percent bare soil on the hillslope above the road increased significantly from low to high burn severity, and the hillslopes burned at high and moderate severity had much more deep sheetwash and rilling compared to the hillslopes burned at low severity. This indicates the much greater amount of runoff and erosion draining on to the road from areas burned at higher severity, and the road segments below areas burned at high and moderate severity had significantly more rill length, rill area, and generally larger rills than segments below areas burned at low severity.

Road segment slope was the most important control on the percent of segment length with rills in areas burned at high and moderate severity. Road segments with slopes of 5% or less were generally not rilled and tended to capture the sediment from upslope burned areas. Road surface area was not an important control on road surface rilling except in areas burned at low severity, indicating the relative importance of road surface area for generating runoff in less-severely-burned areas. A comparison of predicted runoff and erosion from hillslopes versus a typical road segment showed the increasing dominance of hillslope runoff and sediment with increasing burn severity.

Seventy-four percent of the 141 road segments had only one drainage feature, indicating that the road segments tended to collect the dispersed runoff and sediment from the burned hillslopes and then discharge 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 collection and delivery of 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 to either outslope the roads or greatly increase the frequency of constructed drainage features immediately after wildfires, particularly for steeper road segments in areas burned at high or moderate severity. A coupling of existing road and hillslope models could help researchers and land managers to better understand and predict the how road segments and burned hillslopes interact to increase runoff, sediment, and road-stream connectivity.

Table 1.1. List of independent and dependent variables.

Independent variables	Dependent variables
Upslope contributing area (ha)	Proportion of road segment length with rills
Upper hillslope gradient (%)	Percent of road segment area covered by rills
Upper hillslope bare soil (%)	Percent of segment area with sediment deposits
Upper hillslope rock cover (%)	Total cross-sectional area of the drainage features (m^2)
Upper hillslope vegetation cover (%)	
Road segment slope (%)	
Road segment area (m^2)	
Road segment length (m)	
Segment area x slope	
Segment length (m) x slope^2 (%)	
Road surface bare soil (%)	
Road surface rock cover (%)	
Road surface vegetation and litter cover (%)	

Table 1.2. Mean, standard deviation, and range of the hillslope and road segment characteristics by burn severity. The numbers in parentheses at the top of each column are the number of segments. Different letters indicate significant differences, and if no letters are present there were no significant differences.

Hillslope and segment characteristic	Burn severity					
	High (n=54)		Moderate (n=37)		Low (n=50)	
	Mean ± St. dev	Range	Mean ± St. dev.	Range	Mean ± St. dev.	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] ± 9	2 - 35	17[ab] ± 8	3 - 37	21[b] ± 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] ± 4	1 – 15	9[b] ± 5	1 - 19	10[b] ± 5	1 - 19

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

Table 1.3. 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.

Model characteristics	All data	Burn severity		
		High	Moderate	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*	<.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	<.0001	<.0001	<.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 x slope squared				
Partial R^2		0.02		
Parameter estimate	n/a	0.00003	n/a	n/a
p-value		0.04		
Segment area x slope				
Partial R^2				0.23
Parameter estimate	n/a	n/a	n/a	0.0002
p-value				0.0004

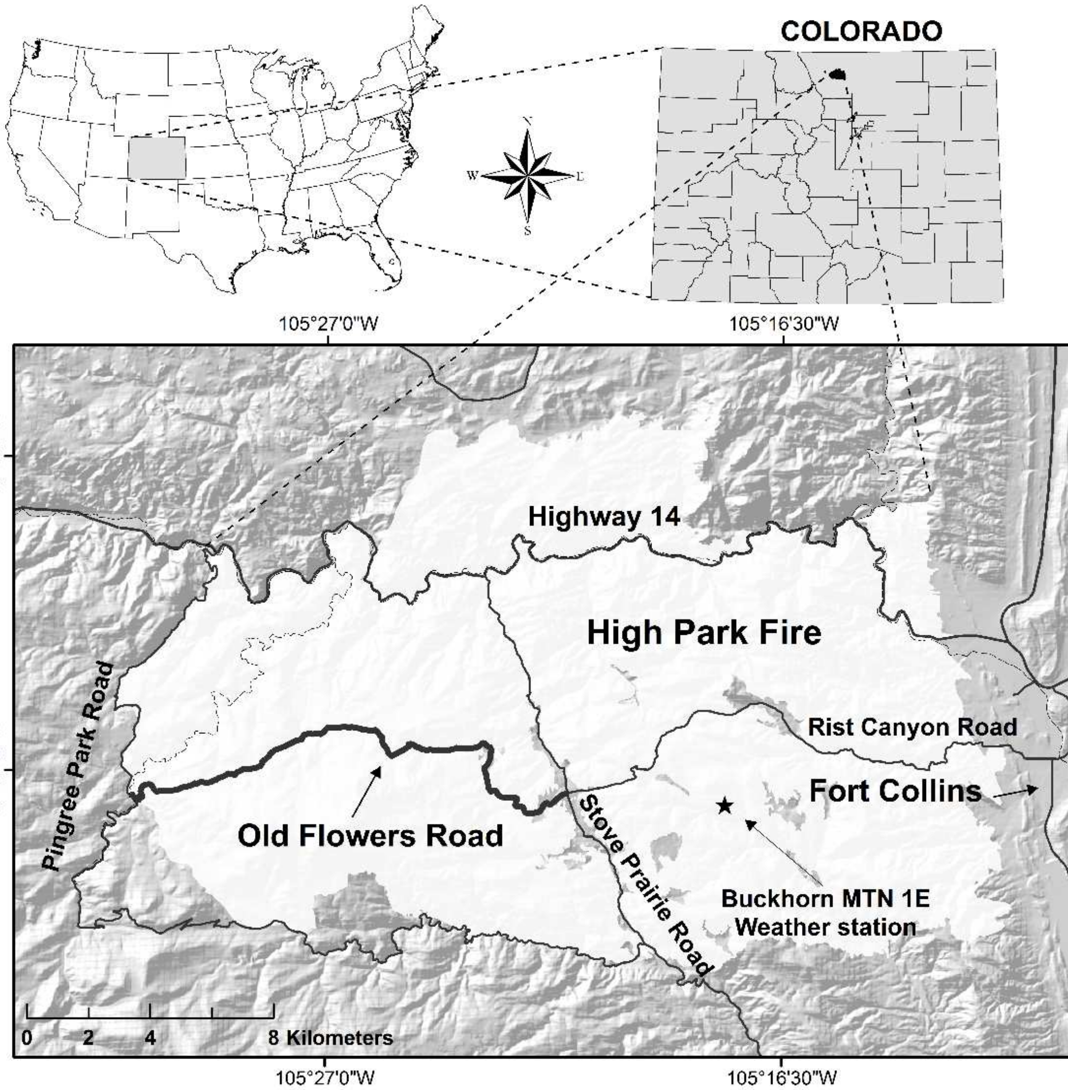

Figure 1.1. Location of Old Flowers Road and the High Park Fire, Colorado. White areas were burned, and gray areas were unburned.

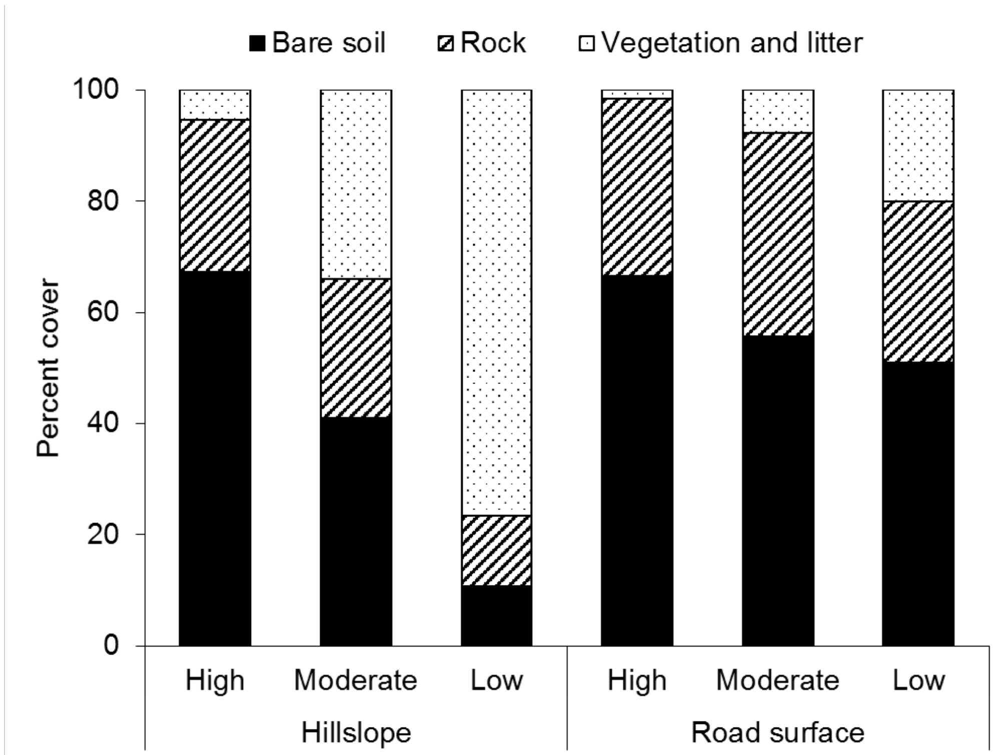

Figure 1.2. Mean surface cover by burn severity for the upper hillslope and active road surface, respectively.

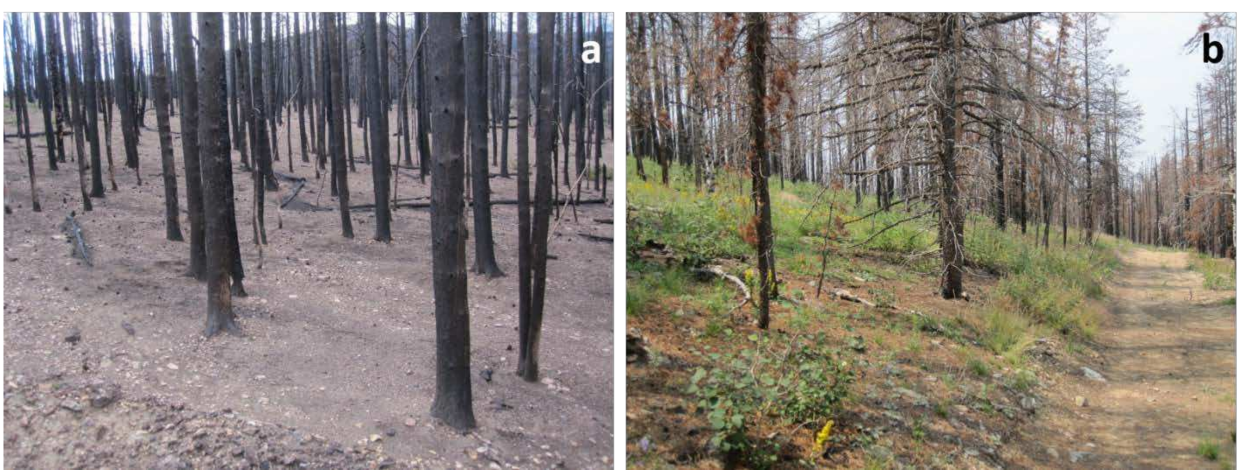

Figure 1.3. a) Representative hillslope from an area burned at high severity that experienced extensive rainsplash and sheetwash erosion. b) Representative hillslope burned at low severity showing much more live vegetation, some residual charred litter, and minimal surface erosion.

Figure 1.4. 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 only 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) Single, deeply incised gully leaving a 51-m long road segment that was in an area that burned at high severity. This gully extended at least 10 m to the ephemeral stream at the base of the slope, and the large size of this drainage feature can be attributed primarily to the combination of runoff from the burned hillslope and the 15% slope of the road segment.

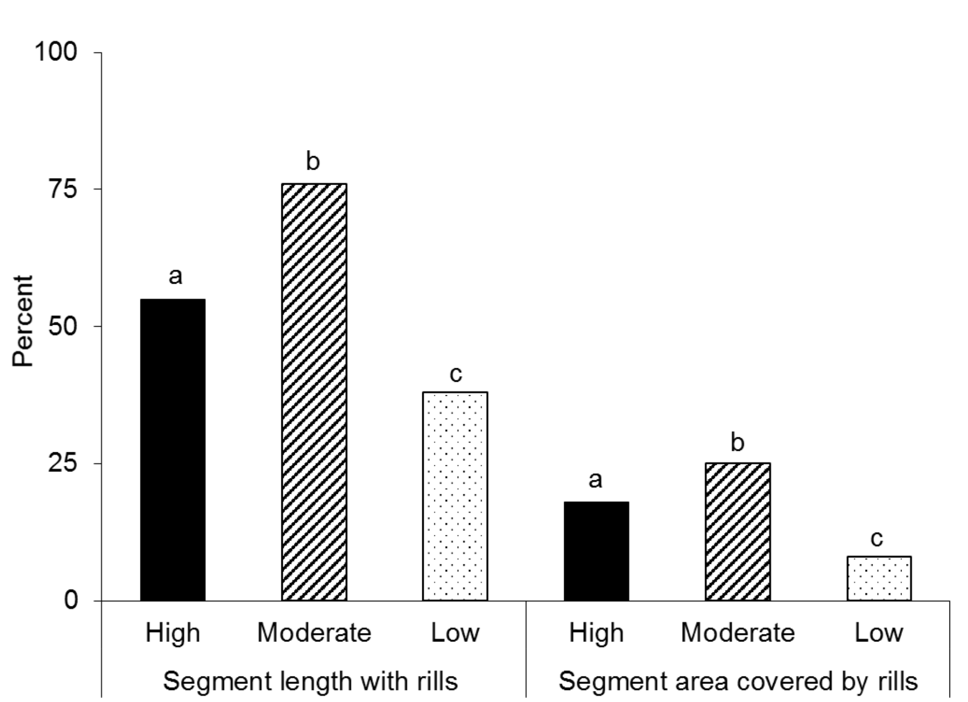

Figure 1.5. Mean percent of segment length with rills and mean percent of segment area covered by rills by burn severity. Different letters indicate significant differences.

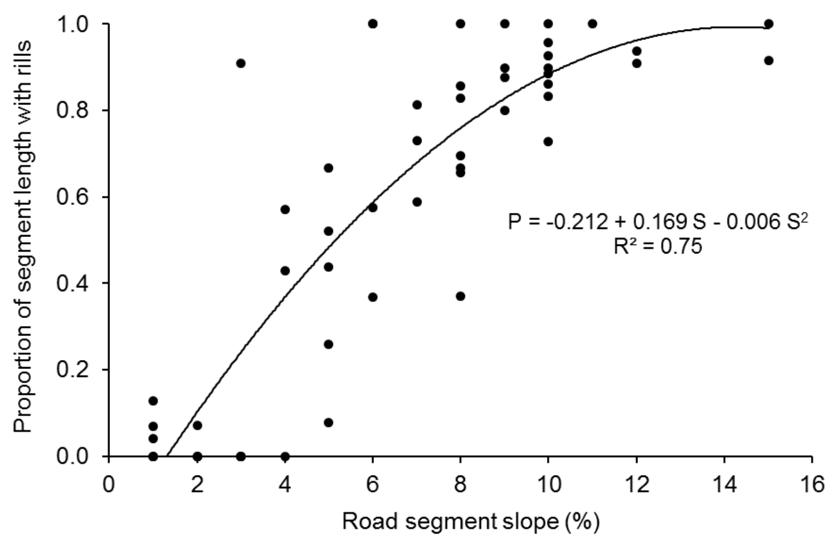

Figure 1.6. Proportion of road segment length with rills (P) versus segment slope (S) for the segments in areas burned at high severity. The polynomial regression equation is only valid up to its maximum value at 15%.

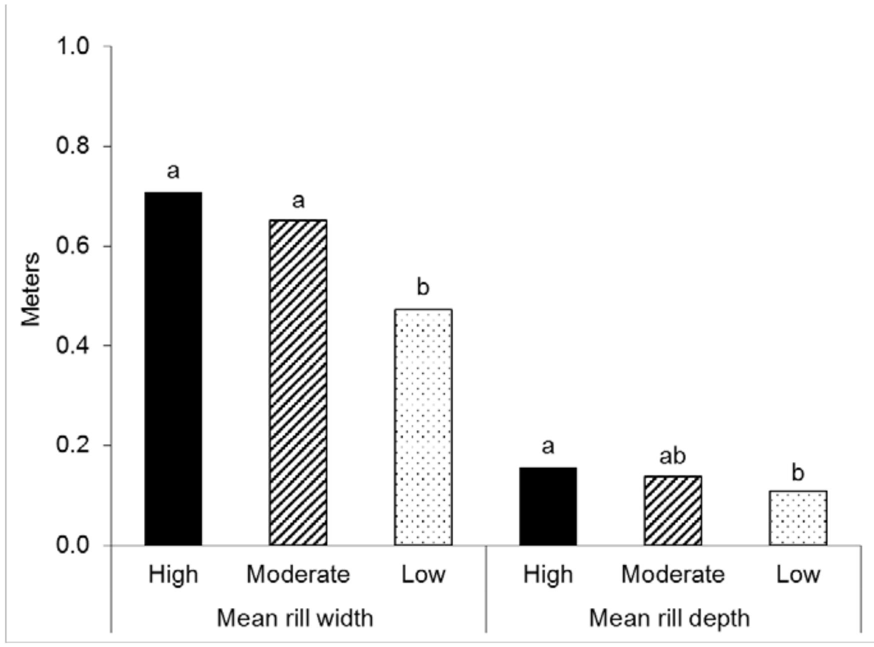

Figure 1.7. Mean rill width and rill depth by burn severity. Different letters indicate significant differences.

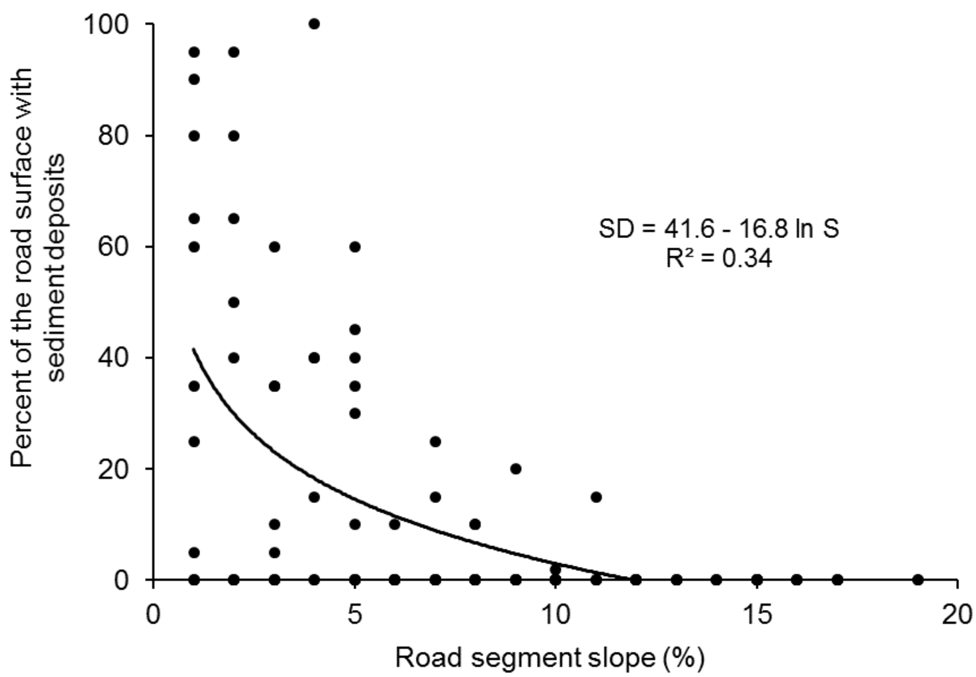

Figure 1.8. Percent of the road surface with sediment deposits (SD) versus road segment slope (S).

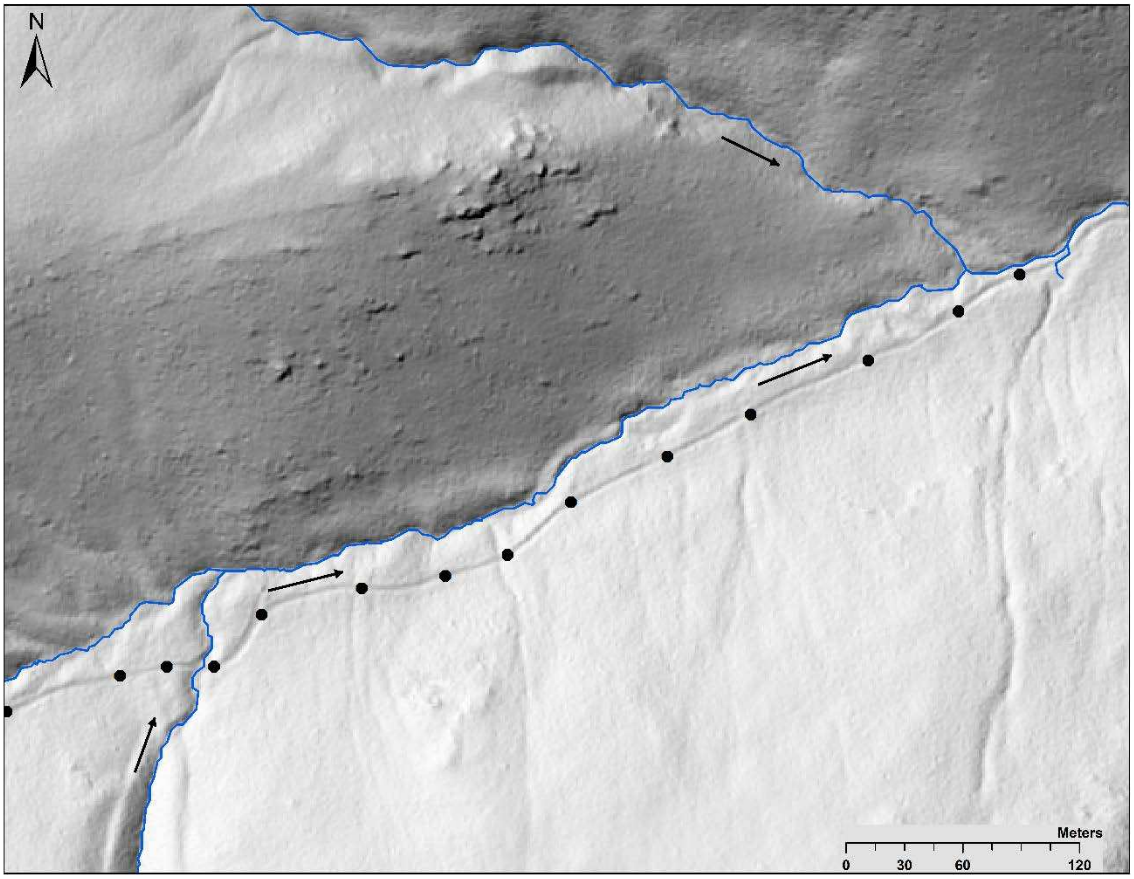

Figure 1.9a. Section of the Old Flowers Road running next to the stream. Black dots show the beginning and end of each road segment as identified by the field survey, and the arrows indicate the flow direction.

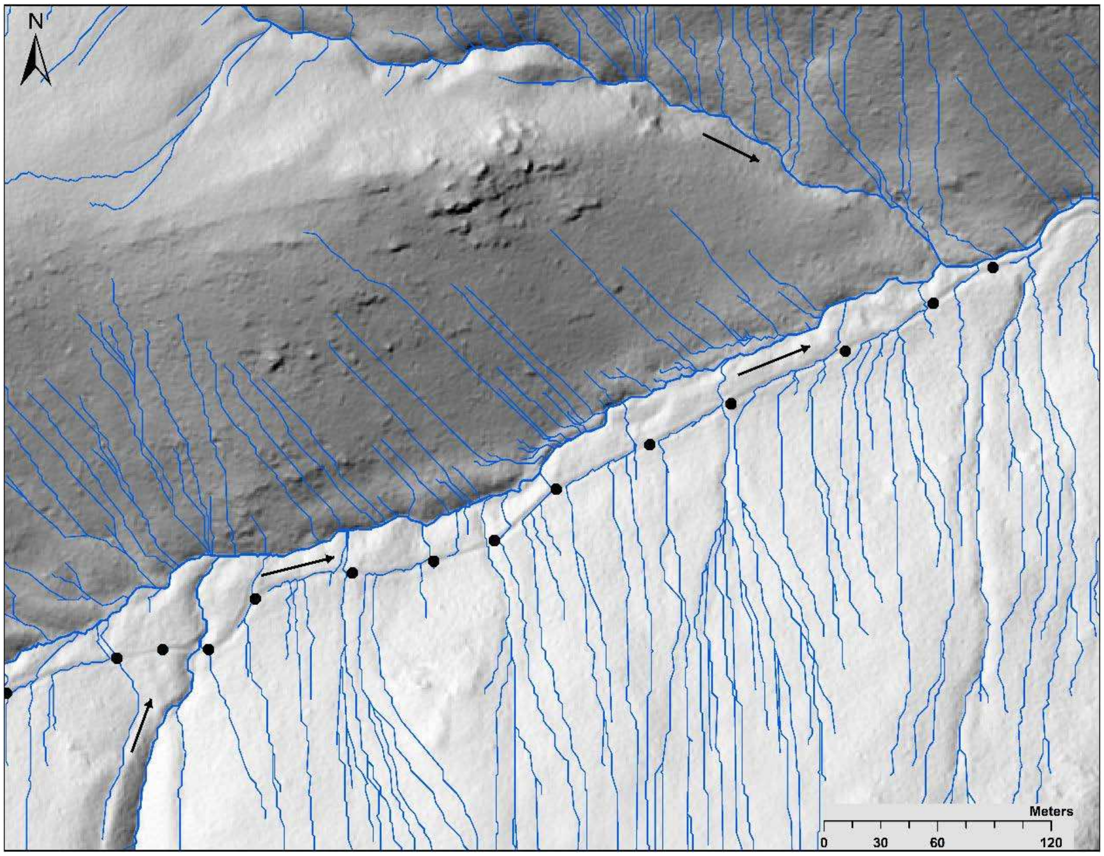

Figure 1.9b. Section of the Old Flowers Road showing how the road segments collected the dispersed runoff from the upper hillslope and then funneled this to a single drainage point.

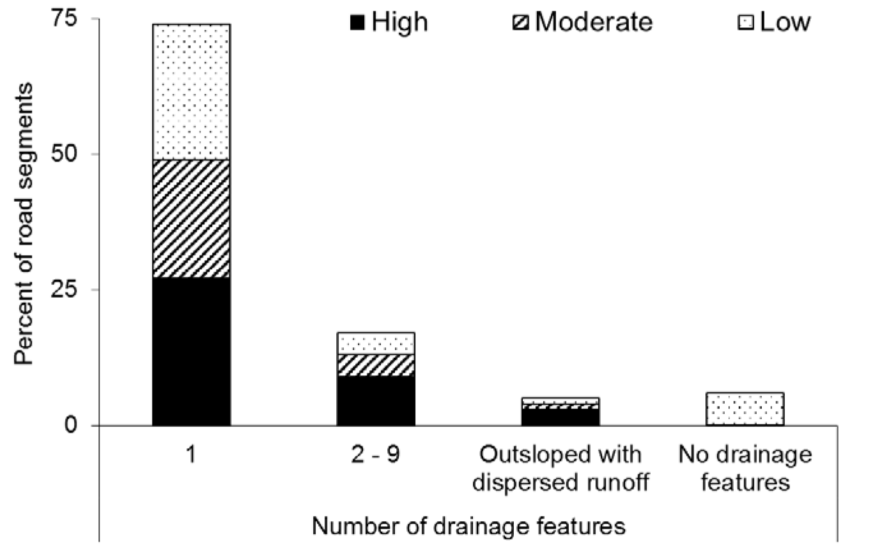

Figure 1.10. Percentage of all road segments by number of drainage features and burn severity.

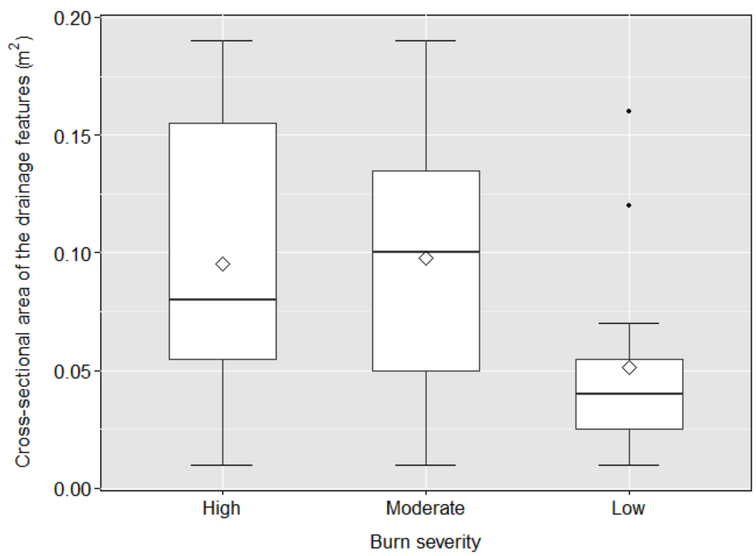

Figure 1.11. Boxplots of the cross-sectional areas of the representative drainage features by burn severity. The lines in the boxes are the median, the diamond is the mean, and the boxes represent the 25th and 75th percentiles. The upper and lower whisker extend from the box to the highest or lowest value that is within 1.5*IQR of the boxes, where IQR is the distance between the 25th and 75th percentiles. Data beyond the end of the whiskers are outliers and plotted as points.

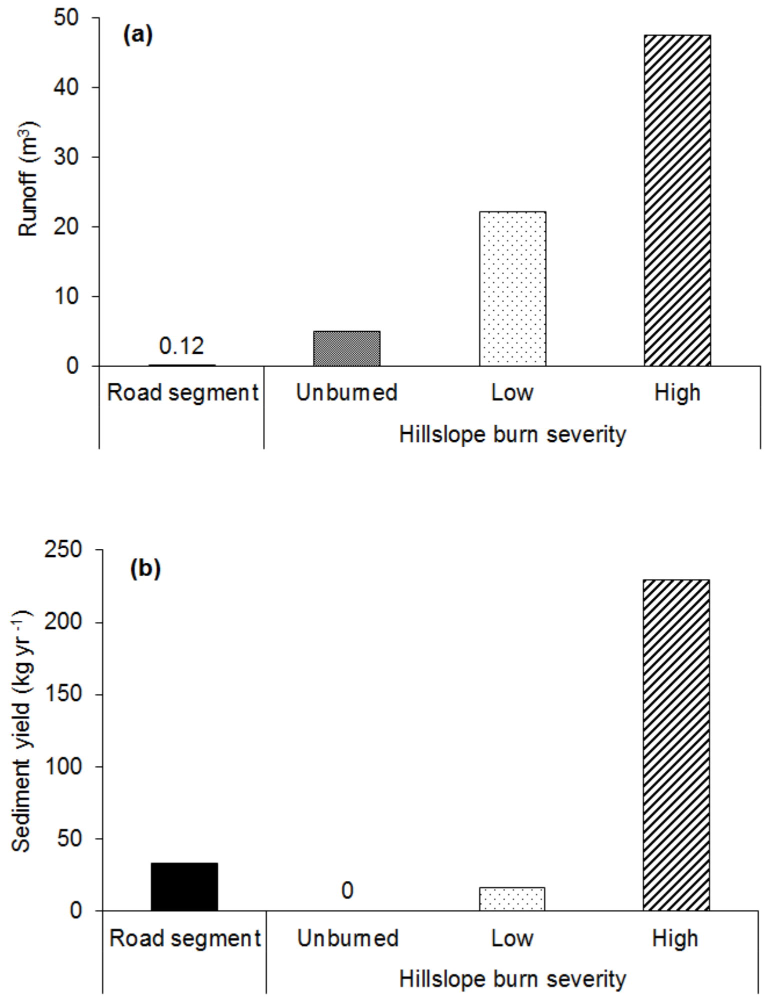

Figure 1.12. Comparison of the (a) predicted surface runoff (m^3) and (b) predicted sediment yields (kg yr^{-1}) from an average road segment using WEPP:Road and an unburned, low severity, and high severity hillslope above the road using Disturbed WEPP. The modeled hillslope used the mean values for hillslope length, slope, and soil type.

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PART II: EFFECTS OF CLOSED ROADS, TRAFFIC, AND ROAD DECOMMISSIONING ON INFILTRATION AND SEDIMENT PRODUCTION: A COMPARATIVE STUDY USING RAINFALL SIMULATIONS

1. INTRODUCTION

Sediment production and delivery from unpaved forest roads can adversely impact streams and water quality, with negative consequences for aquatic habitat and water resources infrastructure (Motha *et al*., 2003; Goode *et al*., 2012). Unsealed road surfaces are a major source of runoff due to the highly compacted area that produce overland flow and allow rapid surface runoff (Ziegler *et al*., 2000). Cutslopes also can intercept subsurface flow, transforming the subsurface flow to yet more overland flow (Wemple and Jones, 2003; Negishi *et al*., 2008). The amount and energy of surface runoff determines the erosive force applied to the road surface by overland flow (Luce and Black, 1999). Surface erosion then is largely controlled by the interaction of flowpath length, which controls the amount of runoff, and slope, which controls the energy (MacDonald and Coe, 2008).

The extent to which the road surface runoff is concentrated or dispersed then affects the potential for hillslope rilling and sediment delivery from concentrated outflows (Takken *et al*., 2008). Roads with ditches and culverts therefore tend to capture more flow and sediments which are delivered to a single point below the road, modifying preexisting flow paths in the hillslope and increasing road-stream connectivity (Croke and Mockler, 2001) and road sediment delivery.

A common way to reduce the adverse environmental impacts of roads is to remove or decommission a road that is no longer needed or desirable (Switalski *et al*., 2004). Decommissioning treatments can vary from relatively cheap and simple methods, such as closing the road by installing a gate or other barrier, to more expensive methods as full recontouring (Madej, 2001; Switalski *et al*., 2004). While closing a road is the least expensive treatment, simply closing a road, even for several decades, may not restore infiltration rates to the values observed in an undisturbed forest. In Idaho the saturated hydraulic conductivity of an abandoned road after thirty years with no traffic was still only 7-28 mm hr^{-1} (Foltz *et al*., 2009). In Peninsular Malaysia an abandoned logging road had more than 80% vegetation cover after 40 years, but the saturated hydraulic conductivity of 62 mm h^{-1} was still an order of magnitude lower than the value of 675 mm h^{-1} for the adjacent hillslopes (Ziegler *et al*., 2007).

Although closing a road may not restore infiltration rates, the partial recovery in infiltration, when combined with the lack of traffic and the increase in surface cover by vegetation and litter, can greatly reduce road sediment production. For example, after 30 years an abandoned road in Idaho had 98% ground cover, and rainfall simulations yielded a mean sediment concentration of 2.2 g L^{-1}, which was only 14% of the value from a similar road subjected to one season of logging traffic two years before the rainfall simulation (Foltz *et al*., 2009).

Numerous other studies have shown how traffic increases road sediment production by increasing the supply of fine material through abrasion and crushing of the road surface materials, as well as the pumping of fine sediment to the surface (Reid and Dunne, 1984; Luce and Black, 1999; Ziegler *et al*., 2001; Sheridan *et al*., 2006). Some reported increases in sediment production due to high traffic include 1.4 times for a gravel road (Grayson *et al*., 1993), 7.5 times for road segments subjected to logging traffic compared to the same roads on days with no logging traffic (Reid and Dunne, 1984), and 2 to 25 times for heavily used road sections by logging trucks compared to lightly used road sections (Foltz, 1996). The complete elimination of traffic can reduce road sediment production by 10 to 60 times relative to roads with regular and high traffic, respectively (Reid *et al*., 1981). Research has also shown that the type of traffic is important, and that the erosion rates from unmanaged ATV trails may equal that an active forest road with regular cars and trucks (Meadows *et al*., 2008). The variability in sediment production rates from roads with different amounts and types of traffic suggest that more rigorous comparisons are needed to better quantify and predict road sediment production under different uses.

A second but less common method of road decommissioning is to rip the roadbed with a bulldozer or other machines to eliminate the compaction (Luce, 1997). The ripping can be followed by the addition of organic materials, such as straw mulch or wood strands to reduce surface erosion, but the effectiveness of just ripping, or of ripping plus mulching, is still a matter of some controversy. Some studies indicate that ripping provides only a short-term, marginal reduction in surface runoff and hence surface erosion. In Alberta, Canada, ripping only decreased the bulk density from 1.60 to 1.40 Mg m^{-3}, or 13% (McNabb, 1994). In Idaho ripping initially decreased the bulk density to 1.50 Mg m^{-3} and increased the hydraulic conductivity from 8 to 30 mm hr^{-1} (Luce, 1997). However, after two simulated rainfalls with 90 mm of rain the bulk density increased back up to 1.70 Mg m^{-3} and the hydraulic conductivity dropped by half to 15 mm hr^{-1} (Luce, 1997). Another study in Idaho showed that two years after ripping the hydraulic conductivity was only 9 mm hr^{-1} (Foltz *et al*., 2007). These results indicate that the initial increase in infiltration due to ripping is very transient. Even the initial increase in infiltration may be of limited value because this is still substantially less than the typical infiltration rate of approximately 40-80 mm hr^{-1} for undisturbed coniferous forests (Robichaud, 2000).

The problem is that relatively few studies have rigorously quantified the effects of different decommissioning treatments on infiltration and sediment production, even though road decommissioning has become an important restoration treatment on both public and private lands (Madej, 2001). For instance, from 1998 to 2002 the USDA Forest Service was decommissioning 3,200 kilometers of road per year at an average cost of $2,500 per kilometer (Schaffer, 2003), and has more recently been decommissioning over 2000 km of roads per year (USDA Forest Service, 2010-2014). Without specific data of the effects of these treatments on runoff, erosion, and road-stream connectivity, the benefits cannot be compared against the costs. Models such as WEPP:Road (Elliot *et al.*, 1999) and SEDMODL2 (NCASI, 2002) can be used to estimate the benefits in terms of sediment production and delivery, but there is a severe lack of process- and treatment-specific data to calibrate and validate these models. An extensive literature review has shown no studies on the effectiveness of road decommissioning treatments for the central or southern Rocky Mountains.

The initial goal of the research was to evaluate the effectiveness of road decommissioning treatments in northcentral Colorado using a combination of sediment fences and road surveys at the road segment scale. The segment-scale measurements can provide useful data for managers, but they do not provide specific process-based data on infiltration and key surface erosion processes, particularly rainsplash and sheetwash. An alternative approach is to use rainfall simulations, as these can readily provide runoff and sediment production data from more controlled comparisons in a shorter time and more cost-effective manner (Ziegler *et al*., 2000; Arnáez *et al*., 2004; Croke *et al*., 2006; Jordan and Martinez-Zavala, 2008; Sheridan *et al*., 2008; Foltz *et al*., 2009; Butzen *et al*., 2014). The implication is that studies using different procedures at different scales may be needed to more rigorously assess the effects of roads, traffic and decommissioning treatments, with rainfall simulations providing detailed comparative infiltration and erosion data, and segment-scale measurements providing data at a scale that is more directly useful for land managers. In this paper we report the plot-scale results using rainfall simulations as these provide the most rigorous means to compare infiltration, runoff and erosion rates among the various treatments and controls. A separate paper will present the results of a multi-year study at the road segment and landscape scale.

Hence the objectives of this paper are to: 1) quantify the differences in infiltration capacity and sediment production between undisturbed forest, closed roads, closed roads exposed to all-terrain vehicle (ATV) traffic, and two decommissioning treatments (ripping only, and ripping plus mulch); 2) quantify the effects of the measured site variables on infiltration and sediment production; and 3) understand how ATV traffic affects plot-scale sediment availability and sediment yields. The results will help parameterize process-based and empirical models such as WEPP:Road, and help guide and quantify the design and benefits of future road closures and decommissioning efforts.

2. METHODS

2.1 Study area

The study area is in the Arapaho-Roosevelt National Forest in northcentral Colorado, about six kilometers southwest of Red Feather Lakes (Figure 2.1). The area has a road density of approximately 1.8 km km^{-2}, and this was established on top of an existing network of trails and roads created by Native Americans, miners, and early settlers. Much of the area was clearcut in the 1950s to 1970s (Veblen and Donnegan, 2005), and since then the roads have been primarily used for recreation, especially by off-highway or all-terrain vehicles (OHV and ATV, respectively). Many of these roads are no longer needed given the reduction in logging and lack of property risk from fires.

The study areas is at an elevation of 2630 to 2850 m in a glaciated, gently rolling, and primarily granitic terrain. Average annual precipitation at the Red Feather Lakes weather station is 460 mm (WRCC, 2016), with about 36% of this falling as snow between October and April (NOAA, 2013). From May through September the precipitation falls primarily as rain, often in brief but occasionally intense thunderstorms (NOAA, 2013). Soils are predominantly Redfeather-Schofield-Rock outcrop association, which are shallow to moderately deep well-drained sandy loams (Moreland, 1980). The vegetation is predominantly lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*), Douglas fir (*Pseudotsuga menziesii*), and quaking aspen (*Populus tremuloides*) in wetter areas.

2.2 Road decommissioning

In early summer 2013 the USDA Forest Service identified 14 km of roads for decommissioning over an area of approximately 16 km^2. The roads selected for decommissioning were distributed among 30 distinct road sections ranging in length from 30 m to 1200 m. These road sections were selected because they were no longer needed for access, posed a disturbance to wildlife, and/or represented a risk to water resources due to their proximity to a stream. Most of the road sections had been closed to traffic for about 25 years, but there are no records of when the various roads were closed. A few of the road sections scheduled for decommissioning were still open to recreational traffic, particularly ATVs.

The roads were decommissioned in September-October 2013. The primary treatment was ripping the road surface to a depth of approximately 0.4 m with a tracked bulldozer pulling three unwinged ripping teeth. Some dead trees were placed on the ripped roads to discourage vehicle traffic. About 40% of the total length was treated with wood-strand mulch and organic fertilizer after ripping, with application rates of 6.2 Mg ha^{-1} and 0.3 Mg ha^{-1}, respectively. This additional treatment was applied according to the proximity of a road section to a stream and the increased risk of sediment delivery.

2.3 Experimental design and plot measurements

The experimental design consisted of five treatments with four replicates each, or a total of 20 rainfall simulations. The five treatments included undisturbed forest as an overall control, closed roads, closed roads subjected to traffic (80 passes of an ATV), and two decommissioning treatments (only ripping, and ripping plus mulching and fertilizer). The simulations on the closed roads are considered a treatment when compared to the undisturbed forest, and a control for evaluating the effects of traffic and decommissioning.

The four plots on closed roads were necessarily placed on two road sections because these were the only closed roads that were not subject to illegal ATV traffic. The effect of traffic was assessed by obtaining permission for an ATV to make 80 passes on the lower portion of each of the two closed roads, and the value of 80 passes was selected as this is relatively typical for a recreational road in this area on a summer weekend. The four plots for each decommissioning treatment were each on a different road section in order to capture as much of the between-road variability as possible. The four plots in the forest were randomly placed in areas adjacent to one of the decommissioned or closed roads. The forest around the plots was mostly mature forest with no indication of recent disturbance, but the tree density was low due to relatively low site quality and possibly some natural or human disturbances decades earlier.

Sediment availability before and after the 80 ATV passes was evaluated by sweeping and collecting the loose surface soil from three 30-cm wide swaths across the active width of each of the two road sections subjected to traffic. This yielded six samples before and six samples after the 80 ATV passes. Each sample was dried for 24 hours at 105°C and sieved to determine the change in mass and particle -size distribution (Topp and Ferre, 2002). The sieve sizes used for the particle-size analysis were 31.5 mm, 16 mm, 11.2 mm, 8 mm, 5.6 mm, 3.35 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, and 0.063 mm.

The rainfall simulations were conducted on 1 m^2 plots that were bounded on the sides and top by sheet metal borders inserted 5-10 cm into the ground (Figure 2.2). The edges were sealed by a mixture of native soil and bentonite. The plots on the decommissioned roads were placed in the center of the road to include one of the ripped furrows created by the bulldozer (Figure 2.2b). Similarly, the plots on the closed roads were placed to include one wheel track and a portion of the center of the road. A thin plastic sheet was attached by staples to the ground in order to collect the overland flow and direct it into a sheet metal collector at the bottom of the plot (Figure 2.2b). The sheet metal collector facilitated the collection of the runoff in one liter wide-mouthed plastic bottles. A plexiglass shield over the plastic sheet and sheet metal collector excluded the simulated rainfall.

Measurements before each rainfall simulation included slope, soil bulk density, soil moisture, surface roughness, and percent ground cover. If present, the width and depth of the furrow was measured at three locations in each plot. Slope was measured with a digital level (Smart Tool®). Bulk density was measured at three locations around the perimeter of each plot by determining the volume of fine sand needed to fill an excavated volume that was approximately 10 cm x 10 cm x 10 cm. One of these samples was taken in a furrow or a wheel track if present, while the other two samples were taken between the furrows or wheel tracks. The excavated soil was dried for 24 hours at 105℃ to determine the gravimetric soil moisture and dry mass (Topp an d Ferre, 2002).

Surface roughness was measured longitudinally (downslope flow direction) and laterally along three transects in each plot using a fine-linked chain, and roughness was calculated as the length of the chain laid over the micro-relief in the plot divided by the length or width of the plot, respectively (Butzen *et al*., 2014). Ground cover was measured on a grid of 100 points in each plot, with each point being classified as bare soil, rock, live vegetation and litter, or wood straw.

Soil water repellency was measured for the four plots in the undisturbed forest using the critical surface tension method (CST) (Watson and Letey, 1970). This method applies drops of de-ionized water with increasing concentrations of ethanol to determine the surface tension at which four of five drops infiltrate within five seconds (King, 1981). The solutions used in this study were 0, 1, 3, 5, 9, 14, 19, 24, 34, and 48% ethanol (Huffman *et al*., 2001), and the corresponding surface tensions of the solutions were obtained from Huffman (2001). Water repellency was measured at three points around the perimeter of the plots at depths of 0, 3, 6, and 9 cm. The water repellency at each depth was the surface tension associated with the concentration of the last solution that indicated soil water repellency, and this surface tension was averaged among the three sample locations to determine the water repellency for each depth for each plot. Lower CST values indicate stronger soil hydrophobicity (Watson and Letey, 1970).

2.4 Rainfall simulations

Rainfall simulations were carried out between July and September 2014, which was 10-12 months after the roads had been decommissioned. Rainfall was applied for 45 minutes using a Purdue-type rainfall simulator (Figure 2.2a), which has an oscillating nozzle centered 3 m above the plot (Foster, 1982). The rainfall simulator was shielded with a tarp to minimize wind effects. The rainfall intensity for each simulation was measured at the end of each experiment by running the simulator for additional 5 minutes and using a 1 m^2 plastic-lined box to measure the runoff rate. Mean rainfall intensity was 44 mm hr^{-1} with minimum and maximum values of 42 and 46 mm hr^{-1}. The rainfall intensity was intentionally higher than the maximum 30-minute rainfall intensity of 25 mm hr^{-1} recorded by five tipping bucket rain gages in the summers of 2013 and 2014 in order to ensure that some runoff was generated from the plots in the forest and on the ripped roads.

The time from the start of rainfall to the beginning of runoff was recorded, and once runoff began samples were collected for the first 30 seconds of each minute in 1000 mL plastic bottles. For the first 20 minutes of each simulation all of these samples were kept and taken to the lab for analysis. From 21 to 45 minutes the runoff and sediment concentrations were much more stable so only every other sample was kept for analysis. Runoff volumes for the samples that were not kept were determined by pouring the samples into a graduated cylinder. The volume of runoff for the other samples was determined in the lab by weighing the sample bottle with its contents, subtracting the weight of the sample bottle, and then converting the mass to a volume by the density of water. Each sample was then filtered through a pre-weighed 5 µm paper filter, and the filters were dried for 24 hours at 105 ℃ to determi ne the mass of sediment in each sample. The volume of runoff was not adjusted for the mass of sediment because the sediment never exceeded 2 g and the runoff volumes measured in the field also included the volume of sediment.

The infiltration rate for each minute was determined by subtracting the runoff rate from the measured rainfall intensity, and infiltration capacity (mm hr^{-1}) was defined as the average infiltration rate for the last five minutes of each simulation. This implicitly assumes a constant depth of pounding, which was generally true except for the first 5-7 minutes of the simulations. For each sample period the sediment yield in g m^{-2} was calculated by multiplying the runoff volume by the sediment concentration in g L^{-1}, and these values were extrapolated in time and then summed to obtain the total sediment yield. At the end of each simulation trenches were cut through the plot to observe the depth and spatial variation of the wetting front.

2.5 Statistical analysis

Given the small number of plots per treatment and that none of the independent or dependent variables were normally distributed, the differences between treatments were analyzed using the non-parametric Kruskal-Wallis test (SAS Institute, Inc., 2002-2010). If there was a significant difference at $p<0.05$, the data were transformed to ranks to satisfy the assumptions for an analysis of variance (ANOVA), and the LSMeans test was used to determinate which means were significantly different. Tukey's method was used for all pairwise comparisons (SAS Institute, Inc., 2002-2010).

Simple linear regression was used to evaluate whether the slope of the mean infiltration rate for each treatment over the last 25 minutes of the experiments was positive, negative, or not significantly different from zero (SAS Institute, Inc., 2002-2010). Spearman correlation coefficients and simple linear regressions also were used to evaluate the interrelationships between plot characteristics, the log-transformed infiltration capacities, and the log-transformed sediment yields.

3. RESULTS

3.1 Plot characteristics

The mean slope of all plots was 6% with a range of 4 to 10%, but there were no significant differences in mean slope by treatment (Table 2.1). The mean bulk density for the forest plots was 1.28 g cm^{-3}, while the mean bulk density for the closed roads was significantly higher at 1.75 g cm^{-3}. The mean bulk density of the plots subjected to traffic was only two percent higher than the mean value for closed roads, indicating that the 80 ATV passes did not further increase the bulk density. Ripping only reduced the bulk density to 1.54 g cm^{-3}, or just 14% less than the closed roads, and the mean bulk density for the ripping and mulching treatment was nearly identical at 1.52 g cm^{-3}. Both of these bulk densities were significantly higher than the mean bulk density for the forested plots. In the decommissioned roads the mean bulk density of the furrows was nearly identical to the mean bulk density outside of the furrows ($p=0.63$).

Mean soil moisture prior to the rainfall simulations was 8.4% for the forested plots, with a wide range of 4% to 18%. In contrast, the mean soil moisture for the closed roads was significantly lower at 4.7% and less variable (s.d.=1.7%) (Table 2.1). Mean soil moisture for the plots exposed to traffic was very similar to the closed roads. The mean soil moisture of 4.1% (s.d.=2.1%) for the decommissioning treatment of only ripping was very similar to the closed roads and roads with traffic, but the mean soil moisture value of 8.4% for ripping plus mulching plots was significantly higher and more variable (s.d.=5.1%) (Table 2.1). The higher soil moisture for the forested plots and the ripping plus mulching treatment may be partly due to the higher litter and mulch cover, which would reduce evaporation.

The lateral and longitudinal roughness ratios for the forest plots were respectively 1.15 and 1.13 (Table 2.1). This relatively high roughness was due to small twigs and branches and the 18-49% live vegetation cover. Mean surface roughness for the closed roads was just 1.01 for both longitudinal and lateral roughness, and these values were significantly lower than the mean values for the forested plots. Both decommissioning treatments significantly increased the roughness compared to the closed roads, particularly in the lateral direction (Table 2.1). This high lateral roughness was due to the placement of the plot to include a furrow, as the furrows had a mean width of 0.33 m (s.d.=0.08 m) and 0.08 m deep (s.d.=0.01 m). The ripping plus mulching treatment had even higher longitudinal and lateral roughness values than only ripping due to the wood-strand mulch. This mulch was not evenly distributed on the plot as much of the mulch had washed or fallen into the furrows, so the mean mulch depth in the furrow was 0.05 m (s.d.=0.02 m).

Ground cover and the amount of bare soil varied significantly among the different treatments (Figure 2.3). The forested plots averaged 98% cover (s.d.=4%), with litter and wood covering 61% (s.d.=16%) of the ground surface, and live vegetation the other 37% (s.d.=14%). In contrast, the closed roads and closed roads with traffic both had an average surface cover of just 13% (s.d.=3%) and this was a combination of rock and coniferous litter (Figure 2.3). The mean ground cover of 33% (s.d.=5%) on the ripping treatment was more than double the value from the closed roads, and this was a roughly equal mixture of rocks and live vegetation plus litter. Mean percent cover on the ripping and mulching treatment was 67% (s.d.=4%), or twice the value of the ripping treatment, and this difference was due to the 48% (s.d.=4%) cover provided by the wood-shred mulch (Figure 2.3).

3.2 Infiltration rates over time by treatment

The overall mean time to the beginning of runoff was 4.5 minutes, and this varied from 3.4 to 6.2 minutes among the different treatments (Figure 2.4). While there were no significant differences in the time to runoff among treatments (p=0.07), the shortest mean time of 3.4 minutes corresponds to the closed roads subjected to traffic, while the longest time of 6.2 minutes was for the ripped and mulched plots followed by 5.5 minutes for the forested plots. This time to runoff was due to the time needed for initial wetting plus ponding.

Each of the treatments showed a sharp decline in infiltration shortly after runoff began except for the ripping and mulching treatment, where the decline was much more gentle (Figure 2.4). The forested plots had a much smaller decline than the other four treatments, and the timing of this decline also was about 1-4 minutes later than the other treatments, indicating a greater moisture storage capacity. The sharpest decline was for the closed roads and the closed roads with traffic, and for these plots the final steady-state infiltration rates of 4 mm hr^{-1} (s.d.=1 mm hr^{-1}) and 5 mm hr^{-1} (s.d.=3 mm hr^{-1}), respectively, were nearly reached just 15 minutes after the simulation began. The ripping treatment also had a sharp although slightly later decline in infiltration, with the rate dropping to only 15 mm hr^{-1} at 15 minutes and then slowly declining to the final value of 9 mm hr^{-1} (s.d.=3 mm hr^{-1}). The ripping and mulching treatment started with a much higher infiltration rate than just ripping and this slowly declined from 30 mm hr^{-1} at 15 minutes to a final infiltration rate of 20 mm hr^{-1} (s.d.=6 mm hr^{-1}) (Figure 2.4).

The pattern of mean infiltration for the forested plots was different in that the infiltration rates increased after the initial sharp drop at about 6-7 minutes (Figure 2.4). The final mean infiltration rate for the four forested plots was higher than the other treatments at 28 mm hr^{-1}, and they also were much more variable as the final infiltration capacity ranged from 13 to 42 mm hr^{-1} (Figure 2.5). Both the increase in infiltration over time and the high variability can be explained by strength and variability in the surface soil water repellency, as the critical surface tension varied from 68 dynes cm^{-1} for plot 3, which had the highest infiltration rate, to 37 dynes cm^{-1} for plot 1, which had the lowest infiltration rate (Figure 2.5). The other two plots had intermediate surface tension values of 55 dynes cm^{-1} (plot 4) and 52 dynes cm^{-1} (plot 2), and both of these plots showed the typical upward increase in infiltration over time as the soil wetted up. In contrast, the plots with no and very strong water repellency (plots 1 and 3, respectively) showed very little change in the infiltration rate over time (Figure 2.5). None of the forested plots had any soil water repellency at three or more centimeters below the surface.

The slope of the mean infiltration rate over the last 25 minutes of the simulations was significantly different from zero for all of the treatments (Figure 2.6). While the forested plots showed an increase in infiltration over time, each of the other treatments showed a linear decrease. This decrease is expected given the decline in hydraulic gradient as the soils wet up. For these four treatments the decline in infiltration and hence the slope of the regression was generally proportional to the infiltration rate at 20 minutes (i.e., the intercept of the regression equation) (Figure 2.6). The ripping plus mulching treatment had the highest infiltration rate at 20 minutes and the greatest decline in infiltration, while the closed roads had the lowest infiltration rate at 20 minutes and the smallest decline in infiltration (Figure 2.6). The plots that were only ripped were intermediate, although the magnitude and change in infiltration over time was more similar to the closed roads than the ripping and mulching treatment.

The mean infiltration capacity for each of the five treatments are plotted in Figure 2.7, and this shows that the forested plots had the highest mean infiltration capacity of 28 mm hr^{-1}, followed by the ripping and mulching treatment at 20 mm hr^{-1}. The infiltration capacities for these two treatments were more than double the closed roads, the closed roads with traffic, and the ripping treatment, and each of these differences were significant (Figure 2.7).

The excavations after the simulations showed considerable variability in the depth and spatial extent of infiltration among the forested plots, with completely dry soils in some portions of the plots with stronger soil water repellency. For the closed roads it was difficult to distinguish the depth or variability of the wetting front as the water infiltrated uniformly into the soil profile, and there was not a clear line between wetting front from the simulated rainfall and the pre-existing soil moisture. The spatial distribution of the wetting front for the two decommissioning treatments was different from the forest and closed road plots, as the soil was completely saturated under the furrows due to the concentration of runoff. Outside of the furrows the soil was wet but not saturated. The saturated zone under the furrow was about 10 cm deep for the ripping treatment and was more than 20 cm deep for some of the plots that had been ripped and mulched.

3.3 Sediment yield

The mean sediment yield from the forested plots was only 2.8 g m^{-2} (s.d.= 3.7 g m^{-2}) (Figure 2.8), but this appeared to be primarily organic matter rather than mineral soil. There was no distinct peak in sediment production associated with the initial high runoff (Figure 2.9), indicating a lack of readily available sediment.

Mean sediment production for the closed roads was 43 g m^{-2} (s.d.= 25 g m^{-2}) or 15 times the mean value from the forested plots, and this difference was significant (Figure 2.8). Sediment yields were highest for the first 15 minutes of runoff, and relatively constant from 20 minutes until the end of the simulation (Figure 2.9). The initial flush of sediment in the first 15-20 minutes is commonly observed in sediment studies and is generally attributed to the presence of readily available sediment. This interpretation is supported by the lower sediment yields for the last 20-25 minutes of the simulation despite the increasing runoff, resulting in no significant correlation between the infiltration rate and sediment yields ($p=0.64$).

Mean sediment production from the plots on the closed roads subjected to traffic was 130 g m^{-2} (s.d.= 64 g m^{-2}), or three times the mean sediment production from the closed roads with no traffic, and this difference was significant (Figure 2.8). The pattern of sediment production over time was remarkable for the very high initial peak as soon as runoff began (Figure 2.9), indicating a large supply of readily available sediment. Sediment yields then declined over time, suggesting a decreasing supply of sediment, but the mean sediment yield over the course of the simulation was always higher than any of the other treatments.

Sediment yields for the ripping treatment were relatively similar to the closed roads for the first eight minutes of the simulation, but the sediment yields for the ripping treatment did not then decline over time (Figure 2.9). This suggests that sediment production for the ripping treatment was not supply limited, and this is supported by the strong correlation between runoff and sediment production (R^2= 0.67; $p<0.0001$). The mean sediment yield for the ripping treatment was 72 g m^{-2} (s.d.= 28 g m^{-2}), and this is 40% more than the closed roads but only 55% of the value from the closed roads with traffic; neither of these differences were significant due to the high between-plot variability for these three treatments (Figure 2.8).

The mean sediment yield from the ripping and mulching treatment was only 16 g m^{-2} (s.d.=5 g m^{-2}) or 22% of the mean value from the ripping treatment, and this difference was significant (Figure 2.8). The pattern of sediment production over time was different than the other treatments (Figure 2.9), as there was not an initial flush with the first runoff and the sediment yields showed a nearly linear increase over the entire 45-minute simulation (Figure 2.9). Like the ripping treatment, there was a strong linear relationship between sediment yield and runoff (R^2=0.90, $p<0.0001$), suggesting that sediment production was not supply limited. By the end of the simulation the sediment production rate from the ripped and mulched plots was approaching the final sediment production rate from the closed roads, indicating that the mulch had a substantial beneficial effect during the first half of the simulation, but this beneficial effect decreased over time.

3.4 Controls on infiltration capacity and sediment yields

When the data from all 20 plots were pooled, the log-transformed infiltration capacity was positively and significantly correlated with ground cover (r=0.89), longitudinal roughness (r=0.88), and slope (r=0.54), and negatively correlated with bulk density (r=-0.83; Table 2.2). The strong positive correlations with ground cover and longitudinal roughness are not independent as these two variables were strongly correlated (r=0.86; Table 2.2), and the plot of infiltration versus ground cover has the closed roads at one end with their low infiltration capacity, low ground cover, and low surface roughness, and the forested plots at the other end with their high infiltration capacity, high ground cover, and high surface roughness (Figure 2.10a). The plots that had been mulched and ripped were more similar to the forested plots, while the plots that had only been ripped were more similar to the closed roads, indicating a clear benefit to mulching after ripping (Figure 2.10a). The significant correlation between plot slope and infiltration capacity is due to the much higher infiltration capacities and slightly higher slopes of the forested plots and the plots that had been mulched and ripped, while the plots on closed roads and ripped roads had lower slopes and lower infiltration capacities (Table 2.1, Figure 2.7).

The decrease in infiltration capacity with increasing bulk density is consistent with basic principles, but in this case there was not a clear distinction between treatments as both the forested plots and the ripped plots had considerable variability in their bulk densities and infiltration capacities (Figure 2.10b).

Infiltration rates for the four forested plots were strongly correlated with soil water repellency (R^2=0.74, p=0.004). Water repellency was not measured on the road plots, but the low infiltration rates on the roads was almost certainly due to compaction rather than soil water repellency (Ziegler *et al*., 2000). Ripping also would eliminate any soil water repellency due to the extensive soil disturbance, so the presumption is that soil water repellency was an important control on infiltration only for the forested plots.

The log-transformed sediment yield was negatively and significantly correlated with ground cover (r=-0.74), slope (r=-0.60), and longitudinal roughness (r=-0.58), and positive and significantly correlated with bulk density (r=0.66; Table 2.2). These results are almost exactly the inverse of the correlations with infiltration capacity, and this is due to both the cross-correlations between variables and the significant negative correlation between infiltration capacity and sediment yield (r=-0.65; Table 2.2). The significant relationship between infiltration capacity and sediment yield is again due to the closed roads and ripping treatment anchoring one end of the regression, the ripped and mulched plots in the middle, and the forested plots falling at the opposite end of the regression (Figure 2.11). The relationship between infiltration and sediment yield is somewhat weaker than most of the other significant correlations because of the high variability in infiltration rates in the forested plots as discussed above and the high variability in sediment yields from the closed roads with traffic as discussed in the next section.

3.5 Effect of traffic on sediment availability and particle size distribution

The 80 passes of an ATV had very little effect on the infiltration rate but tripled the mean sediment yield compared to the closed roads with no traffic (Figures 2.4, 2.9). Much of this increase in sediment yield can be attributed to the increase in available sediment. The mean mass of loose sediment prior to the 80 ATV passes was 2.60 kg m^{-2} (s.d.=0.60 kg m^{-2}), and after the ATV passes this increased by 46% to 3.80 kg m^{-2} (s.d.=0.89 kg m^{-2}). While the two roads had nearly the identical amount of readily available sediment after the 80 passes (3.81 kg m^{-2} and 3.79 kg m^{-2}, respectively), the mean increase of 1.45 kg m^{-2} (s.d.=1.54 kg m^{-2}) for the two plots on road 1 was 56% more than the mean increase of 0.93 kg m^{-2} (s.d.=1.17 kg m^{-2}) for the two plots on road 2. The high variability between measurements within each road meant that this difference was not significant (p=0.66).

Prior to any traffic the particle-size distribution of the loose sediment was generally similar between the plots on each road and between the two roads. Road 2 did have slightly more particles smaller than 0.125 mm and larger than 2 mm, and less coarse sand (Figure 2.12a). The 80 ATV passes substantially increased the amount of medium and coarse sand on road 1, while for road 2 the biggest increase was in the amount of clay, silt, and fine sand (Figure 2.12b). When comparing these results with the rainfall simulation data, the two plots on Road 1 produced 67 g m^{-2} and 86 g m^{-2} of sediment, respectively, while the two plots on Road 2 produced 169 g m^{-2} and 199 g m^{-2}, or 2.4 times the mean value from Road 1. Since the two roads had very similar characteristics and amounts of readily available sediment after traffic, this large difference in sediment yields between the two roads has to be attributed to the much larger increase and amount of fine particles on road 2 (Figure 2.12b).

4. DISCUSSION

4.1 Soil water repellency in the undisturbed forest

Soil water repellency at the soil surface was the most important factor influencing overland flow in the forested plots. Under dry conditions soil water repellency is typical for soils with permanent vegetation cover, such as grasslands and forests (Shakesby *et al*., 2000; Doerr *et al*., 2006). The lack of soil water repellency below the surface is also consistent with most other studies in unburned coniferous forests (Doerr *et al*., 2009). The forested plots were the only plots that showed a mean increase in infiltration over time, and this is consistent with our understanding of how water repellent soils are initially resistant to wetting but become more hydrophilic as the critical soil moisture threshold is exceeded (MacDonald and Huffman, 2004; Doerr *et al*., 2006).

It is noteworthy that plot 2 had the second highest infiltration rate of 33 mm hr^{-1} (Figure 2.5) even though this plot had the second strongest soil water repellency at 52 dynes cm^{-1} of CST. This apparent inconsistency may be explained by the substantially higher antecedent soil moisture content of 14.2% for this plot compared to the values of 5.7-9.7% for the other three plots. The soil moisture value of 14.2% for plot 2 is very close to the soil moisture threshold identified for unburned and low severity plots (MacDonald and Huffman, 2004). Hence the water repellency in plot 2 would quickly diminish as the simulation began, and this can explain the relatively high final infiltration rate of 33 mm hr^{-1}. Plot 4 had slightly less soil water repellency at 55 dynes cm^{-1} of CST, but it took longer for the infiltration rate to increase and the final infiltration rate of 23 mm hr^{-1} was less than in plot 2. This discrepancy is probably due to the much lower antecedent soil moisture content of 5.7% for plot 4, as it would take longer for the soil to reach the critical moisture threshold and some portions of the plot would probably still be water repellent at the end of the simulation given the small-scale variations in soil water repellency (Huffman *et al.*, 2001; Doerr *et al*., 2009; Butzen *et al*., 2014).

These large differences in soil water repellency and infiltration rates among the forested plots contributed to the lack of any significant difference in mean infiltration capacity between the forested plots and the plots that had been ripped and mulched. At larger scales and under wetter soil conditions the mean infiltration capacity in the forest could be substantially higher; reported infiltration rates range from 77 mm hr^{-1} for undisturbed Douglas-fir/lodgepole pine forests in Idaho (Robichaud, 2000) to more than 120 mm hr^{-1} for ponderosa pine forest in Colorado (Martin and Moody, 2001). A higher infiltration rate in the forest would result in a larger difference in infiltration between the forested plots and the two decommissioning treatments and reduce the apparent effectiveness of these treatments.

4.2 Infiltration and sediment production from closed roads and the effect of traffic

The low infiltration capacities of the closed roads measured in this study are consistent with the values reported by other studies. A recent review of 20 studies for different lithologies and climates showed that most of the saturated hydraulic conductivity values fell between 1 and 10 mm hr^{-1}, while steady-state infiltration rates were between 3 and 5 mm hr^{-1}(Ramos-Scharrón and LaFevor, 2016). These low infiltration rates are due to compaction, the destruction of soil aggregates by traffic, and the sealing of the surface by fine particles (Ziegler *et al*., 2000). The low infiltration rates for the closed roads in the present study can be attributed to the same processes, as the low infiltration rates can persist for several decades after road closures (Ziegler *et al*., 2007; Foltz *et al*., 2009). This means that closing a road has relatively little benefit in terms of restoring the normal hydrologic regime.

Mean sediment yields from the closed roads were 43 g m^{-2} or 430 Mg ha^{-1} of active road surface area, and this was 15 times higher than the mean value from the forested plots. In absolute terms this indicates that closed roads can continue producing large amounts of sediment over long time periods, so closing a road will not necessarily eliminate its potential adverse effect on water resources. On the other hand, just 80 passes with an ATV increased the mean sediment yield by a factor of three, so closing roads is still an effective decommissioning treatment in relative terms.

The much higher sediment production rates for roads with traffic are due to the increased supply of readily erodible sediment by abrasion and crushing of the road surface materials, and the upward forcing of fine-grained sediment from the road bed (Reid and Dunne, 1984; Ziegler *et al*., 2001; Sheridan *et al*., 2006; van Meerveld, *et al*., 2014). In this study sediment production from the closed roads declined after about 15-20 minutes, indicating that much of readily available fine sediment had been removed during the first part of the simulation, and this is consistent with previous studies (Ziegler *et al*., 2001; Sheridan *et al*., 2006). After this readily-available fine sediment has been removed, it is harder for rainsplash to detach particles due to the compacted surface and to the development of a thin layer of overland flow that helps protect the road surface from raindrop impact (Ziegler *et al*., 2000; Arnaez *et al*., 2004; van Meerveld *et al*., 2014).

In this study just 80 passes of an ATV tripled the mean sediment production relative to the closed roads without any traffic, but there was a 2.4-fold difference in mean sediment production between the two plots on road 1 versus the two plots on road 2. The 1 m^2 size of the plots means that the primary erosion processes are the interrill processes of rainsplash and sheetwash (Ries *et al.*, 2013), and other studies have shown that interrill erosion is very size selective (Constantini *et al*., 1999; Luce and Black, 1999; Sheridan *et al*., 2008). In Australia particles less than 0.02 mm represented less than 6% of the total sediment on forest roads, but these particles accounted for 50-90% of the total sediment load from rainfall simulations on 6 m^2 plots (Costantini *et al*., 1999). In western Oregon sediment production from graveled roads on a silty clay loam soil were about nine times greater than from roads on a gravelly loam soil (Luce and Black, 1999), again indicating that the abundance of fine particles may be more important than the total mass of loose soil. Given these results, the much greater increase in the amount of fine sediment on Road 2 induced by the 80 ATV passes is the best explanation for the much greater sediment yields from the simulations on road 2 than road 1(Figure 2.12b).

It is not clear why the same number of ATV passes had such a different effect on the amount and particle-size distribution of the available sediment on the two roads. The two roads had the same lithology and particle-size distributions before traffic, but we could not carefully control exactly where or how the ATV drove on the two roads. Repeated passes on the same wheel tracks could have a different effect on the amount and particle-size distribution of the loose sediment, but there have not been any carefully controlled studies to evaluate this issue.

4.3 Effectiveness of the two decommissioning treatments on infiltration and sediment yields

The two decommissioning treatments caused a relatively small reduction in bulk densities, and this probably can be attributed to soil settling over the 10-11 months between the time these roads were ripped and the rainfall simulations. Soil settling is defined as the re-compaction of the soil due to the rearranging of the soil grains over time to decrease void space (SSSA, 2001). In this study the decommissioned roads were subjected to a very unusual large rainstorm that occurred immediately after the roads were ripped but before any mulch or fertilizer could be applied. This storm dropped 206 mm of rain over six days with 90 mm of rain in an 18-hour period, and the six-day rainfall had an estimated return period of 200-500 years (NOAA-NWS 2013). Data from other studies indicate that this large amount of rain, together with the subsequent snow accumulation, snowmelt, and summer rainstorms, would have caused soil settlement and increased the bulk density. In Idaho ripping increased the hydraulic conductivity from 8 to 30 mm hr^{-1}, but after two simulated rainfalls with 90 mm of rain the bulk density increased from 1.50 to 1.70 Mg m^{-3} and the hydraulic conductivity dropped by half to 15 mm hr^{-1} (Luce, 1997). The same study also showed that straw mulch provided minimal protection against soil settling, as there was no difference in infiltration between unmulched and mulched plots after three simulations with 135 mm of rainfall (Luce, 1997). This re-compaction of the soil is primarily a function of the cumulative rainfall and soil physical properties rather than the direct transfer of kinetic energy to the soil from the falling raindrops (van Wesemael *et al*., 1995), and is well documented in the agricultural literature (e.g., Canarache *et al*., 2000; Hamza and Anderson, 2005).

These results are consistent with the present study, as the bulk density from the ripping and mulching treatment was nearly identical to the bulk density from only ripping. This means that the two-fold decrease in infiltration and the three-fold increase in sediment production from the ripped plots as compared to the ripped and mulched plots must be due to other processes than soil settling. The mulching did nearly double the mean surface cover compared to the plots that were only ripped, and the mulch also filled in more than half the furrow depth. This mulch would have several beneficial effects, including the protection of the soil surface and the provision of surface roughness.

Mulch and other surface cover absorbs the kinetic energy of raindrops and thereby protects soil aggregates from being broken apart and individual particles from being detached. This not only prevents rainsplash erosion but also inhibits soil sealing and the resulting reduction in infiltration (Thompson and James, 1985; Moore and Singer, 1990; Grismer and Hogan, 2005; Larsen *et al*., 2009). In contrast to the closed roads, the micro-relief of the ripped soil prevented the development of a thin, uniform layer of overland flow to help protect the soil against rainsplash, so the continuing exposure of the ripped soil rainsplash would provide a continuing supply of sediment.

In the decommissioning plots the furrow played an important role in collecting and directing the runoff from the plots to the plot outlet. About one third of the plot area was occupied by the furrow, and the concentration of runoff into the furrow was most obvious for the ripping treatment where pine needles and small depressions created miniature dams, but these were broken or overtopped by the concentrated overland flow. The more rapid flow in the furrows in the unmulched plots made for a more efficient delivery of the eroded sediment to the plot outlet.

In contrast, the wood strand mulch tended to be concentrated in the furrow, and this trapped more of the runoff, reduced the flow velocity, and increased the opportunity for infiltration. The vegetative regrowth also tended to be concentrated in the furrow (Figure 2.2b), and the root channels will facilitate infiltration. The greater infiltration in the furrow was clearly shown by the greater depth of the saturated zone when the plots were trenched after the simulations. Other studies have shown that wood strands increase depression storage and reduce overland flow velocities (Govers *et al*., 2000; Foltz and Dooley, 2003).

The mulch had an even more beneficial effect on sediment yields. Sediment detachment by rainsplash was observed outside of the furrows for both of the decommissioning treatments, but there was more detachment for the ripping treatment due to the lack of cover. Observations during the simulations and the data on infiltration and sediment yields indicate that the deep mulch cover in the furrow was very effective in trapping sediment and reducing the sediment transport capacity. However, the plots that were ripped and mulched showed a consistent decrease in infiltration and increase in sediment production over the 45-minute simulation, and this indicates that the beneficial effects of mulching will decrease over longer-duration or higher-intensity storms, and in higher rainfall areas. Over the longer term the effectiveness of both decommissioning treatments will depend to a large extent on the rate of vegetative regrowth, as this will both increase infiltration and decrease erosion. We postulate that the relative effectiveness of the ripping and mulching treatment compared to just ripping may be particularly high in the present study given the relatively low amounts and intensity of rainfall in the study area.

4.4 Scale effects

A key issue is the extent to which these results can be extrapolated in space. The infiltration rates from the forested plots were highly variable, and the spatial variability in infiltration and runoff generation has long been recognized (e.g., Betson, 1964; Dunne and Black, 1970). In this study the variability in infiltration over space and time for the forested plots was attributed to the differences in soil water repellency and antecedent soil moisture. At larger scales soil water repellency may be less important because the runoff generated from one area will infiltrate farther downslope (Larsen *et al*., 2009). At larger scales one also would expect a higher mean infiltration rate due to the commonly observed log-normal distribution of point- or plot-scale infiltration rates (Martin and Moody, 2001).

For the closed roads and roads with traffic, the simulation results provide process-based insights and data that are useful for calibrating physically-based models, particularly where interrill erosion is the dominant erosion process. The results also can also help guide future restoration efforts, but it is less clear whether the relative or absolute erosion rates measured in this study can be used to quantify the effects of road decommissioning at the road segment or watershed scales. The primary limitation of the rainfall simulations is that they do not quantify the larger-scale process of rill erosion, as road surface rilling requires the accumulation and concentration of surface runoff from larger areas or longer segments (MacDonald *et al*., 1997; Luce and Black, 1999). The simulation results may be applicable at larger scales under specific conditions, such as outsloped roads where the flow distance is relatively short, or for relatively flat road segments where there is sheetflow rather than rilling. Unit area sediment production rates typically increase when road segments are longer and steeper and rill erosion is an important sediment source (Ramos-Scharron and MacDonald, 2005).

There are additional scaling issues to consider when extrapolating the simulation results to larger scales for the two decommissioning treatments. At the plot scale ripping plus mulching was far more effective in terms of increasing infiltration and reducing erosion than only ripping. At the road segment scale, however, sediment fence data showed that both decommissioning treatments were nearly equally effective in reducing sediment production (Part III). The explanation is that nearly all of the sediment eroded by rain splash and sheetwash, especially for the treatment of only ripping, was captured in the furrows created by the ripping. If the storage capacity of the furrows is exceeded due to ongoing erosion, the plot- and segment-scale erosion rates should begin to converge. The present difference in the relative effectiveness of the two decommissioning treatments at the plot and road segment scales indicates the difficulty of extrapolating the plot-scale results in this chapter to the road segment and watershed scales.

4.5 Management implications

Land managers have a choice of techniques to reduce road surface runoff, erosion, and the delivery of this material to streams. Road closure is the simplest and cheapest decommissioning treatment, and the simulation results indicate that the closed roads generate large amounts of runoff but much less sediment compared to roads subjected to recreational ATV traffic. The decision of whether to close a road, or to undertake more extensive decommissioning treatments, will therefore depend on the management objectives. For example, only closing a road could be justified if the primary objective is to reduce sediment delivery to a stream, regardless of the amount of runoff being delivered. However, if the management objective is to restore the natural hillslope hydrologic functions, or to eliminate road stream connectivity, a more intensive road decommissioning treatment is necessary.

The results show that ripping plus mulching is significantly more effective for increasing infiltration and reducing erosion than only ripping, but this also is not sufficient to fully restore the hydrologic functioning of the hillslope. The final infiltration rate of 20 mm hr^{-1} is nearly 30% below the final infiltration rate of the forested plots, and it can be argued that the infiltration rate for the forested plots will increase over time as the soils wet up while the infiltration rate for the ripped and mulched plots will continue to decline. Similarly, sediment yields from the ripping and mulching treatment were nearly six times larger than the value from the forested plots, and the time trends again suggest that the difference between these two treatments should increase over time. The benefits of the additional cost of mulching have to be compared to the additional costs compared to only ripping, but the mulching would seem to be justified in areas where the protection of water quality is a high management priority.

The time scale of the restoration objectives also is important, as the more intensive decommissioning treatments such as ripping plus mulching will immediately increase infiltration and reduce road-stream connectivity. Closing a road will lead to a relatively rapid decrease in sediment production, while many decades may be needed before the infiltration rate of a closed road begins to approach the value of a natural forest.

5. CONCLUSIONS

Rainfall simulations were used to quantify infiltration and sediment production rates from a natural forest, closed roads, closed roads subjected to ATV traffic, and two road decommissioning techniques. The four forested plots had the highest but highly variable infiltration rates, and this was attributed to the spatial variations in soil water repellency. Sediment yields from the forested plots were very low because of the high surface cover and surface roughness. The final mean infiltration rate of 4 mm hr^{-1} for the closed roads was nearly an order of magnitude lower than the forested plots, and the mean sediment yield was more than an order magnitude higher at 43 g m^{-2}. Eighty passes of an off-highway vehicle had no effect on the final infiltration rate, but tripled mean sediment yields. The two plots with the largest increase in fine (<0.5 mm) sediment had much higher sediment yields, indicating that plot-scale sediment detachment and transport is particle-size selective.

The decommissioning treatment of only ripping had a mean final infiltration rate of 9 mm hr^{-1}, which was double the infiltration rate from closed roads, but this is still a relatively low value and only 32% of the mean final infiltration rate from the forested plots. The mean sediment yield from this treatment was 67% higher than the closed roads, and this was primarily due to the continuing supply of fine sediment. The decommissioning treatment of ripping plus mulching was significantly better than just ripping in terms of both the final infiltration rate and mean sediment yield. The positive effect of mulching on infiltration and sediment production can be attributed to the protection from rainsplash and sealing, the enhanced infiltration in the furrows, and the reduced sediment transport due to the greater roughness and slower flow velocities. Over longer periods and under wetter conditions both of these decommissioning treatments may be progressively less effective as the sediment storage capacity in the furrows is exceeded, but this will depend on the amount and intensity of rainfall, soil type, slope, vegetative regrowth rate, and other site-specific factors. Both longer-term and larger-scale studies under different site conditions are needed to more fully evaluate the effectiveness of these two decommissioning treatments over time.

Table 2.1. Mean (standard deviation) of the plot characteristics by treatment. Different letters indicate significant differences at $p<0.05$.

Plot characteristics	Forest	Closed roads	Closed roads with traffic	Ripping	Ripping and mulching
Slope (%)	8 (1)	6 (1)	5 (1)	6 (3)	8 (2)
Bulk density (g cm^{-3})	1.28^{a} (0.21)	1.75^{b} (0.08)	1.79^{b} (0.08)	1.54^{c} (0.21)	1.52^{c} (0.13)
Soil moisture (%)	8.4^{a} (4.2)	4.7^{b} (1.7)	4.1^{b} (0.2)	4.1^{b} (2.1)	8.4^{a} (5.1)
Roughness ratio (lateral)	1.15^{a} (0.10)	1.01^{b} (0.01)	1.02^{b} (0.01)	1.13^{a} (0.02)	1.20^{a} (0.03)
Roughness ratio (longitudinal)	1.13^{a} (0.08)	1.01^{b} (0.01)	1.01^{b} (0.01)	1.06^{a} (0.04)	1.14^{a} (0.05)

Table 2.2. Correlation matrix of Spearman correlation coefficients for the 20 rainfall simulations. * indicates that the correlation is significant at p≤0.05, and ** indicates that the correlation is significant at p≤0.01.

	Slope (%)	Bulk density	Soil moisture	Rough. ratio	Ground cover	Infiltration capacity
Bulk density (g cm^{-3})	-0.61**					
Soil moisture (%)	0.38	-0.24				
Roughness ratio	0.50*	-0.76**	0.25			
Ground cover (%)	0.59*	-0.91**	0.28	0.86**		
Infiltration capacity (mm hr^{-1})	0.54*	-0.83**	0.41	0.88**	0.89**	
Sediment yield (g m^{-2})	-0.60*	0.66**	-0.16	-0.58*	-0.74**	-0.65**

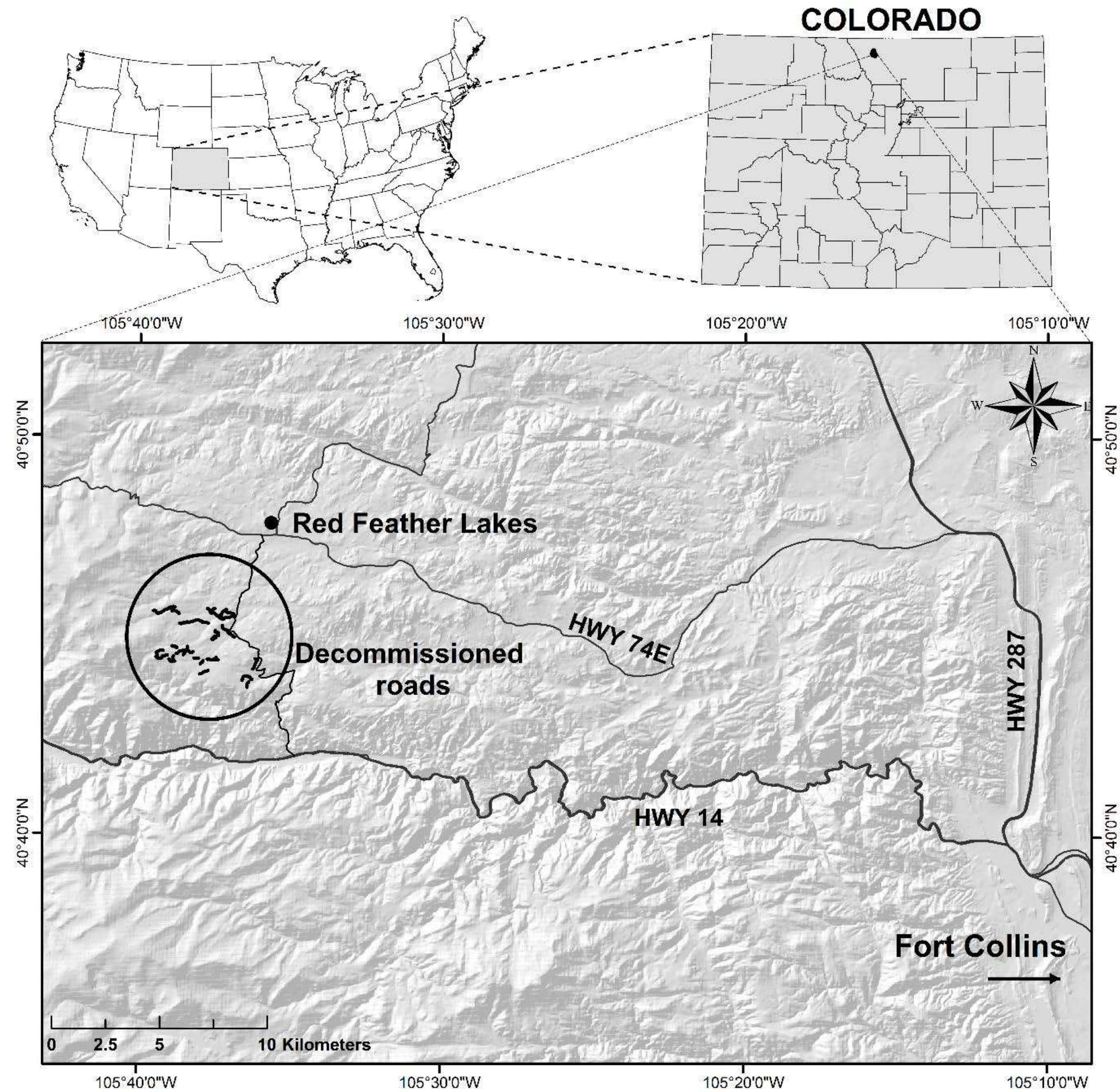

Figure 2.1. Location of the decommissioned roads in the Arapaho-Roosevelt National Forest that were the subject of this study.

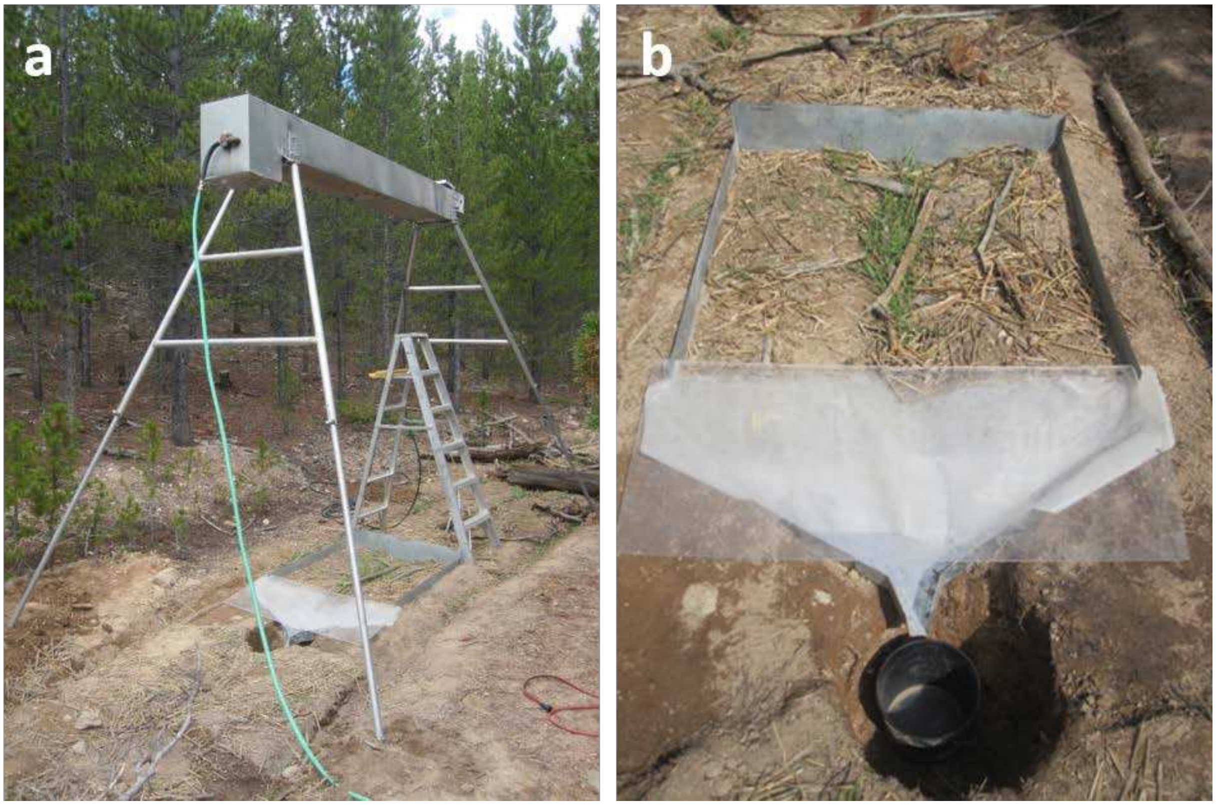

Figure 2.2. a) The Purdue-type rainfall simulator set up above a plot on a decommissioned road that had been ripped and mulched with wood strands and fertilizer. b) Detailed view of the plot prior to the rainfall simulation showing the central furrow, wood-strand mulch, and limited vegetative growth in the 10 months since the road had been treated.

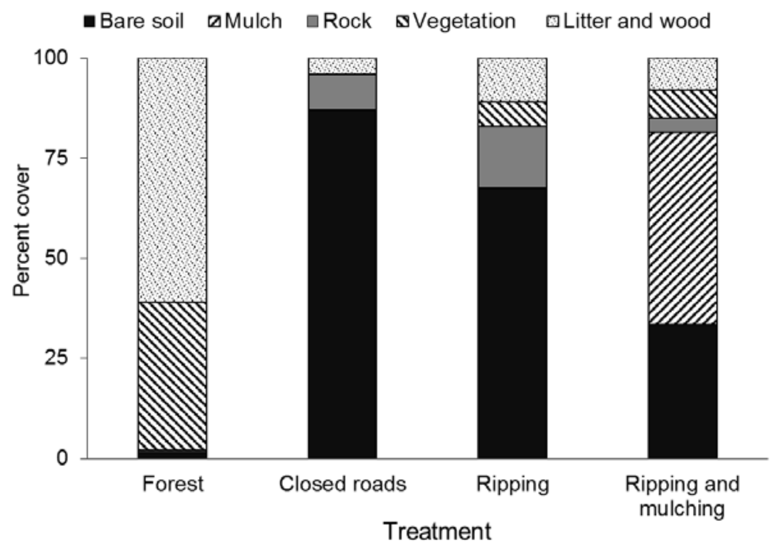

Figure 2.3. Mean percent ground cover for the undisturbed forest plots, closed roads, and the two decommissioning treatments. Cover data for the closed roads with traffic are combined with closed roads because the values were nearly identical.

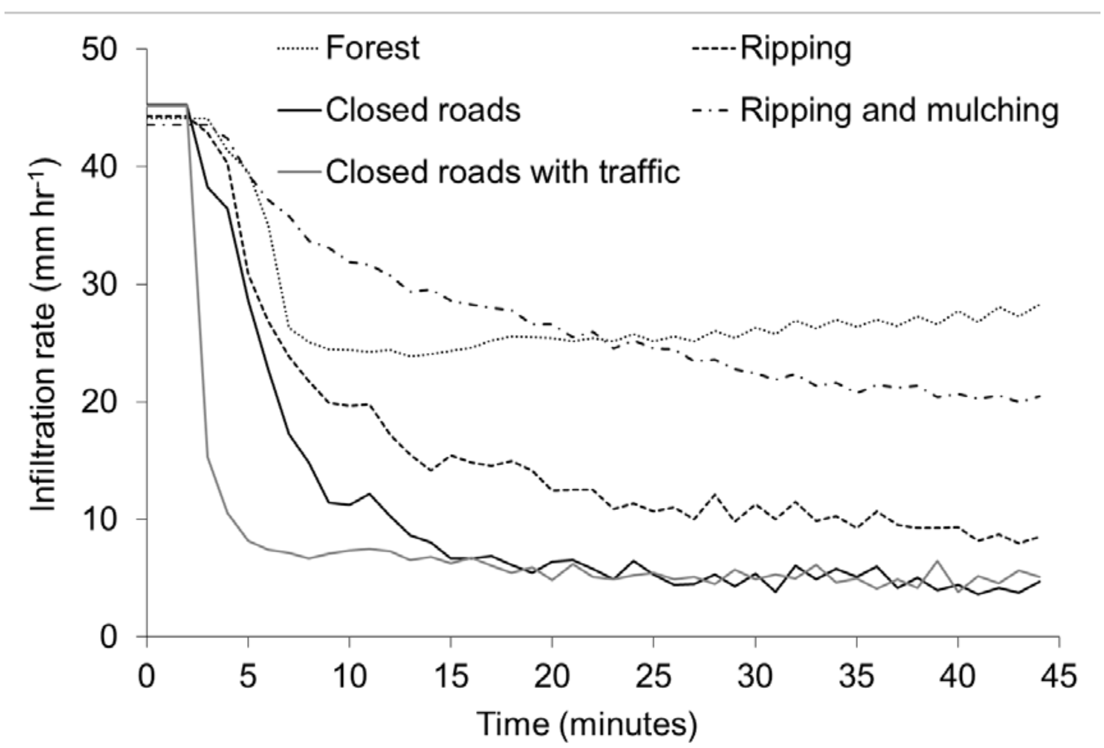

Figure 2.4. Mean infiltration rates over time for each of the five treatments.

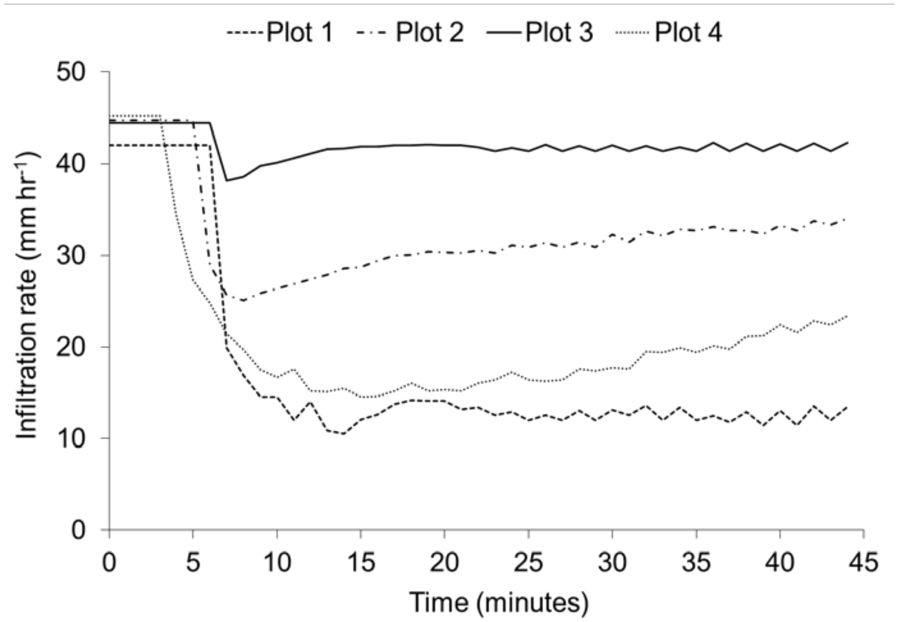

Figure 2.5. Infiltration rates over time for each rainfall simulation in the forest.

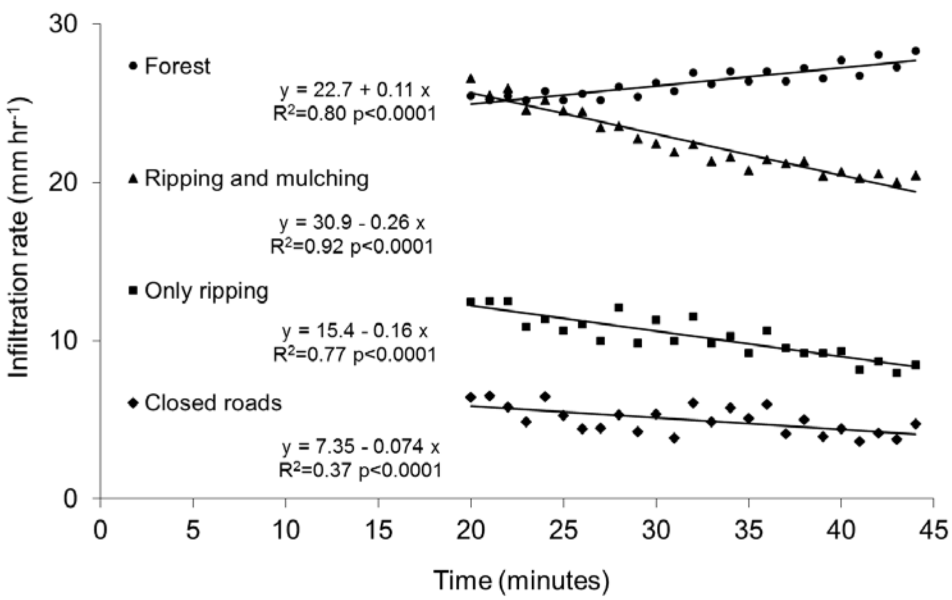

Figure 2.6. Mean infiltration rates by treatment for the last 25 minutes of the simulations. Regression lines are plotted in real space for each treatment, with the regression slope indicating the magnitude of the trends over time and the intercept indicating the mean infiltration rate at 20 minutes after the start of the simulation. Roads with traffic are not shown as the infiltration rates were nearly identical to the closed roads.

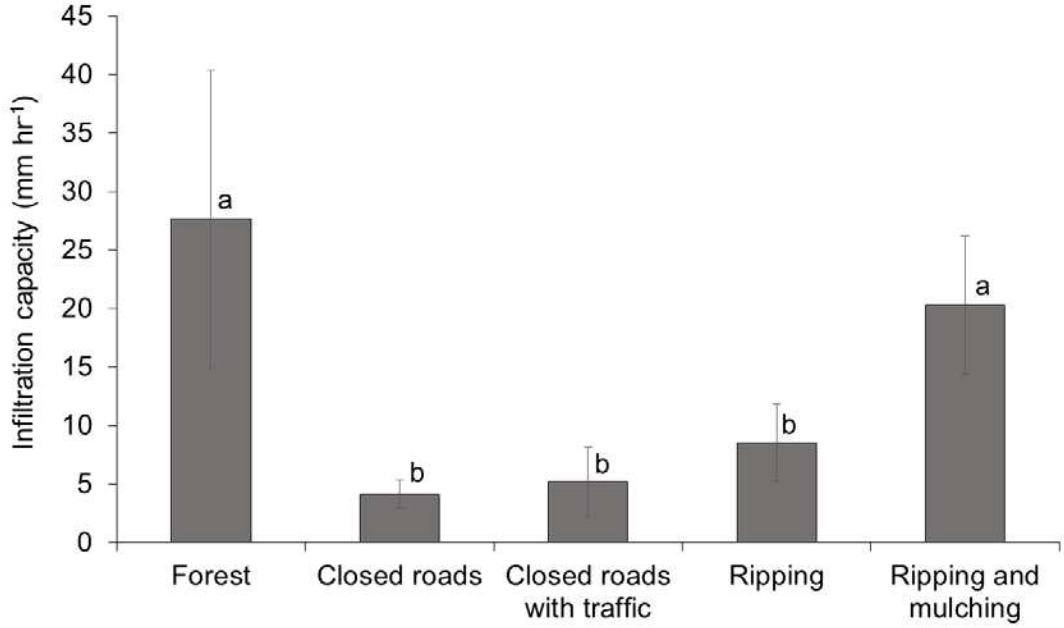

Figure 2.7. Mean final infiltration capacity for each of the five treatments. Error bars represent the standard deviation, and different letters indicate significant differences.

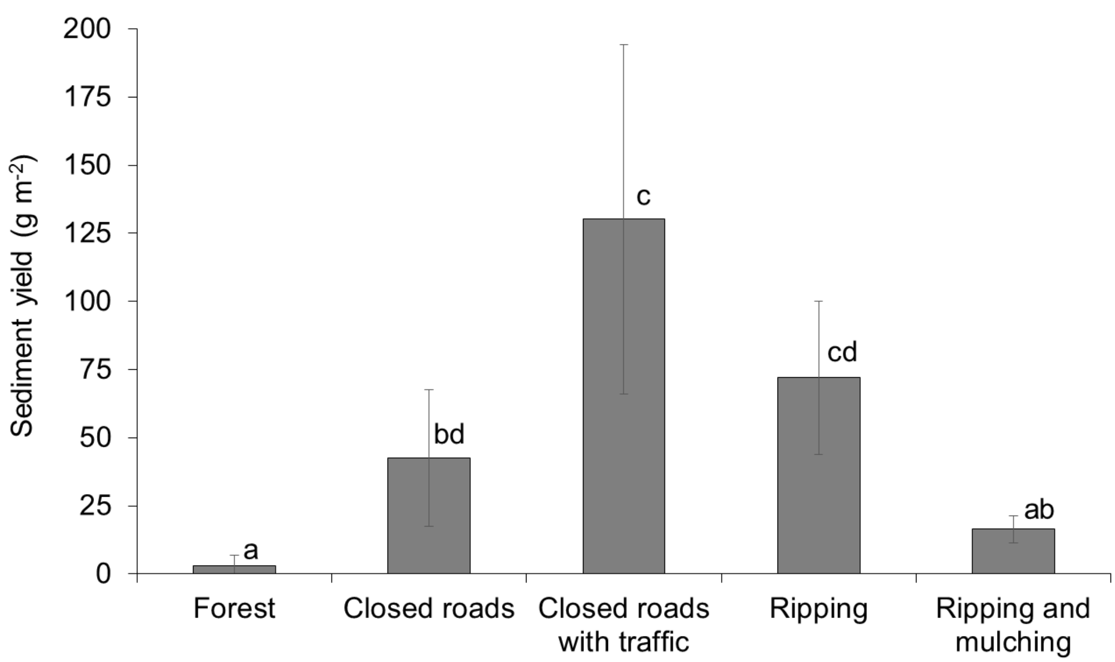

Figure 2.8. Mean sediment yield by treatment. Error bars represent the standard deviation, and different letters indicate significant differences.

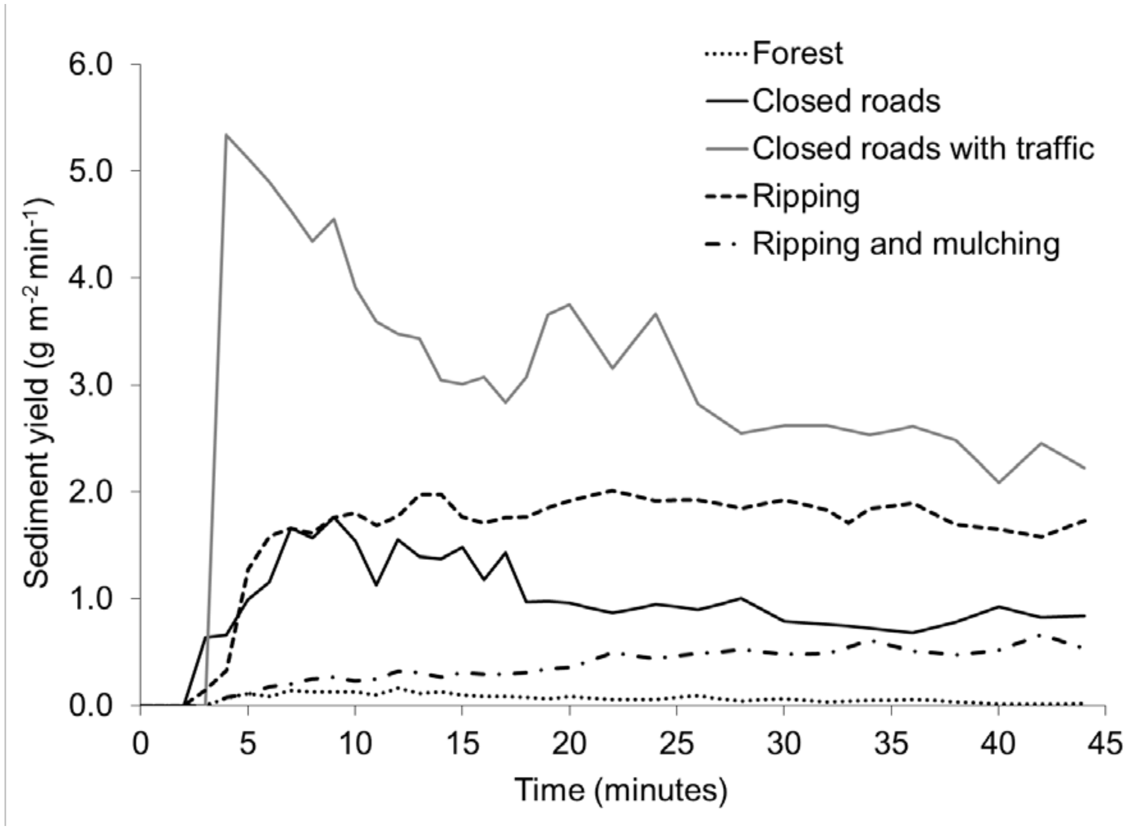

Figure 2.9. Mean sediment yields in g m^{-2} per minute for each of the five treatments.

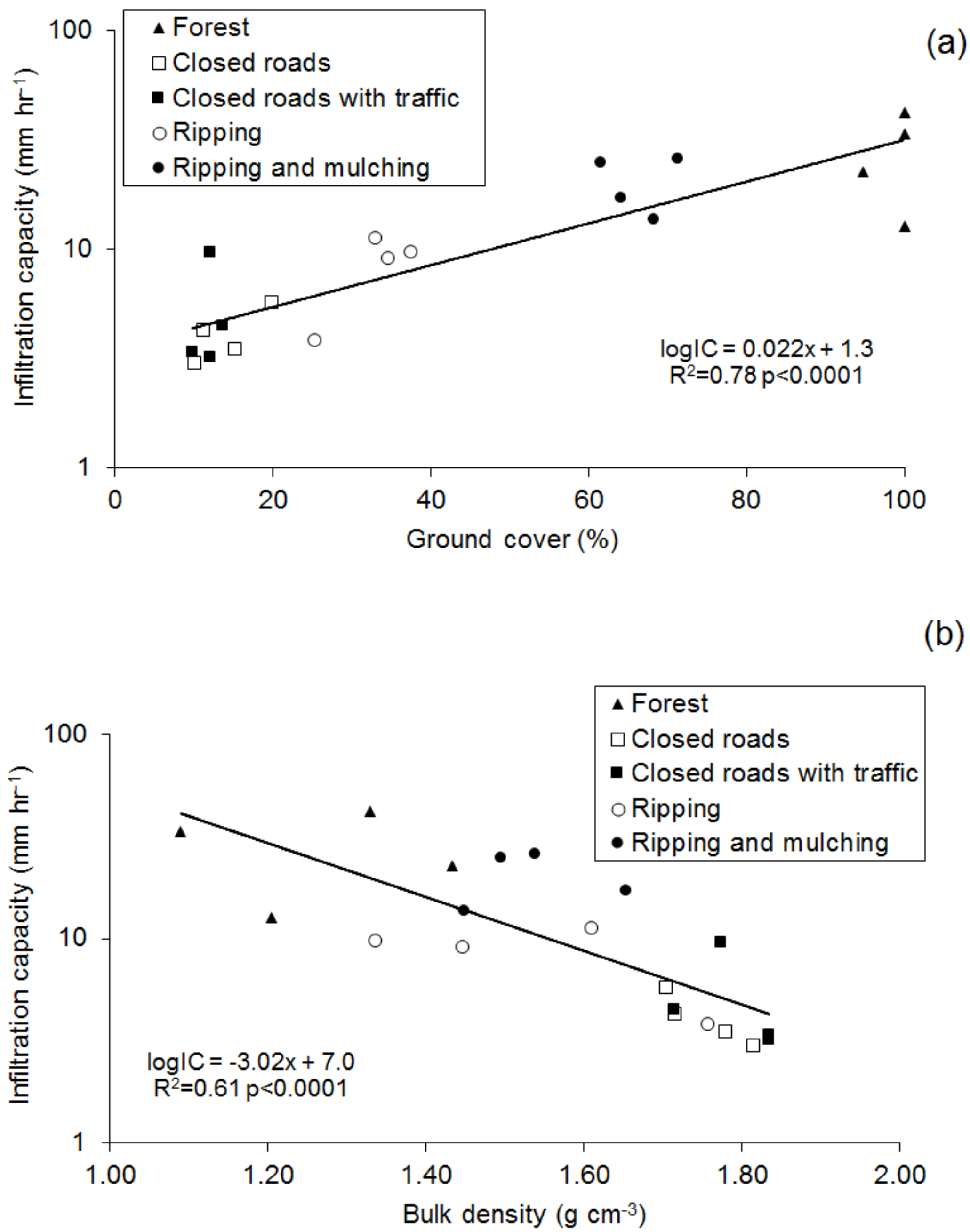

Figure 2.10. Relationship between the log-transformed infiltration capacity and (a) ground cover, and (b) bulk density for all 20 rainfall simulations.

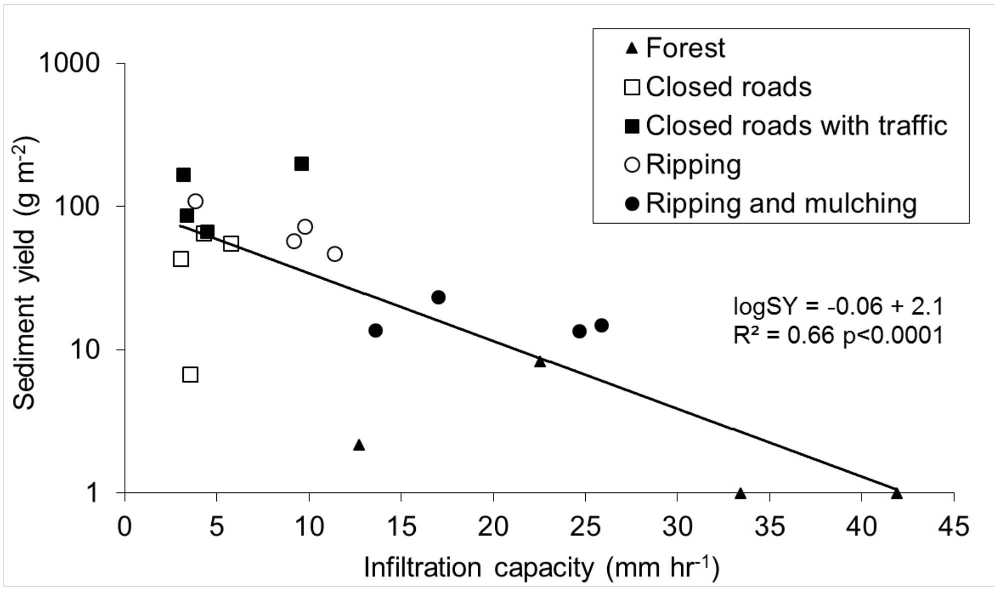

Figure 2.11. Relationship between the log-transformed sediment yield and infiltration capacity.

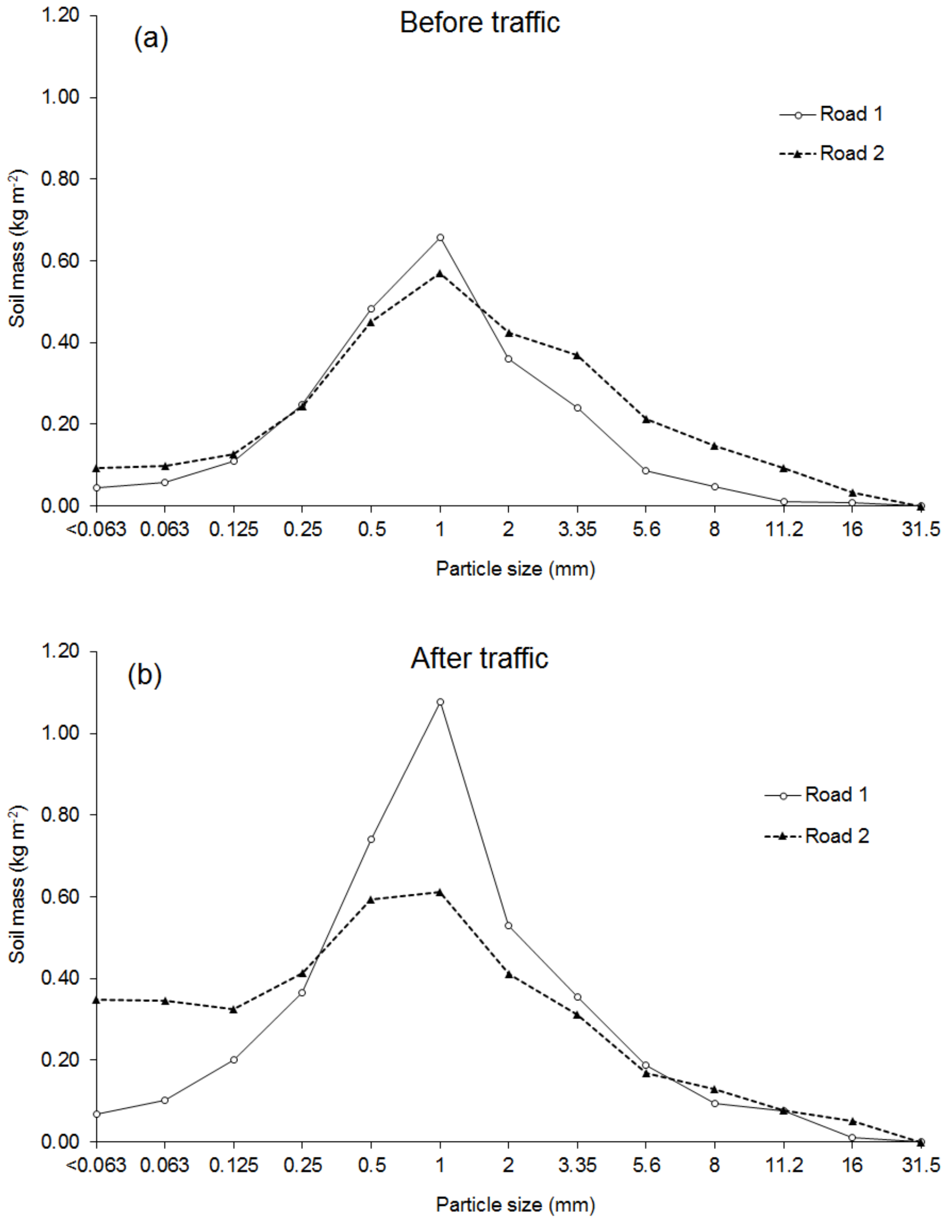

Figure 2.12. Mean mass of loose sediment on the road surface by particle size for roads 1 and 2 before traffic (a) and after 80 passes of an off-highway vehicle (b). Each line represents the mean of three samples. The particle sizes are plotted on a phi (log_2) scale.

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PART III: EFFECTS OF TWO DECOMMISSIONING TREATMENTS ON ROAD SEDIMENT PRODUCTION AND ROAD-STREAM CONNECTIVITY

1. INTRODUCTION

Roads are essential for forest management and recreation activities, but roads can also be a major hydrological disturbance and source of sediment in forested watersheds (Motha *et al*., 2003; Croke and Hairsine, 2006). Actively-used unpaved road surfaces are severely compacted and have correspondingly low infiltration rates (Luce, 1997; Ziegler *et al*., 2007; Foltz *et al*., 2009; Ramos-Scharron and LaFevor, 2016) and high rates of infiltration-excess (Horton) overland flow (Ziegler and Giambelluca, 1997). Saturated hydraulic conductivity values for unpaved roads have been reported as 0.2 mm hr^{-1} to 5.1 mm hr^{-1} (Ziegler and Giambelluca, 1997), 5 mm hr^{-1} (Ramos-Scharrón and LaFevor, 2016), <8.8 mm hr^{-1} (Foltz *et al*., 2007), and 0 to 12 mm hr^{-1} (Luce, 1997). These low values mean that even low or moderate intensity rains can generate infiltration-excess overland flow. In comparison, saturated hydraulic conductivity ranges for undisturbed forests are almost always lower than maximum rainfall intensities, resulting in little or no Horton overland flow (Ziegler and Giambelluca, 1997; Robichaud, 2000).

In sloped areas road cuts can further increase the amount of surface runoff by intercepting downslope subsurface flow (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 amount of road surface runoff is a major control on road surface erosion, and the low infiltration rates means the amount of runoff is directly related to road surface area. The energy of the overland flow is primarily a function of the flow depth and slope, so road segment area times slope is commonly used to predict road surface erosion (e.g., MacDonald *et al*., 1997; Luce and Black, 1999; Ramos-Scharron and MacDonald, 2005). Snowmelt typically generates very little road surface erosion due to the much lower volumes of runoff compared to rainstorms and the greatly reduced detachment due to the absence of rainsplash (Sugden and Woods, 2007; Fu *et al*., 2010).

Road surface erosion also varies with road surface characteristics, including soil texture (Luce and Black, 1999), ground cover (Luce and Black, 1999; Ziegler *et al*., 2000), and time since construction or maintenance activities (i.e., grading) (Luce and Black, 2001; Ramos- Scharrón and MacDonald, 2005; Stafford, 2011). Traffic is another major control on road sediment production (Reid and Dunne, 1984; Coker *et al*., 1993; van Meerveld *et al*., 2014), as this increases the supply of fine material through abrasion and crushing of the road surface materials (Sheridan *et al*., 2006) as well as the pumping of fine sediment to the surface (Reid and Dunne, 1984). This fine sediment is more erodible than the consolidated road surface. The supply of this loose, fine sediment is very dynamic, as traffic increases the supply while surface runoff removes the sediment from the surface (Ziegler *et al*., 2001). Reported increases in sediment production due to high traffic include approximately 1.4 times for a gravel road (Grayson *et al*., 1993), 7.5 times for road segments subjected to logging traffic compared to the same roads on days with no logging traffic (Reid and Dunne, 1984), and 2 to 25 times for heavily used road sections by logging trucks compared to lightly used road sections (Foltz, 1996).

The variability in precipitation, site conditions, and traffic mean that reported road surface erosion rates vary from nearly zero to more than 100 kg m^{-2} yr^{-1} (MacDonald and Coe, 2008). Annual road erosion rates per unit rainfall for studies published since 2000 range from 0.2 g m^{-2} mm^{-1} yr^{-1} to 10 g m^{-2} mm^{-1} yr^{-1} (Fu *et al*., 2010). However, these erosion rates are primarily a concern if they affect the driveability of a road by creating deep rills, or if the runoff and sediment are delivered to a stream, wetland, or lake where they can adversely affect water quality and aquatic habitat.

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). Key factors that affect road-stream connectivity include: the amount of runoff from the road segment; frequency, location, and type of drainage structures; distance from the drainage outlets to a stream; hillslope gradient; downslope infiltration capacity; and the trapping efficiency of obstructions (Megahan and Ketcheson, 1996; Croke and Hairsine, 2006).

An increasingly common way to reduce the most severe adverse environmental impacts from roads is to remove or decommission roads that are no longer needed or desirable (Switalski, 2004). Road decommissioning as a restoration tool was first done on a large scale in the U.S. in the late 1970s in Redwood National Park, California (Madej, 2001), and since then this has become an important component of forest restoration projects on both public and private lands. From 1998 to 2002 the USDA Forest Service decommissioned 3200 km of road per year at an average cost of $2,500 per kilometer (Schaffer, 2003). More recently the USDA Forest Service had been decommissioning over 2000 km of roads per year (USDA Forest Service, 2010-2014).

Decommissioning techniques can be as cheap and simple as closing the road to traffic by installing a gate or other barrier. The other extreme is to completely remove the road by ripping it, removing the crossings, recontouring the road prism, and revegetating the disturbed area (Switalski, 2004). An intermediate approach is to rip the roadbed with a bulldozer or other machines to eliminate the compaction (Luce, 1997), and this can be followed by mulching to reduce surface erosion. The problem is that relatively few studies have measured sediment production and road-stream connectivity prior to and after decommissioning, so the benefits of these efforts on road runoff, sediment production, and sediment delivery are largely unknown. While some studies have measured changes in bulk density or infiltration (Luce, 1997; Madej, 2001; Kolka and Smidt, 2004; Foltz *et al*., 2007; Lloyd *et al*., 2013) there are no segment- or larger-scale studies from the central or southern Rocky Mountains.

The overall goal of this study was to evaluate the effectiveness of two road decommissioning treatments for reducing road sediment production and road-stream connectivity. The objectives were to: 1) quantify the changes in segment-scale sediment production from two decommissioning treatments (ripping only, and ripping plus mulching) versus untreated controls; 2) identify the key controls on road sediment production; and 3) quantify the changes in road-stream connectivity due to decommissioning 14 km of roads. The results can help guide the design and quantify the benefits of future decommissioning projects.

2. METHODS

2.1 Study area

The study area is in the Arapaho-Roosevelt National Forest in northcentral Colorado, about six kilometers southwest of Red Feather Lakes (Figure 3.1). The study roads are at an elevation of 2630 to 2850 m in a glaciated, gently rolling, and primarily granitic terrain. Average annual precipitation at the Red Feather Lakes weather station is 460 mm (WRCC, 2016), with about 36% of this falling as snow between October and April (NOAA, 2013). From May through September the precipitation falls primarily as rain, often in brief but occasionally intense thunderstorms (NOAA, 2013). Soils are predominantly Redfeather-Schofield-Rock outcrop association, which are shallow to moderately deep well-drained sandy loams (Moreland, 1980). The vegetation is predominantly lodgepole pine (*Pinus contorta*), with some ponderosa pine (*Pinus ponderosa*), Douglas fir (*Pseudotsuga menziesii*), and quaking aspen (*Populus tremuloides*) according to aspect, soil wetness, and elevation. Some areas within the overall study area had been clearcut or more recently thinned, but no timber harvests have been conducted for at least a couple of decades. Some residual slash was still present as the decay rate is extremely slow in this dry, cold climate.

2.2 Road decommissioning

In early summer 2013 the USDA Forest Service designated 14 km of roads for decommissioning over an area of approximately 16 km^2. The designated roads consisted of about 30 distinct road sections ranging in length from 30 m to 1200 m.

These roads were selected because they were no longer needed for access, and they either posed a disturbance to wildlife and/or a risk to water resources. Many of the designated road sections had been closed to traffic for about 25 years, but there are no records of exactly when each section had been closed. A few sections were still open to recreational traffic, particularly by all-terrain vehicles (ATVs).

The decommissioning was conducted in September-October 2013, and the primary treatment was ripping the road surface to a depth of approximately 0.4 m. The ripping was done with a tracked bulldozer pulling three unwinged ripping teeth that made three furrows in the roadbed. Some dead trees were placed on the ripped roads to inhibit vehicle traffic. After ripping about 40% of the total length was treated with wood-strand mulch, branches and residual slash, and an organic fertilizer (biosol). The specified application rates of the wood-strand mulch and fertilizer were 6.2 Mg ha^{-1} and 0.3 Mg ha^{-1}, respectively. The mulch and fertilizer was applied according to the proximity of a road section to a stream and the increased risk of sediment delivery.

2.3 Precipitation

Precipitation was measured with five tipping bucket rain gauges with each tip representing 0.254 mm of rainfall. The mean distance between a rain gauge and a road segment with sediment production measurements was 0.52 km, and no segment was more than one kilometer from a rain gauge. Summer rainfall was defined as 1 June through 30 September, as this is when nearly all of the summer thunderstorms and associated road erosion occurs (Welsh, 2008). No sediment was produced during the winter or spring snowmelt. Individual storms were defined as precipitation events separated from each other by one hour with less than 1.27 mm. This short duration was chosen because the time to runoff concentration for the road segments with sediment measurements was much shorter than one hour. A variety of precipitation metrics were calculated for each storm using the RIST program (Rainfall Intensity Summarization Tool) version 3.94 (USDA, 2015), including storm depth (mm), storm duration (hr), maximum 5- (I_5), 15- (I_{15}), and 30-minute (I_{30}) intensities in mm hr^{-1}, and storm erosivity (EI_{30}) in MJ mm ha^{-1} hr^{-1}. Summer precipitation for the five rain gages from 2013-2015 was compared to historical data from Red Feather Lakes for 1985-2012 (WRCC, 2016).

2.4 Road sediment production

Road sediment production was measured with sediment fences for 28 road segments during summer 2013, with 18 of these segments being decommissioned in fall 2013. The other ten road segments were left as controls to quantify the interannual variability in sediment production, as these data were needed to separate the changes in sediment production due to decommissioning from the changes in sediment production due to interannual differences in the amount and intensity of rainfall.

The control segments and many of the segments to be decommissioned were selected because they had a clearly defined hydrologic top and bottom, all of the drainage was collected and delivered to a single point with sufficient cross-slope to install a sediment fence, and they represented a range of segment lengths and slopes. The segments to be decommissioned were also selected so that nine segments were to be ripped and nine segments were to be ripped and mulched.

To the extent possible the control segments were stratified by traffic, with three segments on active roads with high traffic, three segments on roads with low traffic, and four on abandoned roads with no traffic. The high traffic roads were open to all types of traffic, while the low traffic roads were abandoned roads that had only occasional ATV and motorcycle traffic during the snow-free period. Traffic counters indicated a mean of 400 vehicles per week for two of the high traffic roads during summer 2015; the low traffic road was used primarily for recreation by ATVs, and this averaged 80 vehicle passes per week.

With respect to the segments that were to be decommissioned, 13 of these were on abandoned roads, four on low traffic roads, and only one suitable segment could be found for a high traffic road. While we did not measure traffic on the low traffic roads that were decommissioned, field observations indicated that there were less than 80 vehicles per week. This distribution of road segments to be decommissioned by traffic level was consistent with the total population of roads to be decommissioned, as abandoned roads with no traffic accounted for 53% of the total length to be decommissioned, another 42% were low traffic roads, and only 5% were active roads with high traffic. The 18 segments on roads to be decommissioned represented 7.5% or 1.05 km of the total length of roads to be decommissioned.

In 2014 the Arapaho-Roosevelt National Forest identified more roads to be decommissioned, but only a couple of short sections were in our study area. We identified two additional segments and installed sediment fences on these in early summer 2014, with one segment being decommissioned in fall 2014 by ripping and mulching while the other was kept as a control.

One of the control segments established in early summer 2013 was much longer, wider, and more heavily trafficked. In summer 2013 this segment produced 55% of the total measured sediment, and its sediment production per unit area was nine times the mean value from the other 27 segments. This segment also only had one year of valid data as in summer 2014 it was graded and no longer drained to a single point. The sediment production values from this atypical segment dominated the statistical results, so the data from this segment are discussed separately and were excluded from the statistical analyses. A second other segment with only one year of valid data was the high-traffic segment that was decommissioned; this segment was subjected to frequent illegal ATV use in summer 2014 so it could not be considered as either a control or a decommissioned segment.

The sediment fences used to measure sediment production were constructed with a geotextile fabric attached to 1.2 m long rebar that had been pounded into the ground. The entire area for trapping sediment was also covered by the geotextile to facilitate the identification and removal of the trapped sediment. The leading edge and edges of each piece were secured to the surface with landscape staples (Robichaud and Brown, 2002). To the extent possible the sediment fences were installed at the drainage outlet of a road segment (Figure 3.2a), but nine of the sediment fences on closed roads to be decommissioned were installed directly in the road as the roads had no traffic and the drainage points were not well defined (Figure 3.2b).

The presence of a Remote Automatic Weather Stations (RAWS) at Red Feather Lakes helped us identify when storms occurred, and the fences generally were checked at least a couple of times each week in the first summer. This allowed us to identify the approximate rainfall thresholds needed to produce sediment, and the fences were emptied after each major storm event, or approximately four to six times each summer. The sediment measurement procedure was to excavate the accumulated sediment into 20-L buckets, and weigh these with a hanging scale to the nearest 0.5 kg. Two well-mixed 0.5 kg samples of the excavated sediment were taken and placed in air tight plastic bags; the moisture content of these samples was determined by drying for 24 hours at 105 ℃ (Topp and Ferre, 2002). The mean moisture content was used to convert the field-measured wet weights to a dry mass. Since there was no evidence of overland flow or sediment coming onto the road segment from the adjacent hillslope, division of this mass by the active area of the road segment yielded the road sediment production rate in kg m^{-2}.

The frequent checking of the sediment fences indicated that there were no more than six storms each summer that produced sediment. This meant that the each measured sediment production value could be matched to a specific storm, and these data formed the “storm-based” dataset. The storm-based values were summed to generate the total sediment yields for each summer (“summer” [or annual] dataset).

2.5 Road segment characteristics

The key characteristics of each road segment with a sediment fence were measured or estimated. Segment length was measured along the center line of the road with a measuring wheel. Total width was defined as the width of the road surface, while the active width was defined by the actively used road tread. Both widths were measured at a minimum of three locations to determine mean values. Segment slope was measured with a clinometer, and a distance-weighted mean slope was calculated if the slope was not consistent. Road surface area was calculated as the segment length times the active width. Hillslope and cutslope gradients were measured perpendicular to the road segment with clinometers, but only the atypical control segment on the heavily traffic road had a cutslope. Surface cover was classified at a minimum of 100 points systematically spaced along a zigzag transect across the active width, and at each point the surface was classified as bare soil, rock (intermediate axis larger than 1.0 cm), live vegetation, litter, and wood (diameter larger than 2.5 cm).

The ends of each segment were recorded with a handheld GPS so that the exact same segment could be identified after decommissioning. After decommissioning waterbars were constructed as needed to ensure that the segment length and associated sediment production measurements before and after decommissioning were directly comparable.

2.6 Road surveys and assessment of road-stream connectivity

A detailed survey was conducted in June 2013 to characterize 12.3 km of roads that were to be decommissioned, and a similar survey was conducted one and two years after decommissioning to document the effect of the decommissioning treatments over time. The survey identified each hydrologically distinct segment, and each segment was measured similar to the procedure used for the segments with sediment fences except that the surface cover was estimated rather than measured. For each segment we also collected data on the drainage design, road erosion features, road drainage features, and road-stream connectivity.

Drainage design refers to the surface flow paths, and each segment was classified as either planar or outloped since none of the roads had an inside ditch. A planar design means that there is no cross-slope so the water flows down the road until a dip or waterbar diverts it off the outside edge. Outsloped roads have a cross-slope to direct the runoff to the outside edge and drain it in a dispersed fashion rather than allowing it to accumulate and run down the road surface.

Road erosion features refer to the presence or absence of rills on the road surface, where a rill is defined as a channel at least five centimeters deep (SSSA, 2001). None of the segments in the study area had an erosion feature with a cross section larger than 0.09 m^2 that could be classified as a gully (Poesen, 2003). The total length of rills was measured for each segment, 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 drainage feature(s) from each segment were classified as a rill or a sediment plume, as none of the drainage features were large enough to be classified as a gully. Sediment plumes were defined by diffuse sediment deposition as opposed to an incised rill. The length and mean slope of each drainage feature was measured, and the roughness along the drainage feature (i.e., the potential for trapping water and sediment) was categorically classified on a scale of 1 to 4. A roughness of one means that the hillslope was mostly smooth with relatively little litter or potential for trapping water and sediment; two means the hillslope had some litter and perhaps small woody debris with a limited trapping capacity; three means there was more extensive litter and some obstructions such as woody debris or small logs with a substantial trapping capacity, and a value of four means that there were multiple large obstructions, such as logs or rocks, with a very high trapping capacity. The presence and length of the drainage features and the proximity of their distal end to a stream were used to determine the connectivity class for each segment (Table 3.1).

The surveys after decommissioning were used to check for changes in the number and length of rills and sediment plumes, and changes in road-stream connectivity. New or longer rills or sediment plumes were easily identified as the ripping eliminated the pre-existing rills on the road surface, so any new rills or sediment plume coming from the road surface could be easily identified and followed downslope. If there was evidence that runoff or sediment was leaving the road segment, the length was measured to determine if the feature had become longer relative to the previous survey.

2.7 Data analysis

The segment characteristics for the controls and the road segments to be decommissioned were normally distributed, so they were compared using a two-sample t-test. The sediment production data were not normally distributed and often had limited sample sizes for transformations, so these were analyzed using non-parametric methods. Sediment production from the controls and decommissioned segments were compared using the Wilcoxon rank sum test (SAS Institute, Inc., 2002-2010). The sediment production data before and after decommissioning for the controls and decommissioned segments were analyzed using the Wilcoxon signed-rank test as the data were paired rather than independent (Ott and Longnecker, 2008). The differences in sediment production among traffic levels before decommissioning was analyzed using the non-parametric Kruskal-Wallis test instead of analysis of variance (SAS Institute, Inc., 2002-2010).

Non-parametric Spearman correlation coefficients (SAS Institute, Inc., 2002-2010) were used to evaluate the relationships between the various precipitation metrics and both the storm-based and annual road sediment production values. We also identified the minimum 5-, 15-, and 30-minute rainfall intensity thresholds needed to generate at least 0.5 kg of sediment for each segment with a sediment fence during the three years of the study.

The effects of the different rainfall metrics and the segment characteristics on summer sediment production were first analyzed by a multilevel linear mixed model with PROC MIXED (SAS Institute, Inc., 2002-2010). The random subject was each of the 26 road segments with three repeated measurements over time, corresponding to summer 2013, 2014, and 2015, respectively. The between-subject variables were percent bare soil, percent slope, and road segment area (m^2). The within-subject factors were the 30-minute rainfall intensity, rainfall erosivity, year, and traffic level (none, low, and high). Rainfall depth was not included due to the collinearity with rainfall erosivity. Traffic was a within-subject factor due to the change to no traffic after the road segments were decommissioned. We could not separately include the effect of decommissioning as a factor, so the change in traffic due to decommissioning was used to consider the effect of this treatment. For this analysis the sediment production data were log-transformed as they were highly skewed, and segments with no sediment production were assigned a value of 0.5 kg. Road segment slope and segment area were centered by their corresponding means.

The multilevel linear mixed model indicated that there was no significant correlation among measurements made on the same segment over time. Therefore a general linear model was used to identify the significant controls on summer sediment production at the road segment scale (SAS Institute, Inc., 2002-2010).

The controls on the storm-based sediment production values were analysed using repeated measures modeling with PROC MIXED (SAS Institute, Inc., 2002-2010). This analysis was only done for the 27 road segments in the first period of 2013, as this maximized the size of the dataset (27 segments x 5 measurements). For each segment we used the precipitation data from the nearest rain gauge. The same between- and within-subject factors were used as in the summer-based analysis, but in this case the traffic levels were constant over time so traffic was a between-subject factor.

The main controls on the proportion of road segment length with rills were identified by multiple linear regression with stepwise model selection (SAS Institute, Inc., 2002-2010). The independent variables were traffic, segment slope (%), area (m^2), and percent bare soil. Variables were only included if they were significant at $p \leq 0.05$. Traffic was considered as a binary variable with the presence of traffic as 1 and the absence of traffic as 0. These same independent variables plus hillslope roughness and slope below the road were used to evaluate the main controls on the length of the drainage features. The changes in road-stream connectivity due to decommissioning were analyzed by comparing the percentage of road segments and road length for each connectivity class before and after the decommissioning treatment.

3. RESULTS

3.1 Characteristics of the road segments with sediment fences

The mean length of the road segments with sediment fences was 55 m (s.d.=18 m), and the minimum and maximum lengths were 25 m and 95 m, respectively. The mean active width was 2.2 m (s.d.= 0.5 m), and the mean total width was 2.7 m (s.d.=0.6 m). Mean segment slope was 9%, and the range was from 5% to 17%. Mean percent bare soil was 70% (s.d.=15%). The characteristics of the control segments and the segments to be decommissioned were very similar (Table 3.2), with the biggest difference being the higher but not significant difference in the amount of bare soil on the control segments (p=0.07). This difference can be attributed to the differences in the amount of traffic, as three of the control segments with sediment fences were on active roads with high traffic, and these averaged 98% bare soil, while only one of the segments to be decommissioned had high traffic. Similarly, only four of the control segments had no traffic and these averaged only 64% bare soil, while 13 of the segments to be decommissioned had no traffic and hence less bare soil than the segments with traffic. The data in Table 3.2 do not include the one much larger segment on a heavily trafficked road, as this was 131 m long with an active width of 3.8 m.

3.2 Precipitation and sediment production before decommissioning

In 2013 mean summer precipitation from the five rain gages was 332 mm with relatively little variation among the five rain gages (s.d.=18 mm), but the summer has to be broken into two periods due to the decommissioning that took place in early September (Figure 3.3). The first period of 1 June to 7 September had a mean rainfall of

126 mm (s.d.=14 mm). Given that this first period does not include the last three weeks of September, this mean rainfall is only slightly below the 28-year mean summer precipitation of 149 mm (s.d.=57 mm) at the Red Feather RAWS station.

In early September 18 of the 27 segments were ripped, but before any of mulch or fertilizer could be applied the Colorado Front Range was subjected to a highly unusual, long-duration storm from 10-16 September 2013. Hence the data from 8-30 September comprises the “second period” for summer 2013 (Figure 3.3).

The mean rainfall of 126 mm during the first period was relatively consistent among the five rain gages (s.d.=14 mm). There were 63 individual storms, but the vast majority of these storms were very small as the mean depth was only 2 mm. The rainfall intensities also were very low with a mean maximum I_{30} of only 3 mm hr^{-1} (Table 3.3). There were only two storms in the first period that had more than 10 mm of rainfall (Figure 3.4a), and only five storms had a maximum I_{30} greater than 10 mm hr^{-1} (Figure 3.4b). The maximum I_{30} from any rain gage was only 25 mm hr^{-1}. Mean rainfall erosivity was 519 MJ mm ha^{-1} hr^{-1}, and again the variability was relatively low as the coefficient of variation was only 13% (Table 3.3).

Total sediment production from 27 of the 28 fences in the first period of 2013 was 2150 kg, while the one large, heavily trafficked segment produced 2580 kg or 30% more than all of the other 27 segments combined. For the other 27 segments the mean sediment production normalized by active area was 0.62 kg m^{-2} (s.d.=0.84 kg m^{-2}) for the first period, but this varied greatly as the range was from zero to 3.0 kg m^{-2}. There was no significant difference in sediment production between the controls and the segments to be decommissioned (p=0.42) (Figure 3.5).

The sediment production data were highly skewed, as the mean was nearly twice the median value of 0.31 kg m^{-2} (Table 3.4). Only five road segments produced more than 1.0 kg m^{-2} (Figure 3.5). Three of these five segments were to be decommissioned but had substantial amounts of ATV traffic. The other two high-producing segments had high traffic, with one being a control and the other to be decommissioned. The slope, length, and other characteristics of these five segments were not exceptional, suggesting that traffic was an important control on road sediment production.

Most of the road segments that produced little or no sediment were abandoned roads, and the mean sediment production from the roads with no traffic was only 0.20 kg m^{-2}. Mean sediment production from the while roads with low and high traffic was much higher at 1.5 and 1.1 kg m^{-2}, respectively (Figure 3.6). Mean sediment production from segments with no traffic was significantly lower than the mean sediment production from segments with either low or high traffic ($p<0.0001$), but there was no significant difference in mean sediment production between low and high traffic.

The high sediment production from roads with low traffic may be due to the type of traffic, as the low traffic roads were only used by ATVs, while the roads with high traffic had more regular cars and pick-up trucks but fewer ATVs. ATVs can generate more sediment than regular vehicles due to their knobby tires and more aggressive driving (Meadows *et al*., 2008). Rills also were present on four of the six road segments with ATV traffic had (mean length= 41 m, mean depth=0.08 m), while only one of the segments with high traffic was rilled.

The small amounts and intensities of rain meant that very few storms produced sediment. For the roads with traffic some sediment was generated for some I_{30} values below 5 mm hr^{-1}, but substantial amounts of sediment were only produced when the I_{30} exceeded 10 mm hr^{-1}. The five times that the sediment fences were emptied corresponded to the five storms that had I_{30} values larger than 10 mm hr^{-1}, and the data from these five measurements comprises our “storm-based” dataset. These five storms did not always generate measurable sediment, as only one segment produced at least 0.5 kg of sediment from each of these five higher-intensity storms. Ten segments produced sediment from four of these storms, eight segments produced sediment from three storms, three segments produced sediment from two storms, three segments produced sediment from one storm, and two segments never produced any sediment.

3.3 Precipitation and sediment production in the second period after ripping

Mean precipitation in the second period was 206 mm (s.d.=8 mm), or 63% more than in the first period (Table 3.3). Eighty-six percent of this rain fell from 8-16 September, with 90 mm of rain falling in 18 hours. The 2- to 7-day rainfall values had an estimated recurrence interval of 200-500 years (NOAA-NWS 2013). Although the total rainfall was almost half of the annual precipitation, the maximum I_{30} was only 16 mm hr^{-1} (Table 3.3). Mean erosivity for the second period was 826 (s.d.=87) MJ mm ha^{-1} h^{-1}, or 59% more than in the first period.

For the nine control segments the mean sediment production during the second period was 0.59 kg m^{-2} (s.d.= 0.61 kg m^{-2}), or 50% higher than in the first period (Table 3.4). This 50% increase is very similar to the 63% increase in total rainfall and 59% increase in rainfall erosivity.

Valid sediment production data were only collected from four of the decommissioned segments during the second period as the sediment fences on the roads had to be removed to allow the roads to be ripped, and the ripping destroyed the water bars and many of the drainage outlets so the road surface runoff was usually not directed into the remaining sediment fences. For these four segments the mean sediment production was 0.63 kg m^{-2} (s.d.= 0.68 kg m^{-2}) (Table 3.4); this is just 43% of the sediment that was produced from these same four segments in the first period despite the higher rainfall and higher erosivity in the second period. There was no significant difference in sediment production between the first and second periods for either the controls or the four decommissioned segments due to the high variability, but the relative data indicate that the decommissioning was very effective as sediment production from the nine controls increased by 50% while sediment production from the four decommissioned segments decreased by more than 50%. The results from the decommissioned segments were not affected by the additional treatment of mulching as the mulch and fertilizer were not applied until October 2013.

3.4 Ground cover, precipitation and sediment production in the first summer after decommissioning (2014)

In June 2014 waterbars were re-established as needed to hydrologically isolate each of the study segments and sediment fences were re-installed to measure sediment production from the decommissioned segments that had been monitored in summer 2013. The surface cover was estimated for all of the segments with sediment fences in September 2014, and there was no detectable change in the amount of bare soil for the control segments. Percent bare soil on the segments that had been ripped also was largely unchanged at 75% (s.d.=14%), while the mean percent bare soil on the segments that had been ripped and mulched was only 29% (s.d.=17%), and this difference was significant (Figure 3.7). The nearly 50% difference in cover on the ripped and mulched segments was due to the 24% (s.d.=15%) mulch cover and the 34% (s.d.=11%) cover due to live vegetation, slash, and litter. By definition the ripped segments had no mulch, and the live vegetation, slash and litter cover was significantly less at only 11% (s.d.=9%); the ripped segments also averaged only 4% live vegetation as compared to 14% for the segments that had been ripped and mulched.

Total precipitation in summer 2014 was 207 mm (Figure 3.3), or 39% more than in the first period of summer 2013 and nearly identical to the rainfall in the second period of 2013 (Table 3.3). There were 108 storms with a mean precipitation of 2 mm, which was the same mean storm precipitation as the first period in 2013, but there were six storms with at least 10 mm of rain and one storm with 30 mm (Figure 3.4a). While the mean storm intensity of 2 mm hr^{-1} in summer 2014 also was slightly less than the mean of 3 mm hr^{-1} in summer 2013 (Table 3.3), there again were five storms with a maximum intensity of at least 10 mm hr^{-1} (Figure 3.4b). The maximum I_{30} of 25 mm hr^{-1} also was identical to the maximum I_{30} in 2013. However, the total erosivity in summer 2014 was only 245 MJ mm ha^{-1} hr^{-1}, or 47% of the value from the first period in 2013 and 30% of the value from the second period.

Mean sediment production for the nine control sites in summer 2014 was 0.86 kg m^{-2} (s.d.=0.95 kg m^{-2}) (Table 3.4). This is only 12% less than the total value for the first and second periods in 2013. Again the data were highly variable, with values ranging from zero to one exceptionally high value of 3.2 kg m^{-2} (Figure 3.5) from a relatively short but wide segment that had very high traffic. This segment accounted for 39% of the total sediment in 2014 and 26% of the total sediment in 2013.

The mean sediment production from the 18 decommissioned segments was only 0.06 kg m^{-2}, or more than an order of magnitude lower than the controls, and this difference was highly significant ($p<0.0001$) (Table 3.4; Figure 3.5). This mean value is only 8% of the mean value from these same segments for the first period of 2013 (before decommissioning) ($p=0.0001$). In contrast, the controls produced almost twice as much sediment in summer 2014 as in the first period of 2013 ($p=0.008$) (Figure 3.5). These results show that the decommissioning treatment was very effective in reducing road sediment production.

The ripping treatment did not appear to be as effective as the ripping and mulching treatment, as only three of the decommissioned segments produced measurable sediment (Figure 3.5), and each of these segments had been ripped but not mulched. One of the ripped segments was 95 m long with a slope of 12%, and this segment produced nearly two-thirds of the sediment measured from the decommissioned road segments. In the first period of 2013 this same segment produced 30% of the sediment from the 18 segments to be decommissioned as it had ATV traffic as well as being long and steep.

The low sediment production from the decommissioned segments did not necessarily mean that there was very little erosion. Field observations indicated that there was often substantial erosion, but the roughness created by the lines of ripping trapped nearly all of the eroded sediment (Figure 3.8). Qualitatively, the roads that had been ripped had more evidence of erosion and deposition (Figure 3.8a, b) than the segments that had been ripped and mulched (Figure 3.8c, d), but only three longer and/or steeper segments had sufficient runoff to deliver sediment into the sediment fence.

3.5 Surface cover, precipitation and sediment production in the second summer after decommissioning (2015)

Each of the road segments with a sediment fence was revisited in spring 2015 to repair the waterbars and sediment fences, as May was relatively wet with 114 mm of precipitation over 27 days. No road surface erosion was observed from either the controls or the decommissioned segments as the maximum I_{30} was just 7 mm hr^{-1}. These wet conditions did facilitate more vegetative growth, and the visual estimates of surface cover in September 2015 indicated about a 10-15% increase in the absolute amount of vegetative cover as compared to September 2014 with no clear difference between the two decommissioning treatments.

Summer 2015 was relatively dry compared to the two previous years as the mean rainfall was 175 mm (s.d.=9 mm) (Table 3.3). Mean storm rainfall and the mean storm I_{30} were very similar to 2014. However, there were only three storms with a maximum 30-minute intensity greater than 10 mm hr^{-1} (Figure 3.4b), and the total rainfall erosivity was only 77% of the value from summer 2014 (Table 3.3). The lower rainfall, smaller number of higher intensity storms, and lower erosivity caused the mean sediment production from the control sites to drop to 0.45 kg m^{-2}, or 52% of the mean value from 2014 (Table 3.4). The data were more highly skewed as the median value was only 0.10 kg m^{-2} or 22% of the mean. This high skew was largely due to a high-producing segment that generated 60% of the total sediment from the 10 control segments. This is the same short and wide segment with very high traffic that produced 26% of the sediment in 2013 and 39% of the sediment in 2014 (Figure 3.5).

The mean sediment production from the 18 decommissioned segments was just 0.01 kg m^{-2} (Table 3.4, Figure 3.5). All of this sediment came from the one very long and steep segment that had been only ripped and generated 65% of the sediment from the decommissioned segments in summer 2014.

3.6 Relationship between rainfall and sediment production

The only rainfall variable that was significantly correlated with summer sediment production was rainfall erosivity ($r=0.47$, $p<0.0001$). In contrast, all of the rainfall variables had similar and significant correlations with the storm-based sediment production values, with the maximum 30-minute intensity having a marginally stronger correlation (Table 3.5). The small differences between the different rainfall variables is due to their strong inter-correlations ($r=0.68$-0.99). The mean I_{15} was only one millimeter higher than the mean I_{30}, while the I_5 was generally about twice the I_{15} (Table 3.5). The mean storm duration was only 0.6 hr (s.d.=1.2).

The 5-, 15-, and 30-minute rainfall intensities needed to generate at least 0.5 kg of sediment varied from 4 to 27 mm hr^{-1} depending on the road segment and the rainfall intensity interval (Figure 3.9). For the segments with no traffic the median threshold declined from 17 mm hr^{-1} for the I_5 to 11 mm hr^{-1} for the I_{30}. This decline is presumably due to the longer intensities having higher intensity bursts embedded within them. The median I_5 and I_{15} thresholds for the segments with traffic were lower at just over 10 mm hr^{-1} (Figure 3.9).

3.7 Key controls on road segment-scale sediment production

The general linear model indicated that traffic (p<0.0001) and the road segment characteristics of slope (p=0.0008) and percent bare soil (p=0.02) were the significant controls on summer sediment production. The overall R^2 of the model was 0.65 (p<0.0001). Segments with no traffic had significantly less sediment production (p<0.0001), and the model confirmed the lack of any difference in sediment production between high and low traffic segments (p=0.43). The importance of slope and percent bare soil is consistent with many other road erosion studies.

The storm-based repeated measures analysis indicated that traffic (p<0.0001), rainfall intensity (p<0.0001), and segment area (p=0.02) were the significant controls on road sediment production during the first period in 2013. Both the summer and storm-based models emphasized the important role of traffic, but they differed in the selection of the other significant variables. The inclusion of rainfall intensity in the storm-based model is expected given that the importance of rainfall intensity for short-term road erosion, and the exclusion of bare soil is due in part to its strong correlation with traffic. It is less clear why segment slope was significant for the summer model while segment area was significant for the storm-based model, but one or both of these variables are nearly always included in road erosion models (Anderson and MacDonald, 1998; Fu *et al.*, 2010).

3.8 Road survey results and road-stream connectivity prior to decommissioning

The summer 2013 survey of the 12.3 km of roads to be decommissioned identified 185 hydrologically-distinct road segments. The mean segment length of 66 m (s.d.=61 m) and mean active width of 2.1 m (s.d.= 0.7 m) were very similar to the values from the segments with sediment fences. The mean segment slope of 6% (s.d.=4%) was lower than the mean slopes of 9-10% for the segments with sediment fences, but this is expected as the sediment fences were not placed on flatter segments that were unlikely to produce sediment. The mean surface cover consisted of 76% bare soil, 10% rock, and 14% live vegetation, and again these values were relatively similar to the mean cover values from the segments with sediment fences (Figure 3.7). Abandoned roads accounted for 6.5 km of the length to be decommissioned, while 5.2 km were classified as low traffic, and only 0.6 km was classified as high traffic. Eighty-six percent of the length to be decommissioned had a planar design, and the other 14% had an outsloped design with almost no drainage features.

Seventy-four percent of the road segments or 55% of the total length did not have any rills on the road surface. The 26% of road segments with rills were significantly steeper as the mean slope of 10% (s.d.=4%) was double the mean slope of the segments without rills ($p<0.0001$). The segments with rills also were significantly longer as their mean length of 114 m (s.d.=85 m) was more than double the mean length of the segments without rills ($p<0.0001$). Multiple linear regression also showed that the proportion of the segment length with rills significantly increased with increasing segment slope and increasing segment area (R^2=0.38). Segment slope was the more important of these two variables as it explained 30% of the variability.

Fifty-five percent or 102 of the 185 road segments had a distinct drainage feature in terms of a rill or sediment plume. Over 90% of the drainage features were sediment plumes, while only eight segments had both a rill and a sediment plume and no segments had only a rill (Figure 3.10a). This predominance of sediment plumes is consistent with the low rainfall intensities and resulting low runoff rates and sediment transport capacities. The mean length of the sediment plumes was just 13 m (s.d.=13 m), and this can be attributed to the relatively low rainfall and the low mean hillslope gradient of 11% (s.d.=7%). The hillslopes below the road also had relative little roughness as the mean roughness on the four-point scale was only 2.0.

Eight segments had both a rill and sediment plume, and the mean length of these combined features was much longer at 92 m (s.d.=95 m). The data were highly skewed because the rill and plume from three adjacent segments coalesced to create a unique drainage feature that averaged more than 150 m in length and was connected to a stream. The remarkable length of these eight drainage features also can be attributed to ATV traffic generating large amounts of sediment, a relatively long mean segment length of 94 m, and a mean segment slope of 13.5% (s.d.=4%), which is more than three times the mean slope of the road segments without a rill or sediment plume. The hillslopes below these eight segments also had a mean gradient of 23% (s.d.=8%) as compared to only 9% (s.d.=7%) for the segments without a rill or sediment plume.

Multiple linear regression indicated that plume length was only weakly related to road segment area, segment slope, and traffic (R^2=0.21). Road segment area was the most important of these variables as this explained 16% of the variability in plume length, while slope explained another 3% and traffic only 2%. Surprisingly, sediment plume length was not significantly related to either hillslope roughness or the gradient of the hillslopes below the road.

About 30% of the road length to be decommissioned was 10 to 100 m from the nearest stream, while the remainder was 100 to about 1000 m from a stream. Overall, only 10% of the 185 segments or 12% of the total road length was connected to the stream network prior to decommissioning (Class 4 in Figure 3.10b). The mean drainage feature length for 15 of the 18 segments connected to a stream was only 8 m (s.d.= 8 m), indicating that most of the segments were connected because they were immediately adjacent to a stream. The other three connected segments were the adjacent segments with a combined rill and sediment plume that extended for more than 150 m.

3.9 Changes in surface cover, drainage features, and road-stream connectivity following decommissioning

The more extensive survey conducted nearly one year after the road decommissioning confirmed that ripping only reduced the amount of bare soil from 76% to 67%, and this decline was due to an increase in vegetation and litter. The segments that had been ripped and mulched averaged only 35% bare soil, and this difference was significant. The mulch only provided 21% ground cover because so much of the mulch had been washed into the furrows. Vegetation, slash, and litter provided 35% cover for the ripped and mulched segments as compared to 22% for the segments treated by ripping. The segments that had been ripped and mulched averaged 18% live vegetative cover versus 11% for the segments that had only been ripped. All of these results are very similar to the more detailed measurements from the segments with sediment fences.

The much more extensive observations from this survey confirmed that the roughness created by the furrows was able to trap nearly all of the eroded sediment from both of the decommissioning treatments. Qualitatively, the segments that had only been ripped tended to have more rilling in the furrows in the steeper sections and more sediment deposition in the flatter sections (Figure 3.8a, b).

The sediment deposition within the furrows meant that there were no new drainage features or changes in the pre-existing features for 174 of the 185 road segments, or 94% of the surveyed length. Eleven segments had new sediment deposition on an existing sediment plume, but this did not increase the length of the pre-existing sediment plume. Eight of the 11 segments with new deposition had only been ripped, but this new deposition was probably due more to the presence of illegal ATV traffic than the presence or absence of mulch. Only four of the 11 segments with new deposition were connected to a stream channel, so the decommissioning reduced road-stream connectivity from 12% to just 2%. The mean length of the sediment plumes for these connected segments was just seven meters (s.d.=5 m), so the combination of illegal traffic and immediate proximity to a stream were the primary controls on road-stream connectivity after decommissioning.

The second post-treatment survey in September 2015 found no changes in the length of the drainage features or in the number of connected segments. The amount of rilling and sediment deposition increased for the road segments that had only been ripped (Figure 3.8a, b), and this was most evident in the steeper segment. The decreasing sediment storage capacity over time is a concern, but over the period of this study the eroded sediment generally has not exceeded the on-segment storage capacity and the surface runoff has not cut through the furrows to transport any of the eroded sediment off the road surface. If some of the ripped segments are subjected to more intense rainstorms, they may again start generating and delivering sediment.

4. DISCUSSION

4.1 Comparison of sediment generation rates with other studies

The measured sediment production rates prior to decommissioning and from the controls are relatively low compared to other studies. While the low sediment production rates can be attributed in part to the relatively small storm sizes and low rainfall intensities, these comparisons should be made with caution as road surface erosion depends on so many factors and is so highly variable from segment to segment (Dubé *et al*., 2004; MacDonald and Coe, 2008; Fu *et al*., 2010). In Idaho erosion rates for unpaved roads in weathered granite with light traffic were from 0.5 to 3.7 kg m^{-2} yr^{-1} (Megahan and Kidd, 1972; Megahan *et al*., 1986). Since the mean precipitation was more than three times the mean value from the Red Feather Lakes, it could be presumed that the higher erosion rates are due to the greater precipitation. However, reported road erosion rates in Western Oregon (Luce and Black, 1999) and California's Sierra Nevada (Coe, 2006) are 0.5 kg m^{-2} yr^{-1} and 0.32 kg m^{-2} yr^{-1}, respectively. These values are comparable to our mean erosion rate of 0.6 kg m^{-2}, even though precipitation in those areas also was more than three times the value from Red Feather Lakes. These differences illustrate the variability of and difficulty in comparing road sediment production rates.

Another six-year study in the central Colorado Front Range reported a mean road erosion rate of 3.5 kg m^{-2} yr^{-1} (Welsh, 2008), or nearly six times the sediment production rate measured in the present study. The mean summer precipitation of 196 mm and mean total maximum 30-minute rainfall intensity of 207 mm hr^{-1} are relatively similar to the values reported here, but the granitic soils derived from the Pikes Peak granite are considered particularly erosive (Welsh, 2008). If we only consider the roads with traffic, our mean sediment production was 1.3 kg m^{-2} yr^{-1} and the large, heavily-trafficked road segment produced 5.2 kg m^{-2} yr^{-1}, in which case our sediment production rates are not so different from the values reported by Welsh (2008). Hence the relatively low mean sediment production rate of 0.6 kg m^{-2} yr^{-1} in the present study can be attributed more to the low sediment production rates from the 17 abandoned roads than the relatively low amounts and intensity of rainfall.

4.2 Effect of traffic on sediment production

The influence of traffic on road sediment production has long been recognized (Reid and Dunne, 1984; Bilby *et al*., 1989; Grayson *et al*., 1993; Sheridan *et al*., 2006; van Meerveld *et al*., 2014), and our data showed a seven-fold increase in mean sediment production for roads with traffic. The surprise was that the data showed no significant difference in sediment production between roads with high traffic of regular vehicles and roads with occasional ATV traffic. The high sediment production rate from roads used by ATVs is consistent with other studies and the high sediment production rates on trails used by dirt bikes (Walsh, 2008; Meadows *et al*., 2008).

Recreational ATVs and dirt bikes may generate substantially more sediment than regular cars and trucks due to how they are used and their tires. ATVs and dirt bikes tend to be driven aggressively in terms of rapidly changing speeds and direction, and sliding around corners. ATV and dirt bike tires also have larger, more aggressive treads so they can be used off road. This combination of driving behavior and more aggressive tire treads increases soil detachment and the amount of loose sediment relative to regular vehicles, particularly on curves and steeper segments (Meadows *et al*., 2008; Welsh, 2008). ATV traffic also can significantly increase rutting (Meadows *et al*., 2008), and the presence of ruts tends to induce rilling and thereby increase road surface erosion (Foltz and Elliot, 1997). In the present study there were no deep ruts on any of the segments with sediment fences, but rills were present on four of the six road segments with ATV traffic and only one of the segments with high traffic. These differences can explain why the road segments with low traffic had similar or higher sediment production rates than the segments with high traffic. This result again illustrates the difficulty in predicting road sediment production based on relatively simple variables such as the number of vehicles.

4.3 Other controls on road sediment production

After traffic, the next most important controls on summer sediment production were road segment slope and percent bare soil. Other studies also have emphasized the importance of road segment slope, and in some road erosion models the effect of slope is further increased by having an exponent between one and two (e.g., Luce and Black, 1999; MacDonald *et al*., 2001; Ramos-Scharrón, 2010). There is a strong physical basis for the importance of segment slope, as shear stress and sediment transport capacity are directly proportional to segment slope (Knighton, 1998). Percent bare soil is usually not an important control on unpaved road sediment production because nearly all roads already have a very high percentage of bare soil. Abandoned roads can have much more vegetation and litter cover, which can greatly reduce road sediment production by protecting the road surface from rainsplash (Foltz *et al*., 2009; Ramos-Scharrón, 2010). In the present study it was difficult to quantify the effect of bare soil as there was not a large amount of variability in the amount of bare soil for the segments prior to decommissioning. The effect of bare soil also was confounded by the larger effect of traffic, as the roads with traffic had more bare soil and higher sediment production rates than either the closed or decommissioned roads. After decommissioning there was a much wider range of bare soil, but most of the decommissioned segments did not produce any sediment and traffic was used instead of decommissioning as the within-subject factor in the multilevel linear mixed model. Further research on roads with differing amounts of ground cover is needed to more rigorously evaluate the effect of ground cover on road sediment production.

The storm-based repeated measures analysis showed that traffic and rainfall intensity were the most important control on road sediment production, followed by road segment area. Each of these factors makes physical sense, and the role of traffic has already been discussed. Rainfall intensity is important because this controls rainsplash erosion and the depth of infiltration-excess overland flow (Ziegler and Giambelluca, 1997; Ramos-Scharrón and MacDonald, 2005; Fu *et al*., 2010). Rainsplash erosion can account for up to 38-48% of the total sediment production on freshly disturbed road travelways (Ziegler *et al*., 2000). Road segment area controls the amount of overland flow, and the depth of overland flow affects the flow velocity, shear stress, and sediment transport capacity (Luce and Black, 1999; Ramos-Scharron and MacDonald, 2005).

The effect of traffic on the rainfall intensity needed to initiate sediment production is an important result that has not been previously identified in the road erosion literature. The data in Figure 3.9 show that the 5-, 15-, and 30-minute rainfall intensities needed to generate at least 0.5 kg of sediment tend to be substantially lower for roads with traffic than for closed roads with no traffic. This difference in the threshold for sediment production cannot be attributed to a difference in infiltration rates as the low infiltration capacity of unpaved roads is primarily due to the compaction (e.g. Ziegler and Giambelluca, 1997) and decades of closure can reduce sediment production but may not increase the road infiltration rate (Foltz *et al*., 2009; Ziegler *et al*., 2007). The results of the rainfall simulations in Part II also show nearly identical infiltration rates for closed roads with no traffic and closed roads subjected to ATV traffic. The lower threshold for segments with traffic also cannot be simply attributed to a lower percentage of bare soil, as the four control segments with no traffic averaged 64% bare soil, and this amount of cover is not sufficient to greatly reduce surface erosion rates (e.g., Larsen et al., 2009). This means that the much lower rainfall intensity threshold for roads with traffic is most likely due to the amount of readily available fine sediment on the road surface, as the supply of loose fine sediment is much lower in the absence of traffic (Reid and Dunne, 1984; Ziegler *et al*., 2001; Sheridan *et al*., 2006; van Meerveld, *et al*., 2014). In the absence of traffic higher rainfall intensities are needed to detach particles from the compacted road surface, while relatively low rainfall intensities can generate sufficient runoff to detach and transport the fine loose sediment generated by regular vehicles and ATVs.

4.4 Road stream connectivity before decommissioning

Prior to decommissioning 12% of the road length was connected to the stream network. This is very similar to the value of 15% reported for the central Colorado Front Range (Libohova, 2004), but low relative to the values of 25% and 32% relatively wet areas in California's Sierra Nevada (Coe 2006) and northwestern California (Raines, 1991), respectively. Road-stream connectivity for an area in southeastern Australia with comparable annual precipitation was even higher at 38% (Croke and Mockler, 2001).

Road-stream connectivity depends on several interrelated factors, including proximity of the roads to a stream, climate, and topography. In the present study the mean drainage feature length for 15 of the 18 connected segments was only 8 m (s.d.=8 m). This indicates that the main control on road-stream connectivity in the present study was the distance between the road and a stream. Since the mean distance for the other three segments was 150 m, and about 30% of the total surveyed length was within 100 m of a stream, the low road-stream connectivity is not solely a function of the distance to a stream.

Climate is an important control on road-stream connectivity because this affects both the amount of road surface runoff and stream density. In the study area much of the precipitation falls as snow, which generates low road runoff rates. The low amounts and intensities of rainfall during the rest of the year also limits the amount of road surface runoff and hence the length of drainage features (Montgomery, 1994; Croke and Mockler, 2001; Coe, 2006). The amount of precipitation is also a control on stream density, and in the semiarid climate of the Colorado Front Range contributing areas on the order of one hectare are needed for initiating ephemeral channels (Henkle *et al*., 2011). Stream densities will therefore be lower than in wetter climates, and this will increase the distance to a stream and decrease the frequency of the road-stream crossings that can be a major cause of road-stream connectivity (Lane and Sheridan, 2002; Croke *et al*., 2005; Aust *et al*., 2011; Brown *et al*., 2013). Road-stream crossings accounted for 59% of the connected road segments in California (Coe, 2006) and 33% of the connected segments in a portion of the Deschutes River watershed in Washington (La Marche and Lettenmaier, 2001), but the present study found only one stream crossing over the 12.3 km of surveyed roads. The two segments feeding into this crossing were not even classified as connected because they were on a well-vegetated abandoned road in a meadow with no evidence of overland flow or surface erosion.

With respect to topography, road-stream connectivity will increase as slopes become steeper (Wemple *et al*., 1996; Libohova, 2004; Croke *et al*., 2005). In Oregon rill and gully incision and road-stream connectivity significantly increased when slopes were greater than 40% (Wemple *et al*., 1996). In the present study the mean gradient of the hillslopes below the surveyed roads was only 11% and nearly all of the drainage features were sediment plumes rather than rills. The sediment plumes were generally very short as a result of both the limited amount of runoff and the gentle terrain, and these factors contributed to the low road-stream connectivity of just 12%.

Another cause for the the low connectivity in the study area is because so many of the surveyed roads were older abandoned roads with no inside ditches or cross-drains. Both the age of the road and the presence or absence of engineered drainage structures are important factors for drainage feature length and road-stream connectivity

(Brake *et al*., 1997; Croke *et al*., 2005; Coe, 2006). Newly-constructed roads in Idaho has a significantly longer mean drainage feature length of 53 m, and this was attributed to the large amounts of erosion immediately after construction (Megahan and Ketcheson, 1996). The lower sediment production from abandoned roads also can reduce road-stream connectivity (Croke *et al*., 2005; Coe, 2006). In California's Sierra Nevada an insloped road with relief culverts more than tripled the mean length of drainage features (rills or sediment plumes) (Coe, 2006), and the longer drainage features will increase road-stream connectivity. The lack of inside ditches and cross-drains in our study contributed to the low rate of road-stream connectivity.

4.5 Effectiveness of the two decommissioning treatments and management implications

Field observations indicate that the ripping treatment was less effective than ripping and mulching in reducing road surface erosion, but the sediment fence data did not show any significant difference between the two treatments. The lack of any significant difference is not surprising since only three of the decommissioned segments produced sediment in summer 2014 and only one segment produced sediment in summer 2015. The qualitative observation of more surface erosion from the ripping treatment are supported by the results of the rainfall simulation study in part II. These simulations showed that the ripping plus mulching treatment more than doubled the mean infiltration capacity of the ripping treatment, and generated only 22% of the mean sediment yield.

The question is whether the segments that have been ripped will eventually produce sufficient runoff and sediment to overwhelm the on-segment storage capacity and deliver sediment off site and potentially to a stream. The amount of storage can become largely moot if there is sufficient vegetative regrowth to restore infiltration and reduce sediment production to levels comparable to adjacent unroaded areas. The problem is that the vegetative regrowth rate in the study area is very slow due to the dry, cold climate and the coarse-textured, low-nutrient granitic soils. The mulch and fertilizer facilitate vegetative regrowth relative to the ripping treatment, but the most important effects of the mulch and slash are to provide some immediate ground cover and slow the overland flow in the furrows.

Longer-term studies are needed to fully evaluate the effectiveness of these two decommissioning treatments over time, but at least in the short term mulching can substantially reduce the risk that ripped roads will produce enough runoff and sediment to overcome the segment-scale storage capacity. To reduce costs the mulching can only be applied on the steeper segments that are in close proximity to a stream. Mulching may also be more important in areas with higher amounts and intensities of rainfall where it could make a greater difference in the amount of runoff and erosion relative to only ripping.

5. CONCLUSIONS

This study found that the decommissioning treatments of ripping, and ripping plus mulching, were both effective in terms of greatly reducing sediment production at the road segment scale. Mean sediment production rates decreased from 0.73 kg m^{-2} before decommissioning to 0.06 kg m^{-2} and 0.01 kg m^{-2}in the first and second years after decommissioning, respectively. These rates were significantly less than the corresponding mean values of 0.86 kg m^{-2} and 0.45 kg m^{-2} from the 9-10 control segments. Field observations indicated that the ripped areas had more surface erosion than areas that had been ripped and mulched, but nearly all of the eroded sediment was trapped in the furrows created by ripping. The slower regrowth and less cover on the ripped segments means that the sediment storage capacity is decreasing over time. These results indicate that the combined treatment of ripping and mulching is more effective at reducing sediment production than only ripping, and mulching is particularly important for steeper road segments.

The annual and storm-based analyses of the sediment production data show that the presence or absence of traffic was the main control on road sediment production. Unit area sediment production from roads with traffic were almost seven times higher than the rates from abandoned roads. We also found that just 80 passes of an ATV can significantly increase the amount of fine, easily-erodible sediment on the road surface, and this is probably why sediment production rates were similar between roads that had low amounts of ATV traffic and roads that had higher amounts of car and light truck traffic.

Road surveys were conducted for 12.3 km of roads prior to and after decommissioning. Only 55% of the 141 road segments had a rill or sediment plume, and except for three segments the mean length of these features was just 13 m. The short length and relative paucity of drainage features can be attributed to the relatively dry climate, gentle topography, and lack of ditches and drainage structures. Prior to decommissioning 12% of the total road length was delivering runoff and sediment to a stream, and the decommissioning treatments were effective in reducing this connectivity to just 2%. Most of the road-stream connectivity prior to decommissioning and all of the connectivity after decommissioning was due to road segments being immediately adjacent to a stream. Overall this study indicates the importance of recreational ATV traffic on road sediment production, that ripping and mulching is a more effective treatment than just ripping, and the importance of decommissioning those roads in closest proximity to a stream.

Table 3.1. Definition of the connectivity classes used to classify each road segment.

Connectivity class	Definition
1	No drainage feature, indicating a very low potential for sediment delivery.
2	Drainage features less than 10 m long, indicating a very low potential for sediment delivery.
3	Drainage feature more than 10 m long but does not extend to within 5 m of an ephemeral or permanent stream channel. These are considered to have a moderate to high potential for sediment delivery.
4	Drainage feature extends to within 5 m of the stream. The associated road segment is classified as connected and is assumed to be delivering runoff and sediment to the channel network.

Table 3.2. Mean road segment characteristics and number of segments by traffic level for the 19 decommissioned segments and 10 control segments (27 established in summer 2013 and 2 established in summer 2014). Values in parentheses are standard deviations.

Road segment characteristic	Controls (n=10)	Decommissioned (n=19)
Length (m)	48.0 (12.5)	58.3 (19.2)
Total width (m)	3.0 (0.8)	2.6 (0.4)
Active width (m)	2.4 (0.6)	2.2 (0.4)
Active area (m^2)	117.8 (44.2)	126.7 (48.0)
Slope (%)	9 (4)	10 (3)
Bare soil (%)	79 (17)	65 (13)
High traffic	3	1
Low traffic	3	5
No traffic	4	13

Table 3.3. Total precipitation, number of storms, 30-minute intensities, and total erosivity for 1 June to 30 September for 2013, 2014, and 2015, respectively. The values are the mean from the five rain gages and the values in parentheses are the standard deviation. The maximum 30-minute rainfall intensity is the highest value from the five rain gages.

Rainfall characteristic	2013		2014	2015
	First period[1]	Second period[2]		
Total precipitation (mm)	126 (14)	206 (8)	207 (9)	175 (9)
Number of storms	63 (5)	39 (3)	108 (3)	90 (7)
Mean storm precipitation (mm)	2 (0.2)	5 (1)	2 (0.1)	2 (0.1)
Mean maximum 30-minute rainfall intensity (mm hr^{-1})	3 (0.4)	3 (0.2)	2 (0.1)	2 (0.1)
Maximum 30-minute rainfall intensity (mm hr^{-1})	25	16	25	22
Summed maximum 30-minute rainfall intensities (mm hr^{-1})	198 (28)	98 (6)	250 (9)	217 (20)
Rainfall erosivity (MJ mm ha^{-1} hr^{-1})	519 (66)	826 (87)	245 (47)	189 (40)

[1] 1 June to 7 September 2013

[2] 8 to 30 September 2013

Table 3.4. Mean, median, minimum and maximum road sediment production for the control and decommissioned segments for summer 2013, 2014, and 2015. Standard deviations are in parentheses.

	Control segments				Decommissioned segments			
Sediment yield (kg m^{-2})	First period[1] 2013 (n=9)	Second period[2] 2013 (n=9)	2014 (n=10)	2015 (n=10)	First period[1] 2013 (n=18)	Second period[2] 2013 (n=4)	2014 (n=18)	2015 (n=18)
Mean	0.39 (0.48)	0.59 (0.61)	0.86 (0.95)	0.45 (0.72)	0.73 (0.97)	0.63 (0.68)	0.06 (0.15)	0.01 (0.02)
Median	0.29	0.42	0.67	0.10	0.32	0.51	0.01	0.0
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum	1.4	1.5	3.2	2.3	3.0	1.5	0.60	0.01

[1] 1 June to 7 September 2013

[2] 8 to 30 September 2013

Table 3.5. Mean and standard deviation of the storm-based rainfall characteristics for the first period in 2013, and correlations between each rainfall characteristic and sediment production for the 27 road segments for this same period. Each correlation was significant at $p<0.05$.

Storm-based rainfall characteristics	Mean (s.d.)	Correlation coefficient
Precipitation (mm)	2 (3)	0.33
Duration (hours)	0.6 (1.2)	0.21
Max I_5 (mm hr^{-1})	8 (10)	0.32
Max I_{15} (mm hr^{-1})	4 (6)	0.33
Max I_{30} (mm hr^{-1})	3 (4)	0.34
EI_{30} (MJ mm ha^{-1} hr^{-1})	3 (9)	0.32

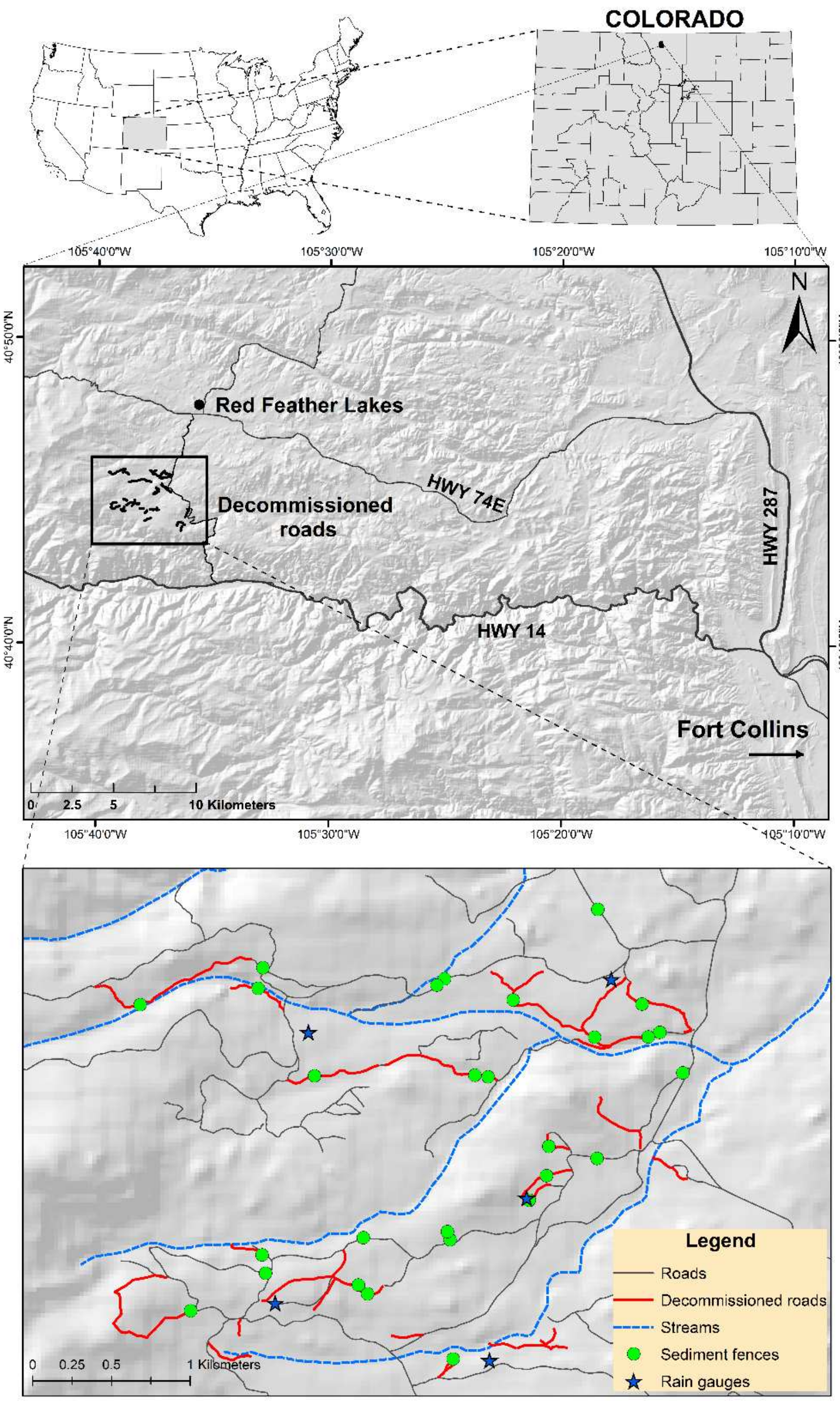

Figure 3.1. Map of decommissioned road sections, rain gauges, and location of sediment fences on control and decommissioned road segments in the Red Feather Lakes area of the Arapaho-Roosevelt National Forest, Colorado, USA.

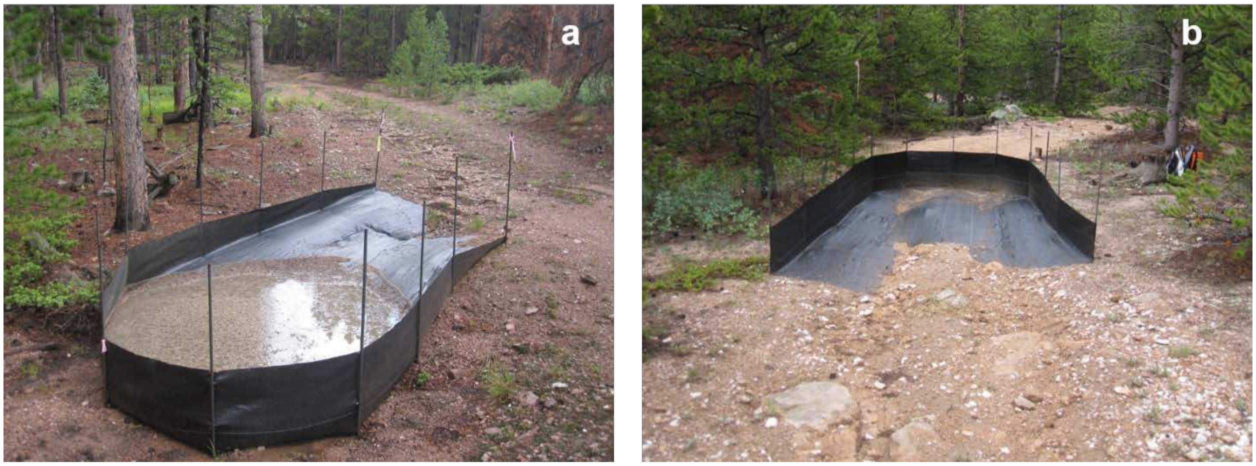

Figure 3.2. Sediment fence at a drainage outlet (a) and on the road surface (b).

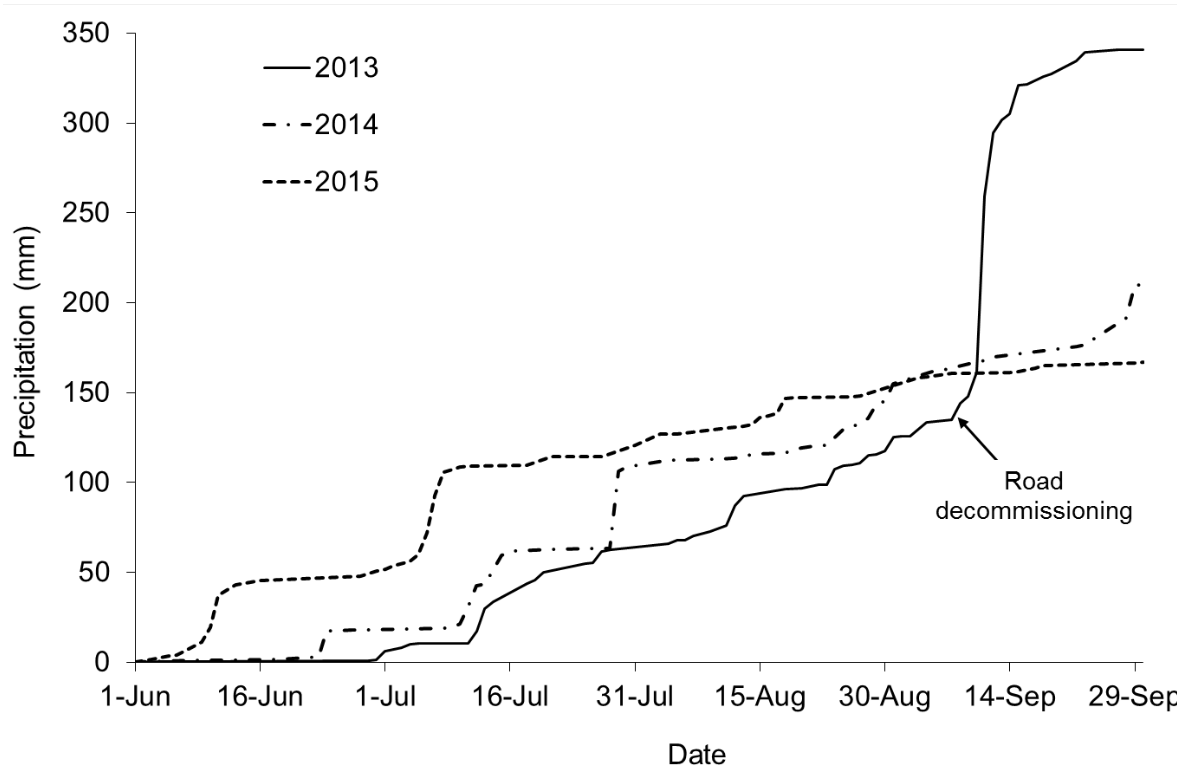

Figure 3.3. Cumulative summer precipitation (1 June to 30 September) for 2013, 2014, and 2015 from the rain gauge closest to the center of the study area.

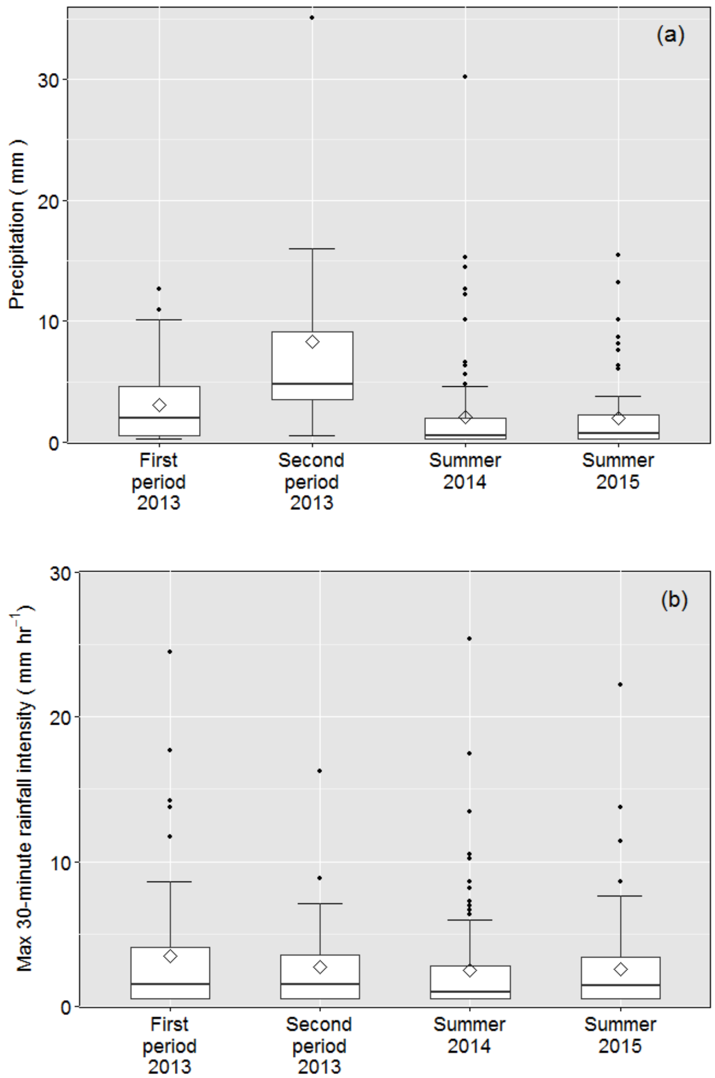

Figure 3.4. (a) Precipitation depth and (b) maximum 30-minute rainfall intensity by storm from the rain gauge closest to the center of the study area for each of the two measurement periods in summer 2013, summer 2014, and summer 2015. For clarity the box plot for precipitation in the second period of 2013 does not include the continuous storm with 90 mm of rain, but its maximum intensity of 16 mm hr^{-1} is included in (b). The lines in the boxes are the median, the diamond is the mean, and the boxes represent the 25th and 75th percentiles. The upper and lower whisker extend from the box to the highest or lowest value that is within 1.5 * IQR of the boxes, where IQR is the distance between the 25th and 75th percentiles. Data beyond the end of the whiskers are outliers and plotted as points.

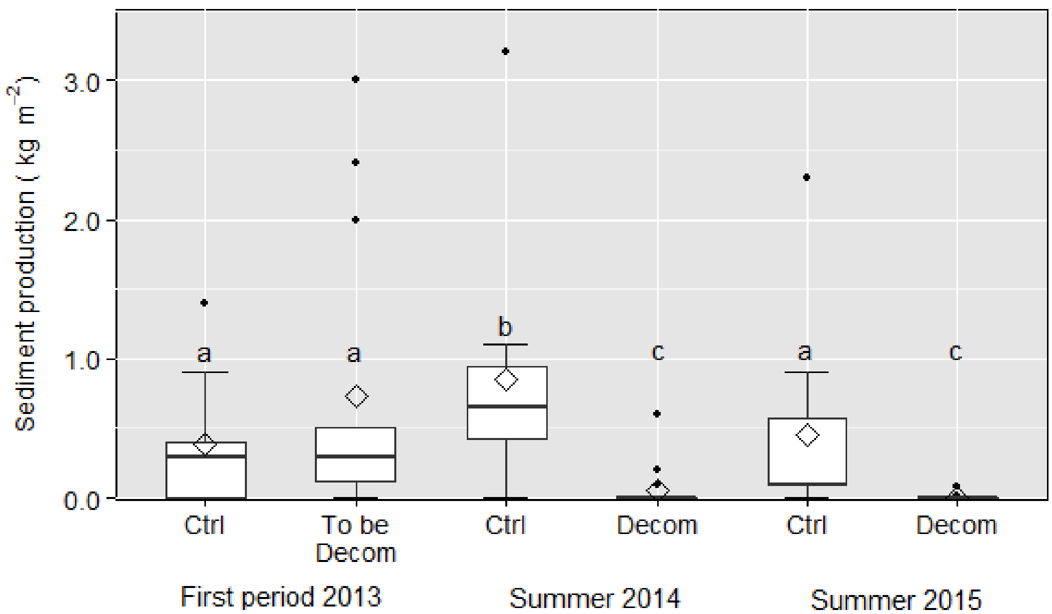

Figure 3.5. Sediment production before decommissioning (first period 2013) and after decommissioning (summer 2014 and 2015) for the control (Ctrl) segments, segments to be decommissioned (To be Decom), and decommissioned segments (Decom). Different letters indicate significant differences. The boxplots are drawn in the same manner as in Figure 3.4. The point at 2.4 kg m^{-2} for the segments to be decommissioned in the first period of 2013 represents two segments, and the exceptionally large and heavily-trafficked active road segment that produced 5.2 kg m^{-2} is not shown.

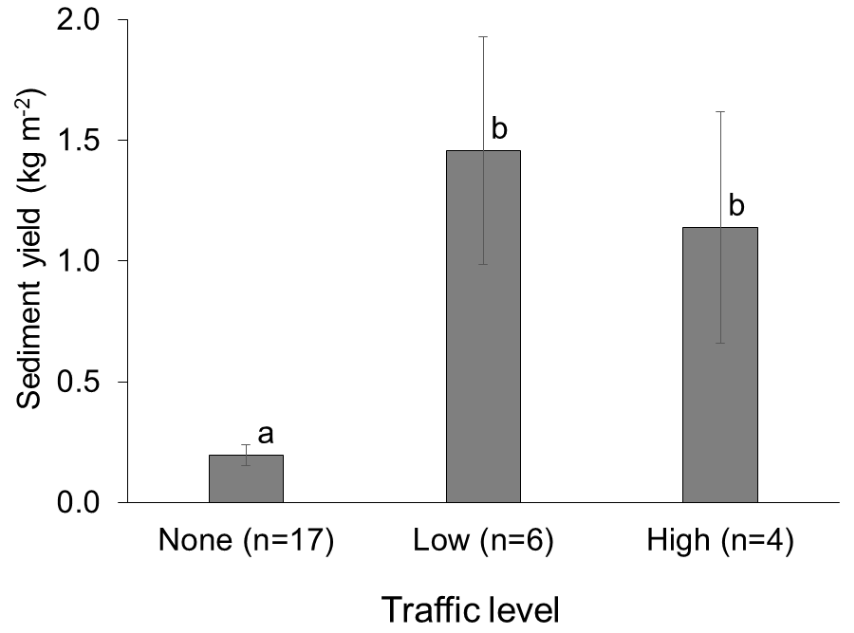

Figure 3.6. Sediment production by traffic level for the first period of summer 2013. Error bars are the standard error, and different letters indicate significant differences.

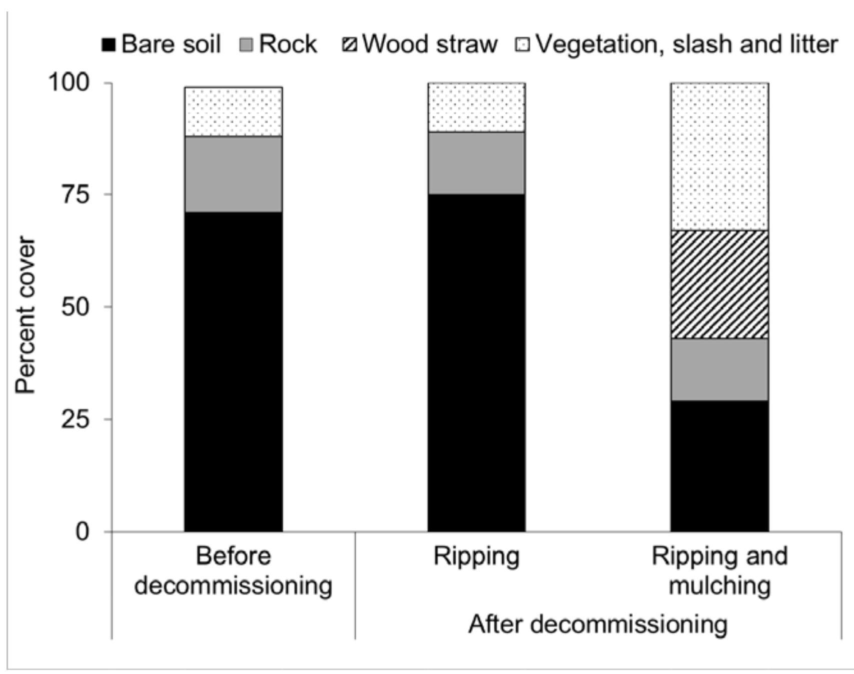

Figure 3.7. Mean surface cover in June 2013 before decommissioning and in September 2014 after decommissioning for each decommissioning treatment.

Figure 3.8. Typical road segments one year after decommissioning. a) Segment with 4% slope that was only ripped. The road surface shows evidence of erosion, but all of the eroded sediment was trapped in the furrows created by the ripping. b) Segment with 9% slope that was only ripped, showing much more eroded, transported, and deposited sediment. c) and d) Road segments that were ripped and mulched showing much less erosion due to the mulch plus greater vegetative regrowth and slash cover compared to the segments that were only ripped.

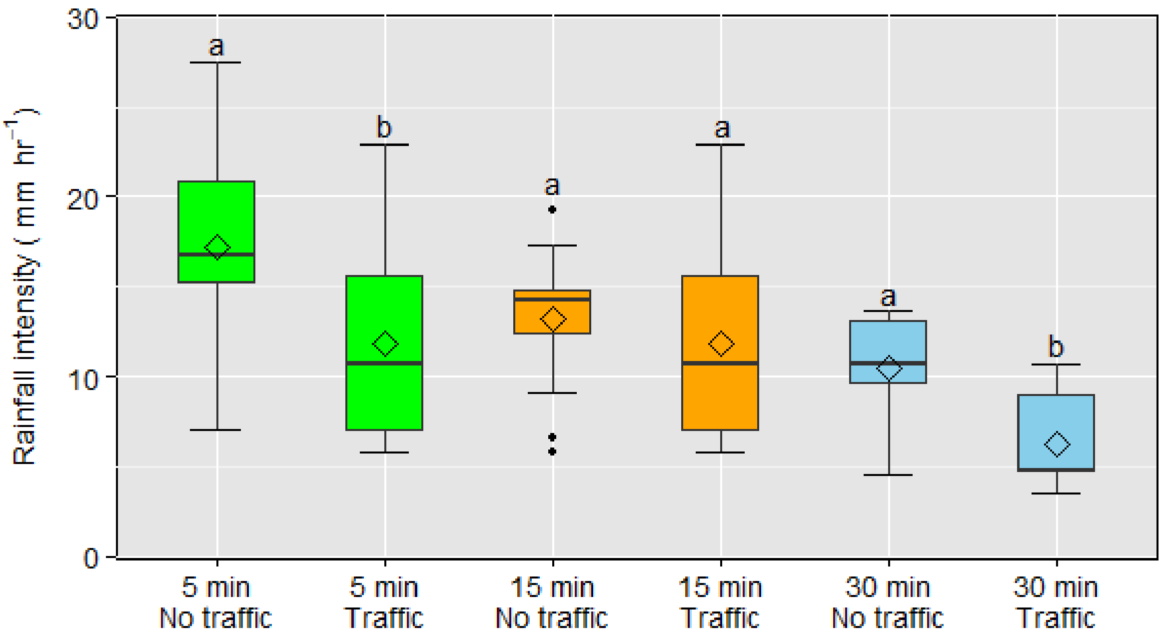

Figure 3.9. Minimum 5-minute, 15-minute, and 30-minute rainfall intensities at which the road segments with no traffic (n~15) and 12 segments with traffic (n~12) produced at least 0.5 kg of sediment. Different letters for each pair indicate that the difference is significant. The boxplots are drawn in the same manner as in Figure 3.4.

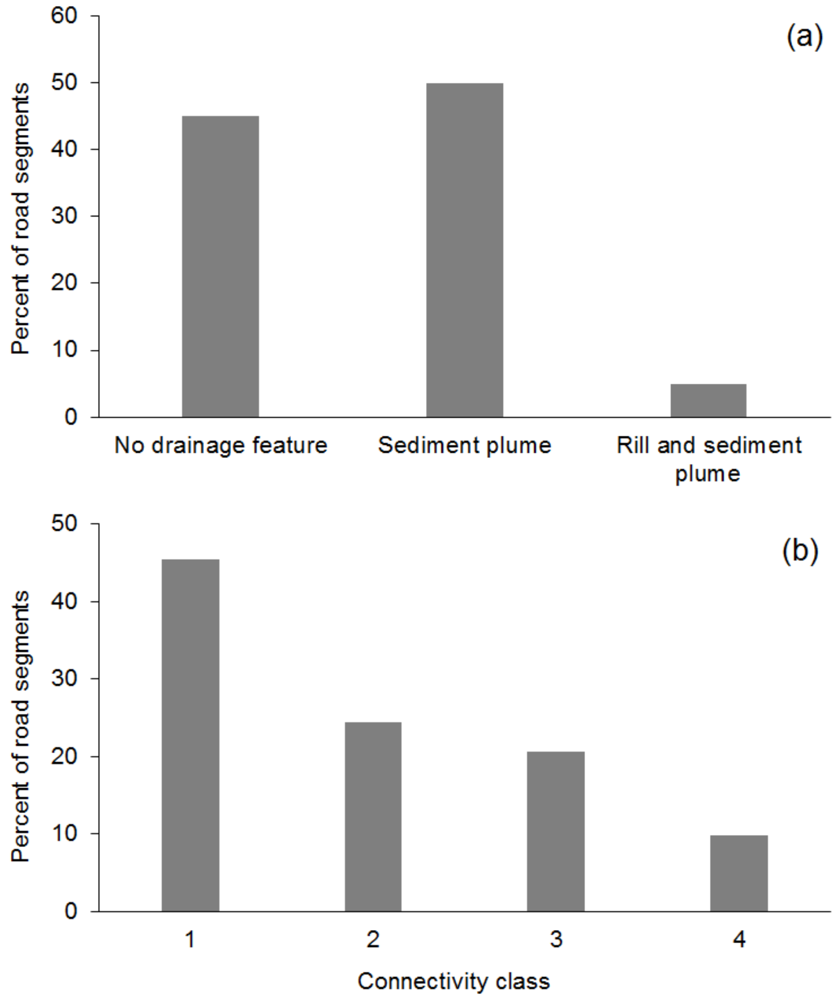

Figure 3.10. Percent of road segments by a) presence and type of drainage feature, and b) connectivity class as defined in Table 3.1 (1 is no drainage feature, and 4 is connected).

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7. OVERALL CONCLUSIONS

Unpaved roads are one of the most significant disturbances in forested areas because their extremely low infiltration rates readily generate overland flow from rainstorms with intensities of more than a few millimeters per hour. They also have very high erosion rates relative to most other land uses because traffic keeps generating loose fine sediment that is easily detached and transported by rainsplash and overland flow. Roads are therefore a chronic source of sediment, and this can be a major problem if a given road is hydrologically connected to a stream or other water body.

High and moderate severity fires are similar to roads because of their low infiltration and high erosion rates in the first two or so years after burning. Several studies have examined how fires affect the need to upsize culverts and improve stream crossings to protect the road, but there no studies have examined how the additional runoff and sediment from burned areas can affect road surface runoff, erosion, and road-stream connectivity. This gap led to the first study, which quantified road surface rilling and road-stream connectivity as a function of fire severity and road segment characteristics. Data were collected from 141 road segments along an unpaved U.S. Forest Service road that traversed areas burned at different severities.

Road segments below hillslopes burned at high and moderate severity had significantly more rilling than road segments below areas burned at low severity, and this can be attributed to the greater amounts of overland flow from more severely burned areas. The percent of segment length with rills, and by implication the amount of sediment eroded from the road surface, also was significantly related to road segment slope as the steeper road segments had more rilling. Conversely the flatter road segments (≤5% slope) had deposits of sediment that originated from the upslope burned areas. For areas burned at low severity road surface area also was an important control on the amount of road surface rilling.

We can generalize that in unburned areas road segment characteristics—particularly road segment area and slope—are the primary control on road runoff and sediment production. In burned areas the hillslopes become a progressively more important source of runoff with increasing burn severity, and this decreases the relative importance of road segment area. Similarly, as burn severity increases the sediment inputs from upslope increasingly dominate the amount of sediment being generated from the road segment, but road segment slope is still a critical control on road surface rilling and whether sediment is deposited on the road surface or transported to a drainage outlet. Process-based models helped confirm the increasing dominance of upslope runoff and sediment with increasing burn severity compared to the runoff and sediment generated from a road segment.

Seventy-four percent of the 141 road segments collected all of the runoff and sediment from upslope, and discharged this combined hillslope and road segment runoff and sediment at a single drainage point. The reduced infiltration and roughness of the burned hillslopes below the road meant that the water and sediment draining from the road—when combined with the runoff and sediment from the hillslope below the road—created rills and sediment plumes that extended for many tens or even hundreds of meters. This caused 100% of the road segments in areas burned at high and moderate severity to be connected to a stream, despite a mean distance of nearly 70 m.

In areas burned at low severity 78% of the road segments were connected to the stream. This indicates that distance to a stream is no longer a major constraint on road-stream connectivity for areas recently burned at high and moderate severity.

Following wildfires land managers need to either outslope the roads or greatly increase the drainage frequency by adding waterbars or rolling dips, especially for steeper segments in areas burned at high and moderate severity. The increase of drainage points will not necessarily reduce or eliminate road-stream connectivity, but it could greatly reduce road surface erosion and hence the need for post-fire regrading to maintain the drivability of a road. As the hillslopes recover roads will again become the primary source of runoff and sediment and road segment characteristics will be the primary controls on the amount of road surface runoff and erosion. Existing process-based road and hillslope models should be coupled to better understand and predict the how road segments and burned hillslopes interact over time to alter surface runoff, sediment production, sediment deposition, and the delivery of runoff and sediment to streams.

Road decommissioning is increasingly used to reduce the adverse effects of roads on aquatic resources, and the most common techniques are road closing and ripping the road surface to eliminate compaction and increase infiltration. The next two parts of this study examined the effectiveness of two decommissioning techniques at the plot scale using rainfall simulations, at the segment scale using sediment fences to measure sediment production, and at larger scales through extensive road surveys.

The rainfall simulations quantified infiltration and sediment production from forested plots, closed roads with no traffic, closed roads subjected to 80 passes of an all-terrain vehicle (ATV), and two road decommissioning treatments (ripping, and ripping plus mulching). Infiltration rates on the forested (lodgepole pine) plots were highly variable as a result of soil water repellency and variations in antecedent soil moisture, while sediment yields were negligible due to the high surface cover and surface roughness. In contrast, the closed roads had a final infiltration rate of only 4 mm hr^{-1} due to the compacted bare surface, and mean sediment yields were more than an order of magnitude higher than the forested plots. The role of traffic was evaluated by having an ATV make 80 passes on an otherwise closed road, and this had no effect on the final infiltration rate but tripled mean sediment yields. The large increase in sediment yields was due to the increased supply of fine (<0.5 mm) sediment caused by the ATV.

Ripping only reduced the bulk density by 14% relative to the closed roads, and this largely explains why the ripping treatment only increased the infiltration capacity to 9 mm hr^{-1}. The ripped plots produced almost twice as much sediment as the closed roads, and this is probably due to the large amounts of readily-available sediment after ripping. The ripping plus mulching treatment was much more effective because this more than doubled the infiltration capacity and decreased sediment production by almost five times compared to just ripping. These results indicate the beneficial effect of mulching with wood straw, and this is due to both the reduction of rainsplash and soil sealing, and the accumulation of mulch in the furrows created by the ripping. The approximately five centimeters of mulch in the furrows provided an increased opportunity for infiltration and greatly reduced flow velocities. These results indicate that closing roads has little effect on runoff but can greatly reduce sediment production due to the lack of traffic, and that mulching after ripping can greatly increase infiltration and reduce erosion relative to only ripping.

The third part of this dissertation evaluated the controls on road sediment production at the road-segment scale, and the effects of two decommissioning treatments on segment-scale sediment production and road-stream connectivity. Data were collected for one summer prior to and two years after decommissioning. Sediment production from 27 road segments prior to decommissioning was highly variable. Traffic was the primary control on road sediment production as the mean sediment production rate from roads with traffic was seven times higher than the mean value for closed roads with no traffic. There was no difference in sediment production between roads with high amounts of regular cars and pickups versus roads with lower amounts of off-highway vehicles (ATVs and dirt bikes). The lack of any difference is attributed to the more aggressive driving behavior and more aggressive tire treads for off-highway vehicles. Rainfall intensity, road segment area, and road segment slope were other significant controls on road segment sediment production, but the relative importance of these factors depended on whether the data were aggregated over the entire year or analyzed on a storm-by-storm basis.

In contrast to the results at the plot scale, both decommissioning treatments were very effective in reducing segment-scale sediment production. The much lower sediment production after decommissioning was largely due to the ability of the furrows to capture and hold all of the runoff and sediment.

Field observations from the repeated road surveys supported the plot-scale results, as the ripping treatment tended to have more surface erosion and sediment deposition as a result of the greater amount of bare soil and slower regrowth. Over time, or in more intense rainstorms, the storage capacity of the furrows may be overwhelmed or rills might cut through the furrows, and the rainfall simulation results indicate that such failures are more likely in the ripping treatment due its lower infiltration and higher sediment production compared to ripping plus mulching.

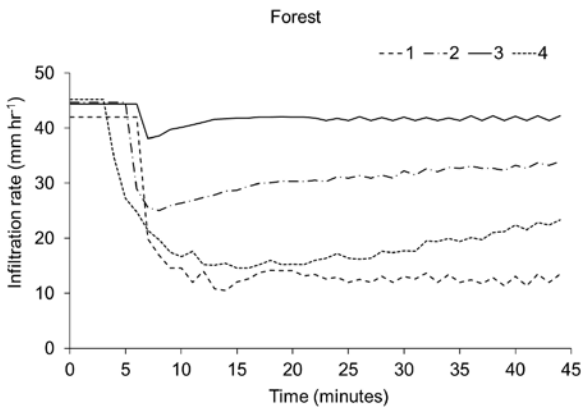
Prior to decommissioning 12% of the road length was connected to a stream. Most of the road-stream connectivity was due to the proximity of a road to a stream, as the mean length of the sediment plumes from connected segments was just eight meters. The relatively low connectivity value of 12% can be attributed to the low precipitation, gentle topography, lack of cross-drains that would collect and concentrate road surface runoff, and the paucity of stream crossings. After decommissioning road-stream connectivity was reduced to only 2%, with this connectivity due to three segments being within 10 m of a stream.

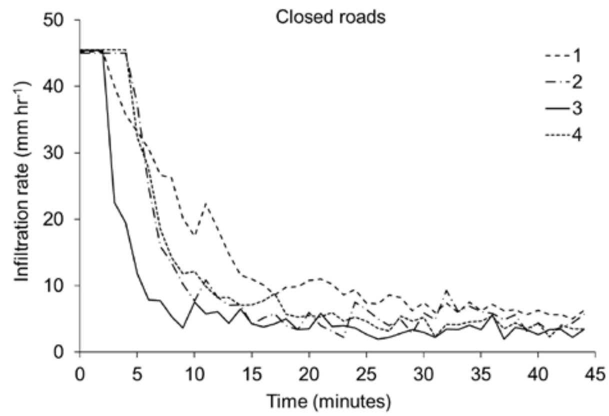
The results from the different scales are consistent in terms of demonstrating the large effect of traffic on road sediment production. Closing roads is effective for reducing sediment production, but in this and other study areas many decades are needed for infiltration rates approach the values for undisturbed forests. The two decommissioning techniques are effective in reducing sediment production at the road segment scale and reducing road-stream connectivity, but the plot-scale results clearly demonstrate that ripping plus mulching was much more effective than ripping in terms of increasing infiltration and reducing sediment production. Over time or in areas with more or higher-intensity rainfall both treatments, and the ripping treatment in particular, may lose their effectiveness as the furrows fill up and overtop with sediment, or are cut through by rills.

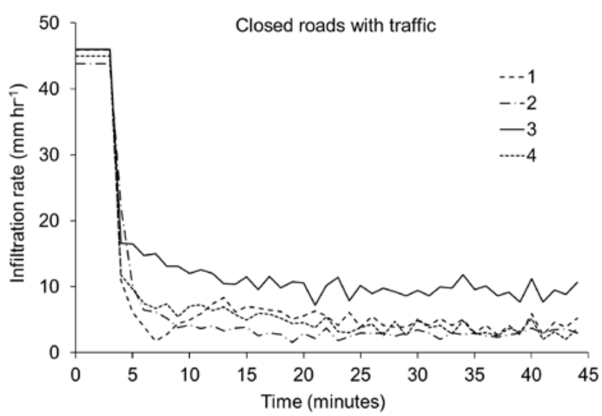
The data presented here can help calibrate and validate process-based road erosion models, further our understanding of road runoff and erosion processes, particularly in burned areas, and guide future road decommissioning efforts.

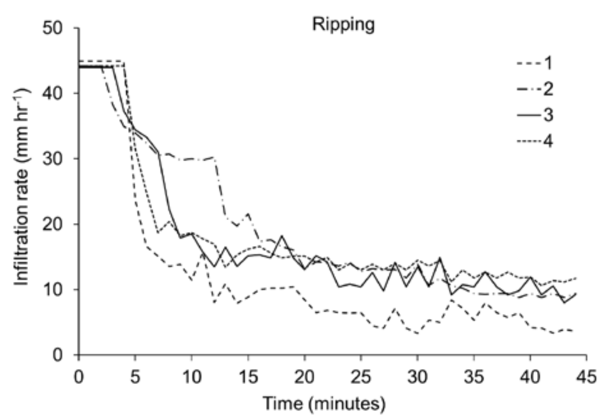
APPENDICES

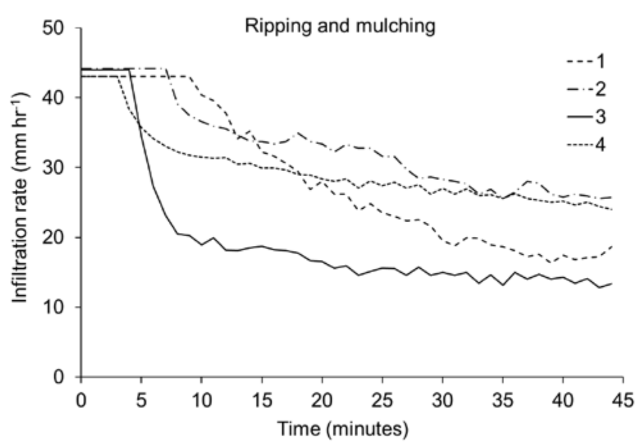
APPENDIX 1. INFILTRATION RATES OVER TIME FOR EACH OF THE FOUR REPLICATED RAINFALL SIMULATIONS BY TREATMENT.



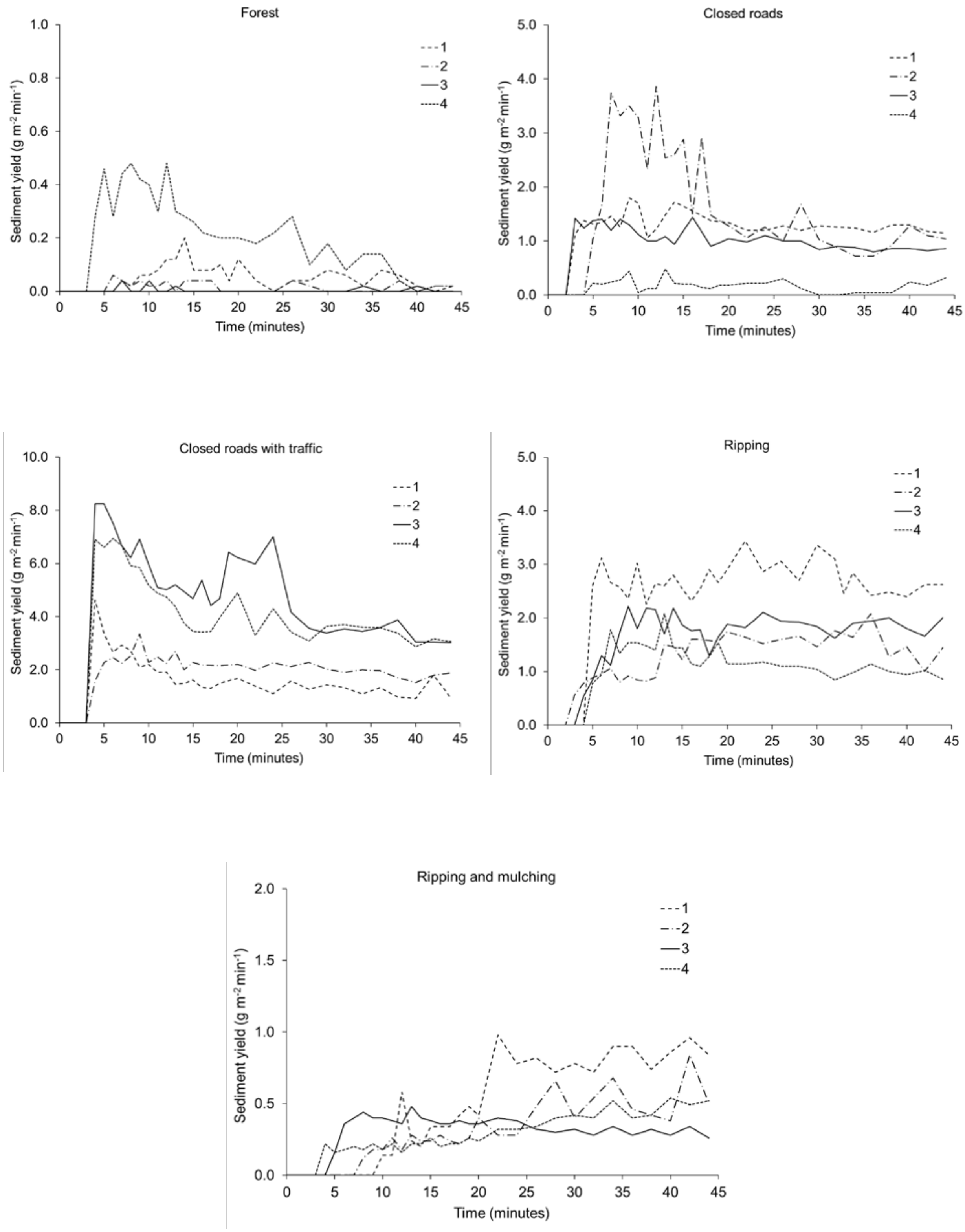




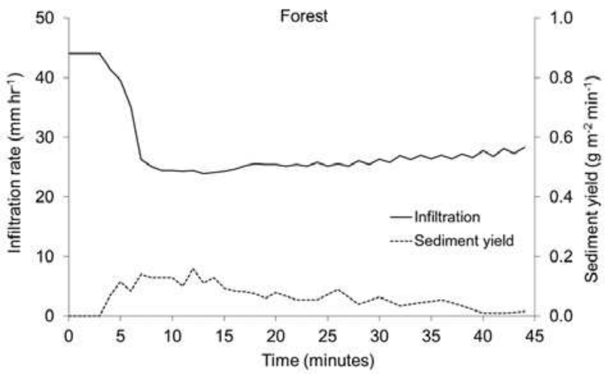


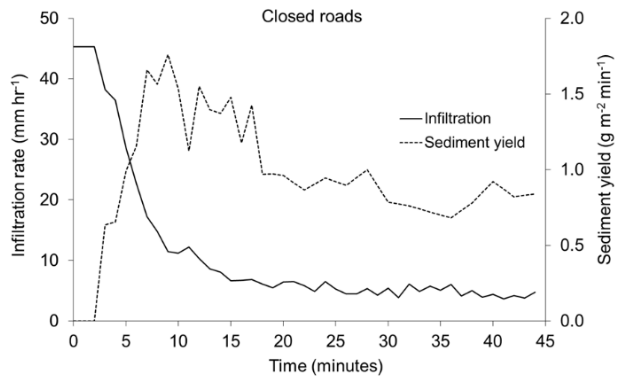


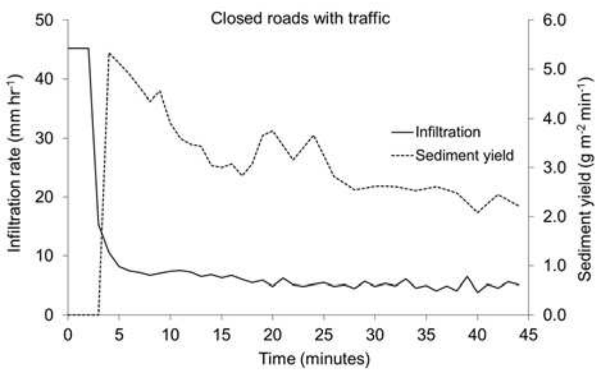
APPENDIX 2. SEDIMENT YIELDS OVER TIME FOR EACH OF THE FOUR REPLICATED RAINFALL SIMULATIONS BY TREATMENT.

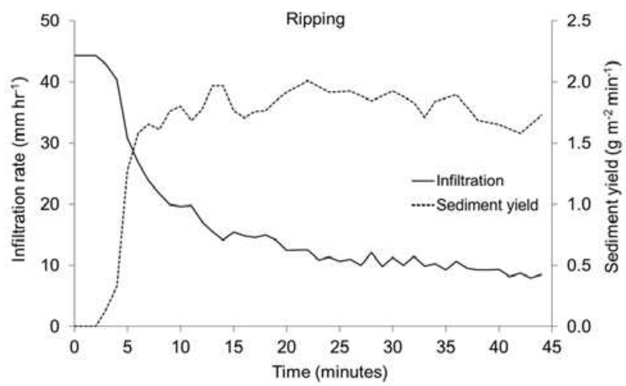


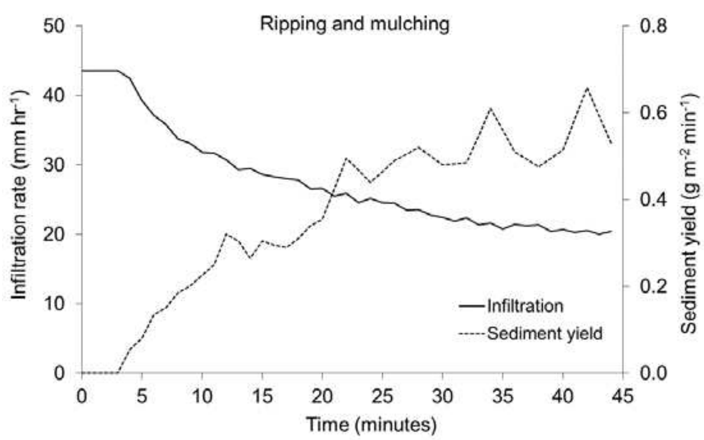
APPENDIX 3. MEAN INFILTRATION RATE AND MEAN SEDIMENT YIELD OVER TIME FOR EACH SET OF RAINFALL SIMULATIONS BY TREATMENT.











APPENDIX 4. PLOT CHARACTERISTICS, TIME TO RUNOFF, FINAL INFILTRATION RATE, RUNOFF RATIO, AND SEDIMENT YIELD FOR EACH OF THE RAINFALL SIMULATIONS BY TREATMENT.

Plot	Treatment	Bulk density ($g\ cm^{-3}$)	Soil moisture (%)	Slope (%)	Long. roughness ratio	Bare soil (%)	Mulch (%)	Rock (%)	Veg. and litter (%)	Time to runoff (sec)	Final infiltration capacity ($mm\ hr^{-1}$)	Runoff ratio	Total sediment yield ($g\ m^{-2}$)
1	Forest	1.21	6.6	8	1.05	0	0	0	100	380	12.7	0.58	2.2
2	Forest	1.09	14.2	8	1.16	0	0	0	100	320	33.4	0.27	0.7
3	Forest	1.33	9.7	9	1.15	0	0	0	100	400	41.9	0.06	0.2
4	Forest	1.43	5.7	6	1.14	5	0	2	93	215	22.5	0.53	8.3
1	Closed road	1.71	7.0	5	1.01	80	0	14	6	160	5.8	0.67	55.2
2	Closed road	1.72	2.9	4	1.01	89	0	7	4	260	4.3	0.75	64.8
3	Closed road	1.82	4.5	7	0.99	90	0	7	3	180	3.0	0.83	43.1
4	Closed road	1.78	4.4	6	1.01	85	0	10	5	278	3.5	0.75	6.7
1	Traffic	1.72	7.9	6	1.00	86	0	11	3	210	4.5	0.81	67.0
2	Traffic	1.84	8.7	5	1.01	90	0	9	1	200	3.4	0.83	86.3
3	Traffic	1.78	7.8	5	1.01	88	0	6	6	210	9.6	0.70	198.7
4	Traffic	1.84	9.5	5	1.01	88	0	10	2	195	3.2	0.81	168.5
1	Ripping	1.76	2.5	5	1.04	75	0	2	23	250	3.8	0.73	109.9
2	Ripping	1.45	6.7	5	1.06	65	0	15	19	170	9.2	0.56	58.0
3	Ripping	1.34	6.4	10	1.07	63	0	33	5	225	9.8	0.60	73.0
4	Ripping	1.61	2.6	5	1.08	67	0	13	20	255	11.4	0.59	46.8
1	Ripping and mulching	1.66	4.9	5	1.08	36	50	2	12	562	17.0	0.34	23.4
2	Ripping and mulching	1.54	10.6	7	1.17	29	51	3	17	450	25.8	0.25	14.9
3	Ripping and mulching	1.45	5.7	9	1.19	32	49	8	11	264	13.6	0.55	13.7
4	Ripping and mulching	1.50	13.4	10	1.13	38	41	1	19	207	24.7	0.31	13.6

APPENDIX 5. GEOGRAPHIC COORDINATES AND CHARACTERISTICS OF THE ROAD SEGMENTS WITH SEDIMENT FENCES. ROAD SEGMENT 16 WAS NOT INCLUDED IN THE STATISTICAL ANALYSES.

Road segment ID	Latitude	Longitude	Treatment	Traffic level	Length (m)	Total Width (m)	Active width (m)	Area (m^2)	Slope (%)
1	40.76463464	-105.6209856	Control	none	44.3	2.4	1.8	80	9
2	40.75923988	-105.6176031	Ripping and mulching	none	74.0	2.6	2.1	155	6
3	40.7573257	-105.6211529	Ripping and mulching	low	41.0	2.3	1.6	66	13
4	40.75942084	-105.6272978	Ripping	none	25.3	2.5	2.1	53	15
5	40.76060386	-105.6324658	Control	high	59.0	4.2	3.2	189	7
6	40.76023816	-105.6330401	Control	high	54.0	4.4	3.1	167	5
7	40.76116294	-105.6461317	Control	low	36.0	2.9	2.4	86	10
8	40.75899697	-105.6553421	Ripping and mulching	low	32.4	2.9	2.4	78	5
9	40.75998888	-105.646466	Ripping and mulching	none	65.0	2.6	2.3	150	14
10	40.7549993	-105.6421898	Ripping	none	63.0	3.3	2.7	170	8
11	40.75510743	-105.6301391	Ripping	none	51.0	3.2	2.4	122	8
12	40.75502068	-105.6291386	Ripping	none	53.0	3.2	2.7	143	8
13	40.7576324	-105.6162608	Ripping	none	33.0	1.6	1.4	46	5
14	40.75736946	-105.6171242	Ripping	low	95.0	2.3	1.8	171	12
15	40.75533064	-105.6145036	Control	none	50.0	2.2	2.0	100	9
16	40.75039873	-105.6209028	Control	high	131.0	5.0	3.8	498	6
17	40.75106836	-105.6245355	Ripping and mulching	high	86.0	2.9	2.5	215	10
18	40.74939391	-105.6246915	Ripping and mulching	none	60.0	2.3	2.3	138	14
19	40.74799078	-105.6259787	Ripping and mulching	none	67.0	2.6	2.3	154	15
20	40.74569422	-105.6319177	Control	none	54.0	2.6	2.3	124	9
21	40.74615698	-105.6321111	Control	none	56.0	2.8	2.8	157	17
22	40.74256475	-105.6380907	Ripping	none	48.0	2.3	1.8	86	8
23	40.7430706	-105.6387759	Ripping	none	78.0	2.1	1.7	133	9
24	40.74576982	-105.6384292	Control	high	38.0	3.9	3.2	122	11

25	40.74474639	-105.6460368	Ripping and mulching	none	58.0	3.2	2.6	151	10
26	40.7436984	-105.6457643	Control	low	65.0	2.4	1.7	111	5
27	40.74152255	-105.6513716	Ripping	low	39.0	2.4	2	78	5
28	40.73887772	-105.63162	Ripping and mulching	none	80.0	2.4	2.4	192	9
29	40.729425	-105.636925	Control	low	23.5	2.4	1.8	42	6
30	40.728458	-105.637717	Ripping and mulching	low	59.0	2.3	1.8	106	8

APPENDIX 6. PERCENT GROUND COVER BEFORE DECOMMISSIONING IN SUMMER 2013 AND AFTER DECOMMISSIONING IN SUMMER 2014 FOR EACH ROAD SEGMENT WITH A SEDIMENT FENCE.

Road segment ID	**Treatment**	**Summer 2013**					**Summer 2014**					
		Bare soil	**Rock**	**Vegetation**	**Litter**	**Wood**	**Bare soil**	**Rock**	**Vegetation**	**Litter**	**Wood**	**Mulch**
1	Control	71	19	6	3	1	71	19	6	3	1	0
2	Ripping and mulching	67	26	0	6	1	32	26	7	5	5	25
3	Ripping and mulching	74	20	3	1	2	25	10	35	5	10	15
4	Ripping	66	26	8	0	0	58	20	2	20	0	0
5	Control	99	1	0	0	0	99	1	0	0	0	0
6	Control	98	2	0	0	0	98	2	0	0	0	0
7	Control	66	25	0	9	0	66	25	0	9	0	0
8	Ripping and mulching	78	12	0	5	5	60	10	3	2	15	10
9	Ripping and mulching	44	25	9	20	2	5	10	20	2	15	48
10	Ripping	50	24	3	22	1	71	25	2	2	0	0
11	Ripping	77	1	3	18	1	95	2	1	2	0	0
12	Ripping	75	14	2	9	0	87	10	1	2	0	0
13	Ripping	55	1	26	16	2	55	1	26	16	2	0
14	Ripping	79	13	6	2	0	90	5	5	0	0	0
15	Control	56	13	0	29	2	56	13	0	29	2	0
16	Control	96	4	0	0	0	96	4	n/a	n/a	n/a	n/a
17	Ripping and mulching	92	8	0	0	0	92	8	n/a	n/a	n/a	n/a
18	Ripping and mulching	50	7	5	36	2	30	5	15	5	10	35
19	Ripping and mulching	47	39	7	7	0	30	20	10	5	0	35
20	Control	62	30	0	7	1	62	30	0	7	1	0
21	Control	67	29	2	1	1	67	29	2	1	1	0
22	Ripping	69	25	0	6	0	75	20	0	5	0	0
23	Ripping	65	26	0	6	3	70	20	0	10	0	0

24	Control	96	4	0	0	0	96	4	0	0	0	0
25	Ripping and mulching	68	13	1	17	1	37	3	0	10	50	0
26	Control	77	17	0	3	3	77	17	0	3	3	0
27	Ripping	60	26	0	7	7	75	20	0	5	0	0
28	Ripping and mulching	64	22	2	9	3	10	25	20	5	15	25
29	Control	n/a	n/a	n/a	n/a	n/a	94	6	0	0	0	0
30	Ripping and mulching	n/a	n/a	n/a	n/a	n/a	63	37	0	0	0	0

APPENDIX 7. SEDIMENT PRODUCTION IN KILOGRAMS AND KILOGRAMS PER SQUARE METER OF ROAD SURFACE ACTIVE AREA BY ROAD SEGMENT FOR THE FIRST AND SECOND PERIODS IN 2013, SUMMER 2014, AND SUMMER 2015. ROAD SEGMENT 16 WAS NOT INCLUDED IN THE STATISTICAL ANALYSES.

Road Segment ID	Treatment	Traffic level	Sediment production (kg)					Sediment production (kg m^{-2})			
			First period 2013	Second period 2013	Summer 2014	Summer 2015		First period 2013	Second period 2013	Summer 2014	Summer 2015
1	Control	none	0.0	0.5	15.2	3.7		0.00	0.01	0.19	0.05
2	Ripping and mulching	none	44.5	0.0	0.0	0.0		0.29	0.00	0.00	0.00
3	Ripping and mulching	low	196.5	50.5	0.5	0.0		3.00	0.77	0.01	0.00
4	Ripping	none	27.6	24.0	3.5	0.0		0.52	0.45	0.07	0.00
5	Control	high	73.4	182.2	120.5	14.0		0.39	0.97	0.64	0.07
6	Control	high	66.0	253.8	80.0	15.2		0.39	1.52	0.48	0.09
7	Control	low	74.6	97.2	95.4	9.8		0.86	1.13	1.10	0.11
8	Ripping and mulching	low	154.8	117.1	3.2	1.0		1.99	1.51	0.04	0.01
9	Ripping and mulching	none	52.1	0.0	0.0	0.0		0.35	0.00	0.00	0.00
10	Ripping	none	9.4	0.0	0.0	0.0		0.06	0.00	0.00	0.00
11	Ripping	none	17.4	0.0	15.7	0.0		0.14	0.00	0.13	0.00
12	Ripping	none	57.9	35.0	23.0	0.0		0.40	0.24	0.16	0.00
13	Ripping	none	0.0	0.0	0.3	0.0		0.00	0.00	0.01	0.00
14	Ripping	low	403.6	0.0	98.6	14.0		2.36	0.00	0.58	0.08
15	Control	none	1.9	1.5	0.0	0.0		0.02	0.02	0.00	0.00
16	Control	high	2580.0	2952.0	n/a	n/a		5.18	5.93	n/a	n/a
17	Ripping and mulching	high	515.6	257.0	546.9	0.0		2.40	1.20	2.54	0.00
18	Ripping and mulching	none	63.3	0.0	2.0	0.0		0.46	0.00	0.01	0.00
19	Ripping and mulching	none	61.3	0.0	0.5	0.0		0.40	0.00	0.00	0.00

20	Control	none	1.0	6.2	46.0	9.7		0.01	0.05	0.37	0.08
21	Control	none	13.1	65.7	160.5	38.8		0.08	0.42	1.02	0.25
22	Ripping	none	4.0	0.0	0.5	0.0		0.05	0.00	0.01	0.00
23	Ripping	none	12.7	1.5	1.8	0.0		0.10	0.01	0.01	0.00
24	Control	high	167.6	151.4	386.3	281.1		1.38	1.24	3.18	2.31
25	Ripping and mulching	none	35.4	0.0	2.2	0.5		0.23	0.00	0.01	0.00
26	Control	low	32.4	16.6	76.7	98.6		0.29	0.15	0.69	0.89
27	Ripping	low	19.6	0.0	0.0	0.0		0.25	0.00	0.00	0.00
28	Ripping and mulching	none	46.6	0.0	0.0	0.0		0.24	0.00	0.00	0.00
29	Control	low	n/a	n/a	33.7	29.1		n/a	n/a	0.80	0.69
30	Ripping and mulching	low	n/a	n/a	210.2	0.0		n/a	n/a	1.98	0.00