



# Reopening abandoned forest roads in northern Idaho, USA: Quantification of runoff, sediment concentration, infiltration, and interrill erosion parameters

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## ABSTRACT

This study measured runoff and sediment concentration from the tire track and from the non-tire track to determine infiltration, interrill erodibility, and vegetative cover impacts of reopening an abandoned forest road. Runoff was lowest on the non-track portion of the abandoned road and highest on the reopened road. Sediment concentrations were significantly higher on the reopened road. Increased sediment concentrations were attributed to decreased vegetative cover, rather than traffic-induced changes in the physical soil properties of the reopened road. Thirty years of no traffic and vegetation regrowth was not sufficient to allow recovery of infiltration to values similar to an undisturbed forest. The study also found a significant dynamic behavior in interrill erodibility with respect to antecedent rainfall. Forest road erosion models that fail to account for this change will overestimate sediment yields.

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## 1. Introduction

Forest road decommissioning has become common practice in watershed restoration efforts (Coghlan and Sowa, 1997; Switalski et al., 2004). Road decommissioning projects are initiated on unneeded, substandard forest roads to reduce erosion, reestablish natural watershed hydrologic patterns, mitigate ecosystem discontinuity, and restore aquatic system health (Bell, 2000; Switalski et al., 2004). Decommissioning strategies range from road abandonment, in which the road is closed to traffic and allowed to naturally revegetate, to road obliteration, in which the road surface is decompacted (commonly referred to as “ripping”), culverts are removed, and the original contour is reconstructed.

Recently, however, there has been increasing incentive to reopen closed forest roads. Reopenings increase forest access for timber harvesting operations, hazardous fuel reduction practices, and woody biomass utilization efforts. As one goal of the US Forest Service's National Strategic Plan, \$8.5 million were allocated to biomass utilization efforts in 2006 to “help meet energy resource needs” specifically by “stimulating commercial use of small-diameter trees from National Forest Service lands for biomass

energy” (Patton-Mallory, 2006). The Forest Service's proposed budget for 2007 included \$292 million for hazardous fuels treatment, with \$5 million intended to foster the biomass utilization market (Patton-Mallory, 2006). There will be continued incentives to reopen closed roads as fuel reduction and biomass utilization efforts increase.

While potential benefits of reopening roads have been recognized, the potential impacts on watershed erosion processes have not been addressed. Forest roads can be a significant source of runoff and sediment production (La Marche and Lettenmaier, 2001; Wemple et al., 1996; Ziegler and Giambelluca, 1997). La Marche and Lettenmaier (2001) proposed that roads have a more persistent impact on hillslope hydrology than other types of disturbances due, in part, to persisting reduced infiltration rates on the compacted surfaces.

Erosion on a disturbed soil, such as a forest road, is determined by infiltration, raindrop splash, concentrated flow, and vegetative cover. Infiltration is the process of water entry into the soil and occurs on all portions of a forest road prism with the highest rate on the cut and fill slopes and much lower on the running surface. Infiltration is often characterized by hydraulic conductivity, the ratio of soil water flow rate to the hydraulic gradient (Fangmeier et al., 2006). One of the several forms of the empirical Green and Ampt (1911) equation for hydraulic conductivity is:

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$$i = K_s \left( 1 - \frac{\psi(S_f - S_i)\theta}{F} \right) \quad (1)$$

where  $i$  is the infiltration rate ( $\text{mm h}^{-1}$ ),  $K_s$  is the hydraulic conductivity ( $\text{mm h}^{-1}$ ),  $\psi$  is the capillary suction (mm),  $S_f$  is the final water content of the soil ( $\text{mm mm}^{-1}$ ),  $S_i$  is the initial water content of the soil ( $\text{mm mm}^{-1}$ ),  $\theta$  is the soil porosity ( $\text{m}^3 \text{m}^{-3}$ ), and  $F$  is the cumulative infiltration (mm). As the cumulative infiltration ( $F$ ) becomes large, the equation approaches a constant value of  $K_s$  known as the saturated hydraulic conductivity.

Raindrop splash is soil detachment and transport resulting from the impact of water drops directly on soil particles. Large quantities of soil are splashed into the air by this process then transported by thin sheet or overland flow. The combination of raindrop splash and overland flow are known as interrill erosion. Flanagan and Nearing (1995) described this process as:

$$D_i = K_i I Q C_s C_v \quad (2)$$

where  $D_i$  is the interrill erosion rate ( $\text{kg m}^{-2} \text{s}^{-1}$ ),  $K_i$  is the interrill erodibility coefficient ( $\text{kg s m}^{-4}$ ),  $I$  is the rainfall intensity ( $\text{mm s}^{-1}$ ),  $Q$  is the runoff rate ( $\text{mm s}^{-1}$ ),  $C_s$  is a dimensionless slope factor, and  $C_v$  is a dimensionless vegetative cover factor.

Concentrated flow of water results in the detachment and transport of soil and is known as rill erosion. Ditches and wheel ruts are the primary locations of rill erosion on forest roads. Rill erosion was described by Flanagan and Livingston (1995) using an excess shear model:

$$D_r = K_r (\tau - \tau_c) \left( 1 - \frac{Q_s}{T_c} \right) \quad (3)$$

where  $D_r$  is the rill detachment rate ( $\text{kg m}^{-2} \text{s}^{-1}$ ),  $K_r$  is the rill erodibility coefficient ( $\text{s m}^{-1}$ ),  $\tau$  is the hydraulic shear of flowing water (Pa),  $\tau_c$  is the critical shear below which no erosion occurs (Pa),  $Q_s$  is the rate of sediment flux in the rill ( $\text{kg m}^{-1} \text{s}^{-1}$ ), and  $T_c$  is the sediment transport capacity of the rill ( $\text{kg m}^{-1} \text{s}^{-1}$ ).

Vegetative cover reduces erosion by the energy absorption of raindrops on live vegetation and surface residue, physical restraint of soil movement by roots, improvement of porosity of the soil by roots, and transpiration which decreases soil water content resulting in increased storage capacity and less runoff. Vegetation on forest roads is most prevalent on the cut and fill slopes and non-existent on the running surface of actively used roads.

The ability to model erosion processes is a powerful tool for land managers in terms of erosion forecasting and land-use planning. The Water Erosion Prediction Project (WEPP) model (Flanagan and Livingston, 1995) is a physically-based erosion model that describes erosion processes in terms of Green–Ampt infiltration (Eq. (1)), interrill erosion (Eq. (2)), rill erosion (Eq. (3)), and the effect of ground cover. WEPP has been used to model the erosion process on forest roads (Elliot and Tysdal, 1999; Foltz et al., 2007; Rhee et al., 2004). These studies assumed active forest roads with significant volumes of traffic that kept infiltration low on the running surface through compaction, kept erosion high by replenishing the supply of sediment, and prevented the establishment of vegetative cover. On roads that have been allowed to revegetate, we speculate that the processes of infiltration, interrill and rill erosion, and vegetative cover will change due to lack of traffic. Studies of road ripping (Luce, 1997) and road obliteration (Foltz et al., 2007) suggest that infiltration and interrill erosion parameters change with lack of traffic. Ziegler et al. (2007) investigated vegetative cover, infiltration, and erodibility (a combination of interrill and rill erosion) on no-traffic Peninsular Malaysian roads that had been allowed to revegetate over a span

of several decades. Ziegler et al. (2000) in a road study in northern Thailand suggested that erodibility was a dynamic parameter that changed both during a storm event and between storm events. Quantifying these changes for a mid-latitude climate can supplement data needed to model forest road erosion.

The purpose of this study was to determine the erosion impacts of reopening an abandoned forest road and to obtain estimates of  $K_s$  and  $K_i$ . Specific objectives were to: (1) determine differences in runoff and sediment production between an abandoned forest road and a reopened forest road; and (2) measure and determine whether differences in  $K_s$  and  $K_i$  exist between the two road types.

## 2. Methods

A series of simulated rainfall events was conducted during May through August 2006 to determine the hydrologic impacts of reopening an abandoned forest road in northern Idaho, USA. Impacts were evaluated based on measurements of runoff, sediment concentration,  $K_s$  and  $K_i$ . Quantifying results in terms of  $K_s$  and  $K_i$  can be useful for making comparisons to other data and is necessary for accurate hydrologic modeling and erosion prediction. Saturated hydraulic conductivity and interrill erodibility are soil properties, whereas runoff and sediment production rates depend on storm intensity and duration.

Abandoned forest roads are often referred to as “brushed-in” roads, describing the process by which vegetation is allowed to reestablish on the former road surface. The term “brushed-in,” as used in this paper, refers to a road that has been closed to traffic and allowed to naturally revegetate; no decompaction techniques have been employed. The term “reopened” refers to a brushed-in road that has been cleared of vegetation, graded to remove obstructing roots, and has received traffic.

Forest roads are typically a single lane (4.3 m wide), which results in two compacted wheel tracks on either side of the road centerline and a less-trafficked, less-compacted area in the center of the road. Consequently, rainfall simulations were conducted in both tire track and non-tire track areas of the road running surface to account for these differences. Plots installed in the tire track areas are referred to as “track” plots and those installed in non-tire track areas are referred to as “non-track” plots.

### 2.1. Site description and road characterization

A study was conducted on the Priest River Experimental Forest, 10 miles north of Priest River, Idaho, USA. Two roads were selected for the study, a brushed-in road and a reopened road (Fig. 1). Roads were selected with the intent of having similar slope, soil texture, and pre-brushed-in traffic conditions (Table 1), such that any observed differences could be attributed solely to road surface changes due to logging truck traffic and grading the road to remove vegetation.

The brushed-in road was constructed in 1975, and received construction traffic plus three to four truckloads of additional logging truck traffic from a small timber sale in the year following construction. The road was closed and received no traffic from 1976 until 1995, when it was flail mowed for access. Flail mowing removed standing vegetation above the surface, but did not remove the root systems. Between 1995 and 2006, it had no traffic and at the time of the study had standing vegetation that included tree seedlings, low to medium size shrubs and alders up to 2 m tall. The brushed-in road had a moss, duff, and vegetation ground cover of nearly 100%. Ground cover due to moss was typically 12–65%. The duff layer was 13–15 mm deep and covered over 90% of the former road surface. There was no visible remnant of the wheel tracks.





Fig. 1. Portable rainfall simulator assembled on a brushed-in road (a) and a reopened road (b) in northern Idaho, USA.

The reopened road was constructed in 1955 and 1956, received little traffic other than construction traffic and then remained idle, and over time became a brushed-in road. The road was reopened in 2004 for a timber sale, received 48 logging truck loads of traffic in 2004, and has received light traffic (e.g., less than one pickup sized truck per week) since the sale. The road had a native surface with no vegetation on the running surface at the time of the study.

2.2. Rainfall simulation

The experimental design was a factorial with two road types (brushed-in and reopened), two plot locations (track and non-track), three storm types (dry, wet, and very wet), and five replicates, which gave a sample size of 60. Plot location was randomly chosen within each road type. Existing vegetation in the plot was not disturbed.

One-meter-square bordered plots were installed using sheet metal borders with a runoff apron on the downhill border (Fig. 2). The sheet metal borders were driven into the soil to a depth of 50 mm to prevent outside water from flowing into the plot. The apron was constructed to direct runoff to a 25-mm pipe opening, from which timed grab samples were taken every minute for the duration of the runoff period. The downhill border and runoff apron were sealed with bentonite to prevent water from flowing under the plot border. Plot slopes ranged from 3 to 8%. The short flow path lengths in these plots prevented rill formation, thus allowing



Fig. 2. Rainfall simulation plots (1 × 1 m) installed in the non-track portion of a brushed-in road (a) and the non-track portion of a reopened road (b) in northern Idaho, USA.

Table 1  
Physical characteristics of brushed-in road and reopened road in northern Idaho, USA.

Road type	Year of construction	Location	Soil texture	Slope (%)	Cover (%)	Root mass (kg m <sup>-2</sup> ) <sup>a</sup>
Brushed-in	1975	Track	SL	9.1	98	0.04
		Non-track	SL	10.8	95	0.04
Reopened	1955	Track	SL	7.5	0	0
		Non-track	SL	6.6	0	0

SL, sandy loam.  
<sup>a</sup> Root mass estimated from Page-Dumroese and Jurgensen (2006).

investigation of the impacts of infiltration, interrill erosion, and vegetative cover.

Rainfall was simulated using a single Spraying Systems Veejet 80100 nozzle 3 m above the ground. Adjustable telescoping legs enabled leveling on uneven ground. A nylon windscreen was used to ensure an even rainfall distribution on the plot.

A sequence of three simulated storms, each with an intensity of  $100 \text{ mm h}^{-1}$  and duration of 30 min, was delivered to the plots. The initial rainfall (called the “dry” run) represented a high-intensity storm on dry soil (e.g., a high-intensity summer thunderstorm) and was applied to the plots under existing soil moisture and low antecedent precipitation conditions. The next rainfall (called the “wet” run) was applied the following day under slightly higher antecedent precipitation conditions and represented what could be expected from a single high-intensity storm in a series of summer-type thunderstorms. The third rainfall (called the “very wet” run) immediately followed the second rainfall and represented a high-intensity storm on a saturated soil with high antecedent precipitation conditions (e.g., a high-intensity spring storm). This series of rainfall events ensured that the soil was saturated during the third storm, such that runoff rates could be used to calculate  $K_s$  and to test for dynamic behavior in  $K_i$ .

The sequence of storms was used to simulate high-intensity rainfall at different antecedent soil moisture conditions. Although the individual storms were not typical for northern Idaho (return period greater than 100 years), the different antecedent soil moisture conditions were representative of different seasons and storm patterns (e.g., typically higher soil moisture in the spring than in the fall and saturated soils after a series of spring-type thunderstorms).

The  $100\text{-mm h}^{-1}$ , 30-min-duration storm was chosen not to represent a specific design storm, but to exceed the infiltration rate at each site. Exceedance of the infiltration rate ensured that the entire plot area contributed to runoff (a requirement for determining both  $K_s$  and  $K_i$ ) and that saturated conditions were reached during the very wet run (a requirement for determining  $K_s$ ). The rainfall rate was measured during a series of calibration runs prior to rainfall simulations. A  $1\text{-m}^2$  plot cover with a mesh screen top to reduce raindrop splash was placed over the top of a trial plot (constructed in the same manner as the simulation plots) to collect and funnel rainfall to an outlet during the calibration runs. Runoff was collected for a known time period (usually 10–15 s) and measured on-site in a graduated cylinder to determine the rainfall rate. This procedure was repeated several times at nozzle pressures varying from 41 to 42 kPa to ensure rate stability during potential nozzle pressure fluctuations during simulations. Rainfall rates varied by less than 5% over this range of nozzle pressures.

Runoff volumes, runoff rates, sediment production, and sediment concentrations were determined by weighing and oven drying the grab samples at  $105^\circ\text{C}$ . Soil samples were taken prior to each rainfall event at a depth of 0–40 mm and oven dried at  $105^\circ\text{C}$  to determine soil water content. Percent ground cover was determined by a point-count analysis of digital pictures of the plots using a 48-point grid overlay similar to the method described by Booth et al. (2005). The spacing between points represented 4-cm spacing with respect to the true plot size. The grid covered 5.6% of the total plot area.

### 2.3. Methods of calculating $K_s$ and $K_i$

Saturated hydraulic conductivity was determined from the very wet runs, as saturated conditions were a requirement for estimation of  $K_s$ . Interrill erodibility was determined from the dry runs, as the dry runs had the most erodible soil conditions. To investigate the dynamic erodibility behavior suggested by Ziegler et al. (2000)

$K_i$  values were also determined for the wet and very wet runs so that comparisons of  $K_i$  among run type could be made.

Two estimates of  $K_s$  and  $K_i$  were obtained for each plot using two independent methods: (1) directly from the measured rainfall simulation data; and (2) a modeling approach using the physically-based Water Erosion Prediction Project (WEPP) model (Flanagan and Livingston, 1995). The parameters are referred to in the paper as “calculated” and “WEPP-derived,” respectively.

The calculated  $K_s$  was estimated as the rainfall rate minus the average of the last five measured runoff rates prior to the end of rainfall from the very wet rainfall simulations. This satisfied the assumptions for the Green–Ampt infiltration expression: (1) there is a distinct and precisely definable wetting front during infiltration that moves progressively downward; and (2) that the soil is uniformly wet and of constant conductivity in the transmission zone behind the wetting front (Hillel, 1998).

The calculated  $K_i$  was determined from the dry runs and was estimated based on:

$$K_{\text{imeas}} = \frac{D_i}{IQ} \quad (4)$$

where  $K_{\text{imeas}}$  is the measured interrill erodibility coefficient ( $\text{kg s m}^{-4}$ ),  $D_i$  is the sediment delivery rate averaged over the entire runoff interval ( $\text{kg m}^{-2} \text{s}^{-1}$ ),  $I$  is the rainfall intensity ( $\text{m s}^{-1}$ ), and  $Q$  is the runoff rate averaged over the entire runoff interval ( $\text{m s}^{-1}$ ) (Fangmeier et al., 2006).  $K_{\text{imeas}}$  was adjusted for ground cover, slope, and root mass to allow a determination of  $K_i$ , which is strictly a function of soil properties (Alberts et al., 1995).

$$K_i = \frac{K_{\text{imeas}}}{K_{\text{igc}}K_{\text{isl}}K_{\text{irm}}} \quad (5)$$

The ground cover adjustment ( $K_{\text{igc}}$ ) was:

$$K_{\text{igc}} = e^{-2.5\text{COVER}} \quad (6)$$

where COVER was the interrill cover ( $\text{m}^2 \text{m}^{-2}$ ) (Lafren and Colvin, 1981). The slope adjustment ( $K_{\text{isl}}$ ) was:

$$K_{\text{isl}} = 1.05 - 0.85e^{-4\sin\Omega} \quad (7)$$

where  $\Omega$  is the plot slope angle (degrees) (Liebenow et al., 1990). The adjustment for root biomass within the 0–0.15 m soil zone ( $K_{\text{irm}}$ ) was:

$$K_{\text{irm}} = e^{-0.56\text{rm}} \quad (8)$$

where rm is the root mass ( $\text{kg m}^{-2}$ ) (Alberts et al., 1995). The value for rm was taken from a previous study in the same drainage (Page-Dumroese and Jurgensen, 2006).

WEPP-derived parameters were estimated using pre-rain soil saturation, bulk density, percent ground cover, and plot geometry. Saturation was estimated based on water content and porosity. A typical value was used for bulk density. Initial  $K_s$  and  $K_i$ , which are user-defined parameters in the WEPP model, were estimated based on the runoff for each plot. Repeated computer runs were performed in which the assumed  $K_s$  was varied until an objective function (Obj) was minimized. The Obj attempts to match the measured and WEPP-predicted runoff volumes and peak flows by minimizing the difference between the measured and predicted values. It is given by:

$$\text{Obj} = (\text{RO}_{\text{meas}} - \text{RO}_{\text{WEPP}})^2 + (\text{Peak}_{\text{meas}} - \text{Peak}_{\text{WEPP}})^2 \quad (9)$$

where  $\text{RO}_{\text{meas}}$  is measured runoff,  $\text{RO}_{\text{WEPP}}$  is WEPP-predicted runoff,  $\text{Peak}_{\text{meas}}$  is measured peak runoff, and  $\text{Peak}_{\text{WEPP}}$  is WEPP-



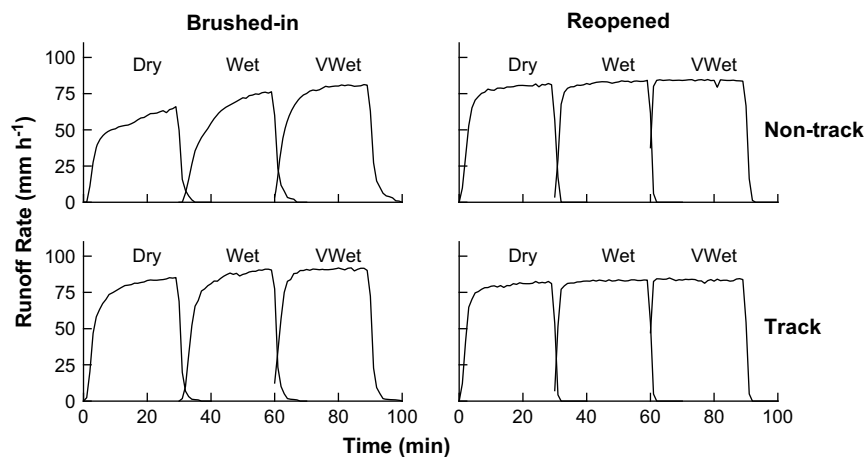


Fig. 3. Composite hydrographs from a series of three 30-min simulated rainfall events on a brushed-in road ( $n = 4$ ) and a reopened road ( $n = 5$ ) in northern Idaho, USA.

predicted peak runoff. Once the optimum  $K_s$  was determined, input  $K_i$  values were varied until the WEPP-predicted sediment loss matched the observed sediment loss.

#### 2.4. Statistical analysis

Statistical analyses were performed on total runoff, mean sediment concentration, and calculation-based  $K_s$  and  $K_i$ . WEPP-based parameters have been presented for comparison, but were not statistically analyzed. Analyses were performed using three-way mixed model analyses of variance (ANOVAs) (Littell et al., 1996) with 'road type' (brushed-in or open road), 'plot location' (track or non-track), and 'run type' (dry, wet, or very wet) as treatment effects. All interactions among treatment effects were considered. Simple main effects were analyzed when one or more significant interactions were present in the full model. Log transformations were performed on sediment concentration,  $K_s$ , and  $K_i$  data to satisfy the assumption of normally distributed residuals. Initial soil moisture was used as a covariate in the  $K_i$  analysis. Tukey's method was used for all pairwise comparisons. Results are reported at the  $\alpha = 0.05$  level of significance.

### 3. Results and discussion

One of the non-track plots from the brushed-in road produced 36% less runoff than the mean of the other repetitions for the same treatment combination. We suspect that either: (1) an unseen macropore was present in the plot and allowed water to move more rapidly into the soil profile; or (2) a broad-leaved plant near one of the plot borders intercepted a significant amount of rainfall and routed it out of the plot. Although it was not possible to investigate the plot macropore structure without massively disturbing the plot, inspection of plot photos confirmed the presence of a leafy plant which may have intercepted rainfall and directed it out of the plot (Fig. 2a). Either case would make this plot from a different population than the other plots used in this study. Furthermore, inclusion of this plot caused the residuals from the mixed model ANOVA to not be normally distributed. Consequently, this plot was not included in the analyses.

#### 3.1. Runoff

Runoff from the reopened road plots began and reached steady state faster than from the brushed-in road, resulting in a hydrograph shape that is typical for a road (Fig. 3) (Foltz and Burroughs,

1990; Sheridan et al., 2008). The hydrographs from the brushed-in road plots had a more gradual approach to steady state runoff and a falling limb at the end of the runoff period similar to those from a forest floor (Robichaud, 2000; Robichaud et al., 2007). Typically, runoff rates from the brushed-in road did not reach steady state until the very wet run, while runoff rates on the reopened road often reached steady state during the dry or wet runs. Additionally, the rising limb of the reopened road hydrographs rose more quickly to rates comparable to those near the end of the previous run. Dissimilarity between the hydrographs of the two road types was attributed to differences in hydraulic conductivity, as well as surface storage and surface roughness due to ground cover differences between the two road types.

Analysis of total runoff indicated 'road type,' 'plot location,' 'run type,' and the 'road type  $\times$  plot location' interaction as significant effects. Because of the significant interaction, we will separately discuss the effects of 'run type' and the effects of the 'road type  $\times$  plot location' interaction.

There were significant differences in total runoff among the three run types, with the dry run producing the least runoff, followed by the wet, and then the very wet run. In other words, a high-intensity storm on a dry soil produced less runoff than a thunderstorm of the same intensity on a wetter soil. This was true for both road types.

The significant 'road type  $\times$  plot location' interaction indicated that 'plot location' had a different effect on the total runoff response for each road (Fig. 3). Runoff rates on the brushed-in road reached steady state faster on track plots than on non-track plots, but there was no difference in the shape of the hydrographs between track and non-track plots on the reopened road (Fig. 3).

This observation was confirmed by the pairwise comparisons. Both plot locations of the reopened road and the track of the

Table 2

Mean runoff and saturated hydraulic conductivity ( $K_s$ ) values from a brushed-in and a reopened road in northern Idaho, USA.

Road type	Plot location	n	Runoff (mm)	CV (%)	$K_s$ (mm h <sup>-1</sup> )		
					n	Calculated	WEPP-derived
Brushed-in	Track	12	38 <sup>a</sup>	11	4	11 <sup>a</sup>	17
	Non-track	15	32 <sup>b</sup>	21	5	15 <sup>b</sup>	34
Reopened	Track	15	39 <sup>a</sup>	6.2	5	17 <sup>b</sup>	18
	Non-track	15	38 <sup>a</sup>	6.9	5	17 <sup>b</sup>	10

Mean runoff includes all three rainfall events. Mean  $K_s$  calculated from the very wet rainfall event only. <sup>a</sup> and <sup>b</sup> superscripts denote groupings of statistically significant values within a response category.

**Table 3**

Range of reported saturated hydraulic conductivity ( $K_s$ ) and interrill erodibility coefficient ( $K_i$ ) for an undisturbed forest floor and forest roads in various conditions.

Surface condition	$K_s$ (mm h <sup>-1</sup> )	$K_i$ ( $\times 10^6$ kg s m <sup>-4</sup> )
Undisturbed forest floor <sup>a,b</sup>	36–1700	0.007–0.2
Road with moderate traffic <sup>b,c,d,e</sup>	0.2–5	1.5–2.0
Skid trail <sup>d,f</sup>	6–80	0.002–4.0
Brushed-in road <sup>g</sup>	7–28	0.9–3.9
Reopened road <sup>g</sup>	13–21	1.0–1.8

<sup>a</sup> Robichaud, (2000). Idaho, USA.

<sup>b</sup> Ziegler and Giambelluca (1997). Thailand.

<sup>c</sup> Flerchinger and Watts (1987). Idaho, USA.

<sup>d</sup> Ziegler et al. (2007). Peninsular Malaysia.

<sup>e</sup> Foltz and Maillard (2003). Idaho, USA.

<sup>f</sup> Covert et al. (2005). Idaho and Montana, USA.

<sup>g</sup> This study. Idaho, USA.

brushed-in road were grouped together with a significantly greater mean total runoff (39 mm) than the mean total runoff from the non-track location of the brushed-in road (32 mm) (Table 2). Additionally, the coefficient of variation (CV) was higher from the brushed-in road than from the reopened road (Table 2). High spatial variability, characterized by a high CV, is a characteristic of undisturbed forest soils (Page-Dumroese and Jurgensen, 2006), while low spatial variability is a characteristic of disturbed forest soils (Arnaez et al., 2004; Ziegler and Giambelluca, 1997).

### 3.2. Saturated hydraulic conductivity

The two calculation methods (calculated and WEPP-derived) predicted similar trends in  $K_s$  among treatments; however, WEPP consistently predicted lower values than did the calculated method (Table 2). On the brushed-in road, the ratio of WEPP-predicted  $K_s$  values to calculated values was 2.7 while on the reopened road the ratio was 1.6. Ziegler et al. (2001) and Loague and VanderKwaak (2002) also found  $K_s$  values in runoff models had to be increased by factors ranging from four to five compared to field-derived (analogous to our calculated)  $K_s$  values. The reasons for these discrepancies warrant further investigation.

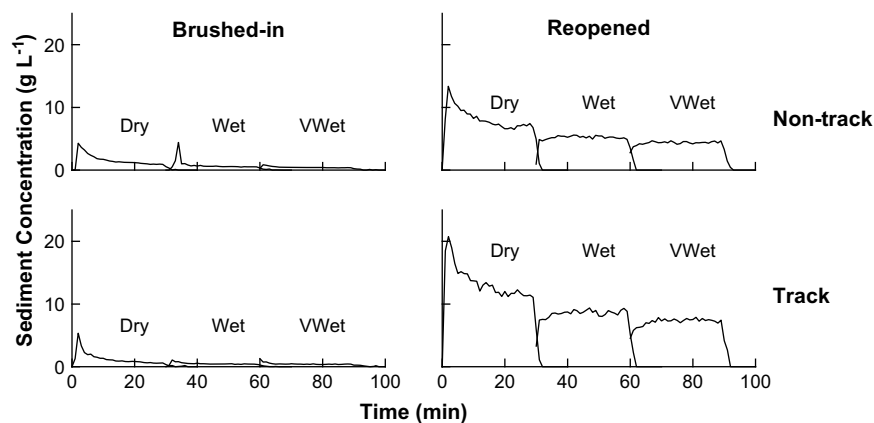
Analysis of  $K_s$  indicated 'plot location' and the 'road type  $\times$  plot location' interaction as significant effects. Because of the interaction, the discussion has been limited to the 'road type  $\times$  plot location' interaction. Pairwise comparisons separated the four combinations of road type and plot location into two groups, one containing the reopened road plots plus the non-track plots on the

brushed-in road (mean  $K_s$  16 mm h<sup>-1</sup>) and one containing the track plots on the brushed-in road (mean  $K_s$  11 mm h<sup>-1</sup>) (Table 2).

The effect of 'road type' on  $K_s$  was significant for track plots, i.e., if only the track areas were compared,  $K_s$  was significantly higher from the reopened road. A higher  $K_s$  in the wheel track on a reopened road than on a brushed-in one is not what we expected. Ground cover, amount of traffic, and depth the road had been cut into the original surface during construction were the major differences between the two roads. We suspect that ground cover on the brushed-in road may have had a disproportionate impact during the dry and wet runs, before vegetation interception was filled and the moss and duff layers became saturated. The moss layer in particular would have had a large storage capacity, as *Sphagnum* moss (present throughout the study area) can absorb up to 16 times its air-dry weight of water (Schouwenaars, 1993). Traffic on the reopened road would be expected to compact the wheel track and, thus, reduce the  $K_s$  compared to that of an unused road wheel track. Ziegler et al. (2007) measured  $K_s$  on forest roads in Peninsular Malaysia and observed that the extent of traffic had a smaller influence on  $K_s$  than did the depth the road had been cut into the original surface during construction. They observed that overland flow was mainly related to the fact that the roads were excavated at least 0.5–1.0 m into the hillslope profile. These depths coincide with weathered subsoil horizons and characteristically low  $K_s$  values. The brushed-in road in our study had cutslope heights of 1–2 m while the reopened road had heights of 2–3 m.

Differences in  $K_s$  between the track and the non-track areas of the running surface of a brushed-in road are analogous to Ziegler and Giambelluca (1997) finding that the running surface and the roadside margins of forest roads in Thailand had different  $K_s$  values. Both the non-track center portion of the road and the roadside margins receive less traffic than does the wheel track portion. Based on the current study, these differences persist over the span of several decades even without traffic. Differences in  $K_s$  should be accounted for when modeling low-use forest roads.

The  $K_s$  values measured on the reopened road are greater than what has typically been reported for forest roads (Table 3). Although there are other possible explanations, as discussed above, it does appear that the amount of traffic received after the road was reopened was not sufficient to reduce  $K_s$  to those values reported for a road with moderate traffic. Both the brushed-in and the reopened road had  $K_s$  values similar to those reported for a skid trail. After 30–50 years with little to no traffic, both roads had an order of magnitude lower  $K_s$  values than an undisturbed forest floor. Based on measurements of 40 years of no traffic and substantial vegetation regrowth on a road in Peninsular Malaysia,



**Fig 4.** Composite sediment concentrations measured from a series of three 30-min simulated rainfall events on a brushed-in road ( $n = 4$ ) and a reopened road ( $n = 5$ ) in northern Idaho, USA.

**Table 4**Mean sediment concentration and interrill erodibility coefficient ( $K_i$ ) values from a brushed-in and a reopened road in northern Idaho, USA.

Road type	Plot location	<i>n</i>	Sediment concentration (g L <sup>-1</sup> )	CV (%)	$K_i$ ( $\times 10^6$ kg s m <sup>-4</sup> )			
					<i>n</i>	Calculated	CV (%)	WEPP-derived
Brushed-in	Track	12	1.1 <sup>a</sup>	75	4	1.5 <sup>a</sup>	27	1.6
	Non-track	15	1.4 <sup>a</sup>	79	5	2.0 <sup>a</sup>	39	2.2
Reopened	Track	15	14 <sup>b</sup>	29	5	1.7 <sup>a</sup>	7.7	1.6
	Non-track	15	8.8 <sup>c</sup>	33	5	1.1 <sup>a</sup>	5.5	1.2

Mean sediment concentration includes all three runoff events. Mean  $K_i$  calculated from the dry rainfall event only. <sup>a</sup>, <sup>b</sup>, and <sup>c</sup> superscripts denote groupings of statistically significant values within a response category.

Ziegler et al. (2007) estimated that several hundred years would be needed for full recovery of  $K_s$  to that of the undisturbed forest floor. The current study conducted in a mild mid-latitude climate compared to the tropical monsoonal climate of Ziegler et al. (2007) suggests that a similar long period of recovery with no traffic and substantial vegetation regrowth is required before roads in a mild mid-latitude climate have  $K_s$  values that approach those of the undisturbed forest floor.

### 3.3. Sediment concentrations

Sediment concentrations were characterized by a sharp peak at the beginning of the runoff period, followed by a rapid decay (Fig. 4). Typically the magnitude of the peak sediment concentration decreased from dry, to wet, to very wet runs, as the amount of readily available erodible material was depleted. Sediment concentrations were two to three times higher from the reopened road than from the brushed-in road (Fig. 4). Variability was lower on the reopened road than on the brushed-in road (Table 4), which indicated less spatial variability on the reopened road.

Analysis of mean sediment concentration indicated that 'road type,' 'run type,' and the 'plot location  $\times$  road type,' interaction and 'road type  $\times$  run type' interaction were significant. Because both 'road type' and 'run type' appear in the significant interactions, we will discuss only the interactions.

The significant 'plot location  $\times$  road type' interaction indicated that 'plot location' had a different effect on the sediment concentration response for each road. Pairwise comparisons separated the treatments into three statistically different groups: (1) the track plots on the reopened road had the highest mean sediment concentrations (14 g L<sup>-1</sup>); (2) the non-track plots on the reopened road (8.8 g L<sup>-1</sup>); and (3) the track and non-track plots on the brushed-in road (1.2 g L<sup>-1</sup>) (Table 4). Higher sediment concentrations from tire track areas of the reopened road were attributed to replenishment of loose materials by traffic and removal of protective vegetation when the road was reopened.

Analysis of simple main effects indicated that the reopened road produced significantly higher sediment concentrations than the brushed-in road for both track and non-track areas. We believe that the vegetative cover, and particularly the duff and moss layers, on the brushed-in road reduced sediment concentrations by slowing runoff and absorbing kinetic energy from raindrop impact.

Significance of the 'road type  $\times$  run type' interaction indicated that 'run type' had a different effect on sediment concentration for each road. Pairwise comparisons yielded identical groupings of run types for each road. There were four significant groupings with two significant groups for each road. Mean sediment concentration from the dry runs on the brushed-in road was in one group (2.2 g L<sup>-1</sup>) and the mean concentration from the dry run on the reopened road was in another group (16 g L<sup>-1</sup>). Mean sediment concentrations from the wet and very wet runs on the brushed-in road were grouped together (average 0.69 g L<sup>-1</sup>) and the mean concentrations from the wet and very wet runs on the reopened road were grouped together (average 9.2 g L<sup>-1</sup>).

Analysis of the simple main effects indicated that 'run type' had a significant effect on sediment concentration for both roads. In other words, a high-intensity thunderstorm on a dry soil produced higher sediment concentrations in the runoff than did the same intensity storm on soils with higher soil moistures.

### 3.4. Interrill erodibility

Direct calculation  $K_i$  values agreed well with WEPP-predicted ones (Table 4). Based on the dry run analysis, there were no significant differences in direct calculation  $K_i$  values among the treatment effects (Table 4). The soil property  $K_i$  was the same for both roads. Because sediment concentrations were due to interrill erosion on the short plots and there was no difference in  $K_i$ , we conclude that sediment concentration was determined more by vegetative cover than by the inherent soil properties or levels of traffic and surface preparation.

'Road type,' 'plot location,' 'run type,' and the 'road type  $\times$  run type,' and 'road type  $\times$  plot location' interactions were significant when the calculated  $K_i$ s were compared among all three run types. Because of the significant interactions, discussion has been limited to the interactions among 'road type,' 'plot location,' and 'run type'. Pairwise comparisons groups were: (1) both dry runs with the highest mean  $K_i$  ( $1.5 \times 10^6$  kg s m<sup>-4</sup>); (2) both wet runs and the very wet run from the reopened road with a significantly lower mean  $K_i$  ( $0.75 \times 10^6$  kg s m<sup>-4</sup>); and (3) the very wet run on the brushed-in road into its own group, with the lowest mean  $K_i$  ( $0.40 \times 10^6$  kg s m<sup>-4</sup>) (Table 5).

Analysis of the simple main effects indicated that 'run type' was significant for both roads. In other words,  $K_i$  was a dynamic parameter, dependent upon antecedent discharge and sediment preparation since the last storm. Decreased erodibility with increasing antecedent rainfall was presumably due to depletion of readily available erodible material. These results support Ziegler et al. (2000), who concluded that sediment transport and production on roads was best modeled by allowing erodibility to change over the course of a storm (inter-storm basis) or between storms (intra-storm basis) in response to the removal and regeneration of easily entrainable sediment. Their road erosion modeling approach was controlled by both a baseline erodibility of the underlying road surface and the removal of a loose, surface sediment layer by

**Table 5**Mean interrill erodibility coefficient ( $K_i$ ) values from three rainfall simulation runs on a brushed-in and a reopened road in northern Idaho, USA.

Road type	Run	<i>n</i>	$K_i$ ( $\times 10^6$ kg s m <sup>-4</sup> )	CV (%)
Brushed-in	Dry	10	1.70 <sup>a</sup>	35
	Wet	10	0.66 <sup>b</sup>	23
	Very wet	9	0.44 <sup>c</sup>	33
Reopened	Dry	9	1.35 <sup>a</sup>	23
	Wet	9	0.87 <sup>b</sup>	27
	Very wet	10	0.73 <sup>b</sup>	27

<sup>a</sup>, <sup>b</sup>, and <sup>c</sup> superscripts denote groupings of statistically significant values within a response category.

overland flow. Foltz et al. (2008) found that rill erodibility on native surface roads decreased exponentially with increasing cumulative flow depth. Accuracy of road erosion modeling could, therefore, be improved if dynamic, rather than constant, soil erodibility parameters were used for prediction.

#### 4. Conclusions

Rainfall simulations were conducted on small scale plots to determine the effects of reopening brushed-in roads on infiltration and erosion and to estimate pertinent erosion modeling parameters. Significantly higher sediment concentrations were obtained from the reopened road plots than from the brushed-in road plots. Therefore, while surface runoff may not increase following road reopenings, there may still be an increase in erosion. The amount of traffic received by the reopened road was not sufficient to significantly change  $K_i$ ; leaving vegetative cover as the major factor in reducing sediment production on the roads used in this study. A thick duff layer and extensive moss coverage on the brushed-in road likely slowed runoff and absorbed kinetic energy from rain-drop impact, reducing interrill erosion.

WEPP-predicted  $K_s$  values were consistently lower than those determined directly from runoff measurements. Small  $K_s$  values are difficult to estimate using the direct calculation method, as small errors in applied rainfall or measured runoff can result in values for  $K_s$  with no physical meaning.

This study combined with one in Thailand suggest that many decades of non-use are required for  $K_s$  values on a road to approach those of the undisturbed forest. After 30 years of non-use the study road had  $K_s$  values closer to those of a skid trail than an undisturbed forest.

The dry run  $K_i$  did not differ between the brushed-in road and reopened road or between the track and non-track areas of either road. The mean measured dry run  $K_i$  was  $1.6 \times 10^6 \text{ kg s m}^{-4}$ . Although there was no difference in the dry run  $K_i$  between the two roads,  $K_i$  values decreased significantly with increasing antecedent rainfall, which implied that  $K_i$  behaves as a dynamic parameter and can change over the course of a rainfall event. This has implications for erosion modeling and prediction, and therefore, also for forest planning and management. Erosion rates will be overestimated, particularly from long-duration storms if a constant interrill erodibility parameter is used.

This study has provided estimates of  $K_s$  and  $K_i$  for abandoned and reopened forest roads and has addressed the impact that reopening abandoned forest roads can have on these soil parameters and on erosion. Further investigation of how: (1) road surface  $K_s$  and  $K_i$  change, both temporally and spatially; and (2) vegetative surface materials recover and impact erosion following road construction and closure would be useful for erosion modeling and future forest planning.

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