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Evaluating Post-Fire Salvage Logging Erosion Mitigation Treatments in the California Sierra Nevada, USA

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ABSTRACT

The effects of salvage logging on runoff and sediment delivery processes are not well understood. We used rill erosion simulation experiments for 3 years after the 2013 Rim Fire to understand how post-fire salvage logging and mitigation practises affect runoff and sediment delivery rates. We assessed soil conditions, surface cover, runoff rates and sediment delivery rates on hillslope plots that were either burned at high severity (controls) or burned at high severity with additional logging treatments including no logging traffic, few pass or many pass skid trails, and skid trails that were treated with subsoiling or ‘drop and lop’ (added wood ground cover). Runoff and sediment delivery responses were generally lower in the controls and plots that were logged with no traffic than in plots that received heavy equipment traffic, regardless of the amount of traffic or whether a mitigation treatment was applied. Responses decreased for all conditions over the three-year study. Logging traffic had the largest impact on soil disturbance and subsequent runoff and erosion. In all 3 years, the many pass plots had ~6 times the sediment concentration in samples compared to the control plots. The drop and lop treatment doubled the ground cover in the first post-fire year compared to its treatment pair but did not effectively reduce runoff or sediment delivery. Subsoiling did increase infiltration but did not reduce bulk density or decrease runoff; it also did not increase sediment delivery or impact vegetation recovery. These findings will be useful in developing comparative modelling tools and in selecting mitigation strategies to reduce sediment delivery rates following the soil disturbance and compaction from post-fire salvage logging.

1 | Introduction

High-severity wildfires frequently consume much of the organic material on the forest floor, rendering the forest soils exposed and susceptible to runoff and erosion (Shakesby and Doerr 2006). The risks of elevated runoff and sediment yields are the greatest until the vegetation has an opportunity to re-establish, generally in the first 3–5 years after the fire though this can take much longer (Robichaud et al. 2013; Wagenbrenner et al. 2021; Zema 2021). Post-fire salvage logging may affect the hydrologic response due to the additional disturbance to soils and remaining vegetation which influences the recovery trajectory of the burned area (Robichaud et al. 2021). Despite the

increasing global practise of salvage logging to recover some economic value from burned timber (Lindenmayer et al. 2004; Thorn et al. 2017), research on post-fire salvage logging has yielded seemingly conflicting results about detrimental disturbance (e.g., Wagenbrenner et al. 2015; Lucas-Borja et al. 2019; Cole et al. 2020; James and Krumland 2018; Olsen et al. 2021; Lewis et al. 2019). Salvage logging upstream of water resources can be particularly controversial because of the potential adverse effects on reservoirs and domestic water supplies (Emelko et al. 2011). Because of the concerns about downstream sedimentation, mitigation measures are often implemented to reduce the effects of post-fire salvage logging on surface water runoff and water quality.

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Numerous studies have shown increases in sediment yields after moderate and severe wildfires which is a combined function of increased soil exposure, reduced infiltration and elevated runoff following increased net precipitation, and increased soil detachment and transport capacities (Martin and Moody 2001; Gartner et al. 2004; Certini 2005; Shakesby and Doerr 2006; Robichaud, Lewis, Wagenbrenner, et al. 2020). The consumption of surface organic layers leaves soils disturbed and susceptible to elevated hydrologic response (Moody et al. 2013). Physical changes in soils such as changes in structure and grain size and the formation or alteration of soil water repellency can impact infiltration processes (Neary et al. 1999). Aboveground, fire consumption of canopy vegetation decreases evapotranspiration and interception, allowing more precipitation to contact and potentially run off the soil surface. In some regions where precipitation falls as mist or small droplets at low intensity, residual large tree branches can intercept rainfall and allow coalescence, leading to increased water droplet size and energy for splash erosion (Cole et al. 2020).

Specific effects from the compounded disturbance of severe wildfire and salvage logging include soil compaction, rutting, the formation of preferential flow paths, reduction or elimination of fire-induced soil water repellency (Wagenbrenner et al. 2015; Leverkus et al. 2021; Prats et al. 2021), and the delay of post-fire vegetation recovery (Donato et al. 2006; Morgan et al. 2015; Olsen et al. 2021; Robichaud et al. 2021; Zituni et al. 2019). The net impacts of logging on the soil profile include increased bulk density and decreased porosity from compaction, reductions in hydraulic conductivity despite lower soil water repellency, changes in particle size and organic matter, as well as more mineral soil exposure at the ground surface (Rab 1996; Malvar et al. 2017; Prats et al. 2019, 2021). The cumulation of these properties can result in decreased infiltration, increased runoff and potentially increased soil erosion. Concentrated flow experiments (Robichaud et al. 2010; Robichaud, Lewis, Brown, et al. 2020; Wagenbrenner et al. 2010, 2016) have shown that the detrimental hydrologic effects of the combined disturbance of wildfire and logging can be 1–2 orders of magnitude higher than fire or logging alone.

Because wildfires and post-fire salvage logging reduce surface cover and reduce infiltration capacity, salvage logging operations often include erosion mitigation treatments aimed at increasing the amount of surface cover or increasing infiltration (Fernández et al. 2021). The effects of soil disturbance on runoff and erosion can be mitigated in the short term by the addition of ground cover in the form of logging slash or other mulch cover (Prats et al. 2019, 2021; Cole et al. 2020; Robichaud, Lewis, Wagenbrenner, et al. 2020). The ‘drop and lop’ treatment was developed to increase surface cover by increasing the amount of wood present on the ground surface. The treatment is similar to ‘lop and scatter’ of logging slash with an emphasis on wood to soil contact, which can reduce soil erosion (Wagenbrenner et al. 2016). While lop and scatter has been practised since at least the late 1980s, only anecdotal observations of the performance of lop and scatter or drop and lop treatment have occurred (Poff 1989). ‘Few pass’ skid trails (≤ 6 passes by heavy equipment) have been exposed to less traffic than ‘many pass’ skid trails (here, > 6 passes by heavy equipment) and are often treated differently, despite studies that show no differences in compaction, runoff, or soil erosion because of the lower usage (Wagenbrenner et al. 2015, 2016).

Subsoiling has been used as a treatment to reduce compaction, aid in infiltration, and reduce competition during early seral forest regeneration (Kees 2008). This method is popular in the Sierra Nevada after timber harvests in unburned stands, and it has been used after post-fire salvage logging since the early 2000s (James and Krumland 2018). Contour subsoiling has been shown to reduce hillslope-scale sediment delivery in the first 3–5 years after post-fire salvage logging in areas where rainfall intensity is relatively low (James and Krumland 2018; Cole et al. 2020). The reductions were associated with reduced slope lengths caused by the ridge-furrow microtopography despite increases in smaller scale erosion rates attributed to greater soil availability for transport. There was no difference in infiltration capacity between plots that were logged and subsoiled vs. plots that were logged only (Cole et al. 2020). Subsoiling of skid trails that did not follow contours led to increased sediment yields from hillslopes (Olsen et al. 2021) and increased rilling and gullying when the gradient exceeds about 5% (Demirtas 2017). The specific effects of subsoiling after post-fire salvage logging on surface roughness and runoff velocity are unknown.

The objectives of this study were to (1) compare the hydrologic responses of logged areas treated with erosion mitigation treatments (drop and lop or subsoiling) to experimental controls, and (2) assess the effects of natural revegetation and time on hydrologic responses. Our hypotheses were that the less-disturbed control and logged only plots would have the lowest runoff and sediment delivery; the few pass plots would have less runoff and sediment than the many pass plots; and the additional ground cover provided by the drop and lop treatment would reduce runoff and sediment as compared to the few pass skid trails. We also hypothesised that the subsoiling treatment would increase infiltration and reduce runoff and sediment yield as compared to the many pass skid trails. We anticipated increases in surface cover over the 3-year study, but no changes in bulk density or infiltration capacity during this relatively short recovery period. The findings from this multi-faceted study will be useful in developing management recommendations and mitigation strategies following salvage logging on burned hillslopes.

2 | Methods

The extensive salvage logging and associated treatments implemented after the 2013 Rim Fire (USDA 2014) provided a unique opportunity to compare and understand the effects of salvage logging and two erosion mitigation treatments on physical soil properties, surface cover and vegetative regrowth, surface runoff and hillslope-scale erosion and sediment delivery. We utilised an unlogged high soil burn severity site and a logged-only (no traffic) site as experimental controls to test for differences among few and many pass skid trails and the drop and lop and subsoiling treatments.

2.1 | Site Description

The 2013 Rim Fire burned 104 000 ha, more than half of which was on the Stanislaus National Forest (USDA 2014) in central California (Figure 1). Mean annual precipitation over the period 1981–2010 averaged 1283 mm annually at the nearby Cherry

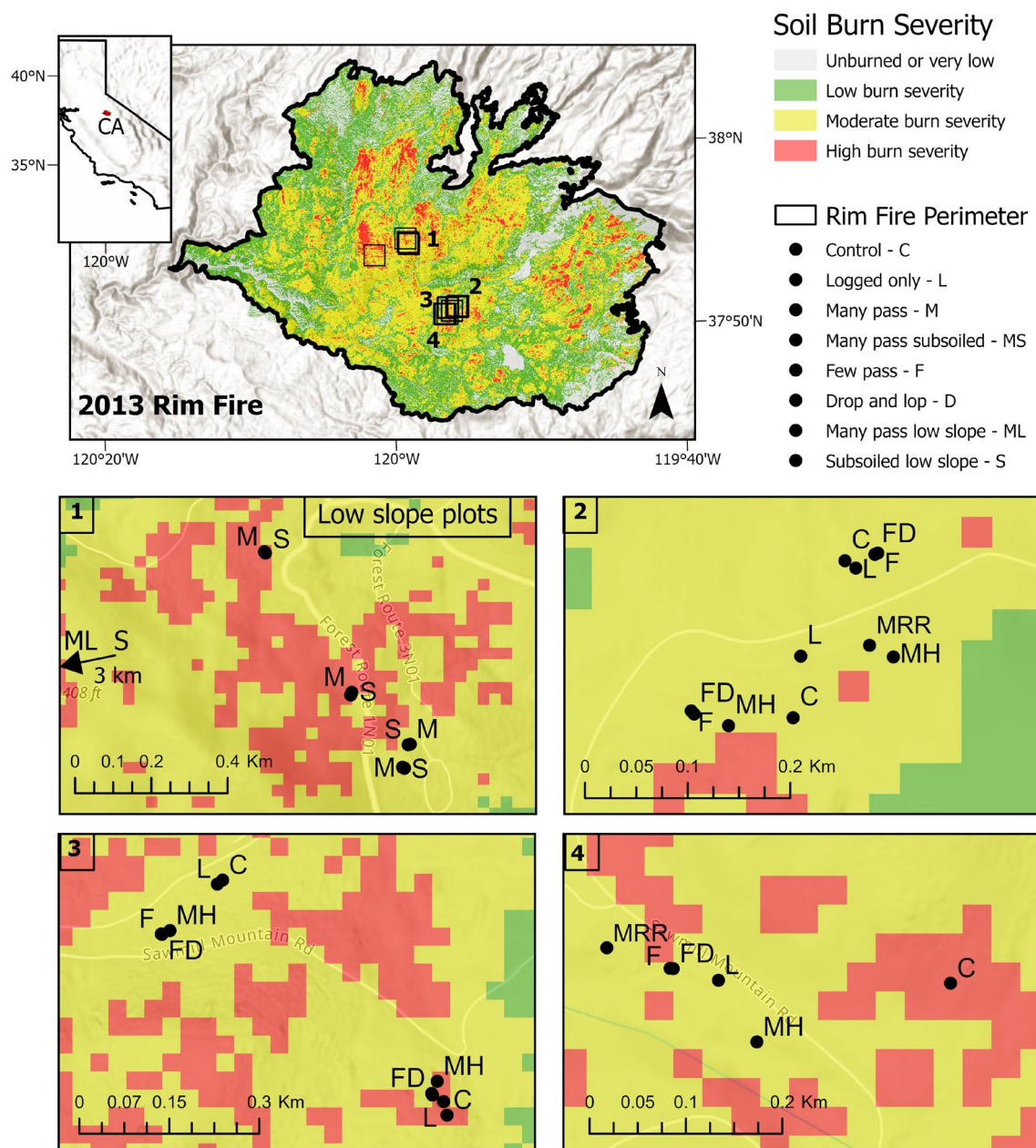


FIGURE 1 | Soil burn severity map of the 2013 Rim Fire in California. The four locations expanded in the lower panels show the paired plot treatment layouts. Plots in Panel 1 are low slope (10%–20%); Panels 2–4 are high slope (20%–30%).

Valley Dam rain gage (37.975N, 119.916W, 1400m elevation) (Western Regional Climate Center 2016). The study area experiences moist winters and dry summers with a Köppen-Geiger classification of Csb. Approximately 90% of the precipitation occurs from October to April. Snow accumulates and forms a transient snowpack in many winters, and summer–fall convective storms occasionally occur. The 1-h, 1-year return interval precipitation amount was estimated to be 13 mm (Perica et al. 2011). The dominant soils in the area are loams and gravelly loams weathered from granitic parent material, of the Holland, Fiddletown, Sites, and Josephine series (NRCS 2020). Pre-fire vegetation was composed of a mixture of ponderosa pine (*Pinus ponderosa*), incense cedar (*Calocedrus decurrens*), sugar pine (*Pinus lambertiana*), Douglas-fir (*Pseudotsuga menziesii*) and oak (*Quercus* spp.). Manzanita (*Arctostaphylos* spp.) was also found scattered within the study area.

All 3 years of the study period (2014–2016) had less than the mean precipitation at the Cherry Valley Dam (Table 1). 2014 and 2015 were particularly dry as the region was experiencing one of the most severe droughts on record (Lund et al. 2018).

The Stanislaus National Forest implemented post-fire salvage logging on approximately 6500 ha (6% of the burned area) along roads within the forest to minimise risk to workers and the public. For the salvage logging operation, trees were cut and piled using tracked feller bunchers except for larger trees, which were hand-felled. Rubber-tired skidders were used to skid the cut trees to landings. We considered six different classes of disturbance as treatments in this study. We implemented runoff experiments on sites within areas that had burned at moderate or high severity and were within or adjacent to the roadside hazard tree removal salvage logging operation (Figure 1).

2.2 | Treatments

We initiated this study amid the progression of salvage logging and subsequent treatments. Subsoiling occurred in some units after logging was completed. Drop and lop was also scheduled to be completed in some units after the logging was complete. Due to the timing and our intent to sample operational salvage logging and skid trails without manipulation for the study, the many pass and subsoiling paired plots were available in a different area than the rest of the disturbance class and treatment

TABLE 1 | Annual precipitation from the Cherry Valley Dam gauge (37.975N, 119.916W, 1400m elevation) for each water year (1 Oct–30 Sep). The long-term (1981–2010) average annual precipitation at this gauge was 1283 mm (Western Regional Climate Center 2016).

Years	Water year precipitation (mm)	Maximum daily precipitation intensity (mm/day)
2013 ^a	829	33.5
2014	710	62.2
2015	649	72.4
2016	1250	138.9

^aEight months missing from record.

combinations (Figure 1). Additionally, some of the many pass plots were inadvertently subsoiled after the first year. In order to include the drop and lop treatment within our initial simulation period, we needed to artificially replicate the drop and lop treatment to achieve paired plots.

Rill plot locations were not randomly located. Rather, the experimental design in Table 2 was followed to reduce subjectivity for soil burn severity, salvage logging, slope class, and treatment application. Within these rules, plots needed to be within 200 m from a road and unobstructed potential flow paths were required to accommodate the experimental setup. Sites were carefully selected to assure minimum variability in treatment conditions and other characteristics including burn severity, pre-fire forest conditions, and hillslope gradients and shape.

All plots were located in areas burned at high soil burn severity based on ground observations (e.g., forest floor consumption, fine root condition, soil structure and ash following Parsons et al. 2010) despite sometimes being mapped as moderate severity. Hillslope gradients were between 20% and 30% (high slope) for all treatments except the paired many pass and subsoiled plots were on plots with gradients of 10%–20% (low slope). Rill plots within treatment sites were located at least 10 m away from roads or other edge effects. Care was taken to select plot locations that were representative of each treatment condition to

TABLE 2 | Disturbance classes, mitigation treatments and slope characteristics. Under slope class, the slope mean is listed and the range is in parentheses. The shaded control and logged only plots are frequently referred to as ‘less disturbed’ compared to the few and many pass plots which have varying degrees of logging equipment traffic and soil disturbance. All plots were located in areas burned at high soil burn severity.

Disturbance class	Post-salvage mitigation treatment	Slope class (%)	Plots (n)	Descriptions
Control		High 24 (22–25)	5	No logging or other additional disturbance besides fire.
Logged only		High 23 (19–25)	5	Burned and salvage logged, no equipment traffic.
Few pass		High 24 (21–27)	5	Low-use skid trail; ≤ 6 equipment passes; typically some residual surface cover; ruts less than 0.1 m deep.
	Drop and lop	High 24 (21–28)	5	At least 50% total ground cover by the felling of burned trees up to 0.4 m in diameter and cutting the downed trees into segments to increase soil to ground contact. Represented in this study by the addition of wood pieces to achieve 50% total ground cover. Applied to one track of each few pass skid trail.
Many pass		High 25 (22–30)	5	High-use skid trail; > 6 equipment passes; typically no surface cover except for some residual slash; ruts sometimes exceeded 0.1 m deep.
		Low 14 (10–18)	5	
	Subsoiled	High 23 (21–25)	2 ^a	Furrows and ridges created by bulldozers with winged shanks (0.4 m depth) in many pass skid trails and landings; best management practise designed to decrease compaction and increase infiltration; no soil cover except for some rock and residual slash. Low-gradient skid trails except for two many pass plots established in the first year that were subsequently subsoiled. Low slope plots were paired with low slope many pass plots on the same skid trails.
		Low 15 (10–20)	5	

^aSampled in post-fire Years 2 and 3 only.

be tested and to allow for treatment replication. Except for the many pass skid trails and paired subsoiling, the treatments were replicated at each location to reduce the influence of conditions at a single site on the treatment results.

'Control' plots were unlogged areas burned and located adjacent to the roadside salvage areas. Our 'logged only' sites were logged during the post-fire salvage operation but had no visible evidence of heavy equipment traffic. The 'few pass' skid trails were areas that were logged and had no more than 6 passes of heavy equipment. The operational 'drop and lop' treatment consists of felling non-merchantable trees 0.1–0.4 m in diameter and cutting (lopping) them into lengths short enough such that the wood has as much ground contact as practical and all wood is within 30 cm of the ground surface. The drop and lop treatment was experimentally replicated by adding cut wood to one track of each few pass skid trail ensuring good wood to soil contact. This was constrained by an upper fuel load of 45 tons ha⁻¹ (20 tons ac⁻¹) which resulted in 53% ground cover in the first study year. We paired the drop and lop treatment with 'few pass' skid trails (≤ 6 passes by heavy equipment) as a cover augmenting mitigation treatment (Table 2).

The 'many pass' skid trails had more than six passes of heavy equipment. The 'subsoiling' treatment was completed by a tracked bulldozer with winged shanks, where the wings (horizontal blades) penetrated 45–60 cm into the soil. We paired the subsoiling treatment with many pass skid trails to test the mitigation effectiveness of the decompaction of the soil on soil water repellency, infiltration capacity, runoff and sediment delivery (Table 2). Because most of the subsoiled skid trails were lower slope (10%–20%), we included many pass plots in both low slope and high slope classes (typically 20%–30%) so that we could compare the many pass plots directly to the controls (high slope), few pass (high slope) and subsoiled plots (low slope) (Figure 1). This full set of treatment and control combinations resulted in a total of 37 plots with 5 plots in each treatment except for two many pass plots on higher slopes that were subsoiled after the first year (Table 2).

2.3 | Rill Experiments

Rill experiments allow direct comparison of runoff and sediment production rates from concentrated flow down a hillslope with given soil, vegetation and flow conditions. They allow direct observation of the rill formation process, hydraulic characteristics and erosion mechanisms under different treatment conditions. We adapted the protocol described by Robichaud et al. (2010) to measure runoff and erosion in plots that were 4 m long by approximately 1 m wide, with both dimensions varying slightly depending on flow characteristics. Water was passed through an energy dissipater and released at the top of the plot at sequential controlled rates of 12, 24, 36 and 48 L min⁻¹ for 15 min each. Runoff velocity was measured between 1 and 3 m from the release point using paired conductivity metres and a saline injection (King and Norton 1992). During each flow rate, six timed runoff and sediment samples were collected at the outlet of the plot which was located 4 m downslope of the release point. Flow was concentrated at the outlet of the plot using sheet metal inserted in the ground to allow sampling. Afterward, samples

were processed in the laboratory to determine overland flow ('runoff'), sediment flux rates and sediment concentrations.

We ran the rill experiments on approximately the same locations and disturbance-treatment combinations (plots) in September 2014, July–August 2015 and July 2016. We refer to the periods by the approximate time since burning, with 2014, the year of the salvage logging, being the first post-fire year.

2.4 | Field Procedures

After the logging and treatments were implemented and before each rill experiment, we measured the surface cover along the rill plots using two 1-m square, 10-cm grid quadrats per plot (Brown and Chambers 1983; Robichaud and Brown 2002). Ground cover classes were recorded as bare soil or gravel (i.e., easily erodible grains; gravel 5–75 mm), litter or wood, live vegetation, tree or root (other) or rock (> 75 mm). Rill ground cover was calculated as the percentage of occurrence among sample points (Robichaud and Brown 2002).

Before each experiment, samples were collected from the top 5 cm of soil near the plot outlets to calculate gravimetric water content. Soil water repellency was measured using the water drop penetration time (WDPT) method at 1 and 3 cm below the soil surface using 8 drops per depth (DeBano 1981). The median WDPT up to 300 s was determined for each depth at each plot and assigned a class following Robichaud et al. (2008). Using a core sampler, soil bulk density was measured at depths of 0–5 cm and 5–10 cm adjacent to each plot within the disturbance-treatment area each year of the experiments, and the bulk density was used as a relative measure of compaction.

We measured 1 min infiltration rates on the plots using a single ring infiltrometer (0.2 m diameter) for 60 min at each plot location each year (Bouwer 1986). The mean of the final 10 min of each sequence was used as the steady-state infiltration rate.

2.5 | Statistical Analysis

Statistical software programmes R and SAS were used to perform analysis (R Core Team 2024; SAS Institute Inc. 2023). Model diagnostics included testing residuals for normal distribution, plotting residuals versus predicted values, plotting residuals versus order and quantile–quantile plots of residuals versus predicted values (Winter 2013) to ensure model assumptions were met. To eliminate zero values for statistical modelling, half of the minimum value (0.0005 g) was added to each sediment value. For the sediment concentrations, we addressed heteroscedasticity in the model residuals by fourth-root transforming the data. Flow rate and depth were log-transformed; flow widths were square-root transformed.

The runoff and sediment flux rates approached a steady-state condition by the fourth sample in each experimental flow rate (Robichaud et al. 2010), thus only samples 4–6 were used to calculate variable means. The mean flow runoff rates and velocities, flow depths and widths and sediment concentrations were calculated only when runoff for that inflow rate reached the plot

TABLE 3 | Infiltration and soil characteristics by treatment. WDPT is the median water drop penetration time test at 3 cm depth; infiltration is the mean steady state value from the ring infiltrometer; mean bulk density is reported at 0–5 cm. Additional depths of WDPT and bulk density are reported in Table S1. Less disturbed control and logged only plots are shaded. Different superscript letters within a measurement and depth (e.g., WDPT across the 3 years) are significantly different at $p < 0.05$. High slope and low slope plots were evaluated separately and there were no significant differences among the low slope plots.

Treatment/ pair	Plots (n)	WDPT 3 cm (s)			Infiltration (mm min ⁻¹)			Bulk density 0–5 cm (gcm ⁻³)		
		Year 1	Year 2	Year 3	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
High slope plots										
Control	5	227 ^A	72 ^{BC}	43 ^{BC}	5.1 ^{AB}	4.1 ^{AB}	6.1 ^{AB}	1.16 ^{AB}	1.16 ^{AB}	1.19 ^{AB}
Logged	5	183 ^{AB}	21 ^C	38 ^{BC}	7.1 ^A	4.4 ^{AB}	5.0 ^{AB}	1.14 ^B	1.14 ^B	1.17 ^{AB}
Few pass	5	4 ^C	1 ^C	1 ^C	0.30 ^B	1.4 ^{AB}	1.9 ^{AB}	1.32 ^{AB}	1.39 ^A	1.29 ^{AB}
Drop lop	5	4 ^C	3 ^C	2 ^C	0.80 ^{AB}	2.4 ^{AB}	2.1 ^{AB}	1.24 ^{AB}	1.28 ^{AB}	1.25 ^{AB}
Many pass	5	4 ^C	1 ^C	1 ^C	0.42 ^B	1.1 ^{AB}	1.3 ^{AB}	1.35 ^{AB}	1.37 ^A	1.38 ^A
Subsoiled	2 ^a	—	1 ^{BC}	1 ^{BC}	—	1.2 ^{AB}	1.8 ^{AB}	—	1.28 ^{AB}	1.25 ^{AB}
Low slope plots										
Many pass	5	3	9	2	0.67	1.0	1.2	1.17	1.06	1.26
Subsoiled	5	1	3	1	2.6	1.1	2.1	1.20	1.30	1.15

^aSubsoiled in Year 2.

outlet. The mean plot values across all flow rates were used in statistical analyses. In SAS, linear mixed-effects models (Littell et al. 2006) were developed for response variables at each site with the fixed effects of treatment (control, logged only, few pass, many pass [high or low slope class], drop and lop and subsoiled), post-fire year (one, two, or three), and the interaction of treatment and post-fire year. For each combination of fixed effects, plot was a random effect. Response (dependent) variables were soil bulk density, WDPT, surface cover, log-transformed runoff rate, square-root transformed flow width, log-transformed flow depth, runoff velocity and fourth-root transformed sediment concentration. For each response, an autoregressive correlation structure was applied to account for the repeated measures in each plot through multiple years (Littell et al. 2006). The significance of differences across multiple comparisons among fixed effects was tested using least-squares means with a Tukey adjustment; differences were considered significant at $p < 0.05$.

3 | Results

3.1 | Site Characteristics

3.1.1 | Soils

Soil characteristics such as water repellency, infiltration and bulk density are impacted by the degree of disturbance of fire and logging, and the recovery trajectory towards a pre-fire or less disturbed condition varies by treatment over time (Table 3).

Water repellency in the control and logged only (less disturbed plots) decreased during the study period from moderate to high to low at 3 cm depth, and the change from Year 1 to Year 2 was significant on the less disturbed plots only (Table 3). Most of the

more disturbed few and many pass plots had WDPT values less than 5 s, indicating no water repellency detected.

Ring infiltration measurements reached near-steady-state infiltration rates after 50 min (median std. of the final 10 min was 0.22 mm min⁻¹). We found higher infiltration rates on the less disturbed control and logged only plots (5.1–5.5 mm min⁻¹) compared to the more disturbed plots (0.94–1.95 mm min⁻¹). There were no statistical effects of time since the fire on infiltration rate. Most treatments saw a slight increase in infiltration rate over time, although values on the disturbed plots were very low in all years. These low infiltration rates could not be explained by soil water repellency which was scarce or absent on most treatments in most years (Table 3).

There were very few differences in bulk density at either depth or over time on the high slope plots (Table 3). The less disturbed control and logged only plots (shaded rows) had the lowest bulk densities (1.14–1.19 g cm⁻³). The highest bulk densities were on the many pass plots in Years 2 and 3 and few pass in Year 2 (1.37–1.39 g cm⁻³), however, these values were only statistically different than the logged only plots in Years 1 and 2 (Table 3). All other treatments had bulk densities ranging from 1.24–1.35 g cm⁻³ in all years. The soil bulk density changed very little throughout the 3 years of the study on all treatments (mean –0.03 g cm⁻³ change). The only treatment where bulk density increased over time was on the subsoiled plots, which had increases of only 0.03 and 0.05 g cm⁻³ on the low slope and high slope plots, respectively. The low slope plots were analysed separately, and there were no significant differences over treatment or time, nor any observable trends over time (Table 3).

Since there were no changes in infiltration rate or bulk density over time, we also compared the treatments using values

TABLE 4 | Plot characteristics by treatment averaged over the 3-year study period: Soil moisture was collected before wetting; infiltration was the steady state value from the ring infiltrometer; bulk density was sampled at 0–5 cm and 5–10 cm depths. The control and logged only plots had no skidder traffic (shaded; see Table 2) and were less disturbed than the other plots.

Treatment/pair	Plots (n)	Soil moisture 0–5 cm (%)	Infiltration (mm min ⁻¹)	Bulk density 0–5 cm (g cm ⁻³)	Bulk density 5–10 cm (g cm ⁻³)
High slope plots					
Control	5	1.4	5.1	1.16	1.16
Logged only	5	2.1	5.5	1.15	1.15
Few pass	5	1.8	1.2	1.33	1.31
Drop lop	5	1.5	1.8	1.26	1.31
Many pass	5	1.4	0.94	1.38	1.39
Subsoiled	2 ^a	1.6	1.5	1.27	1.34
Low slope plots					
Many pass	5	0.8	0.96	1.16	1.28
Subsoiled	5	0.8	2.0	1.22	1.32

^aSubsoiled in 2015.

averaged across the 3 years. Over all years, the infiltration rate from the ring infiltrometer was more than double on the control and logged only plots (~5 mm min⁻¹) compared to the more disturbed plots (1–2 mm min⁻¹) (Table 4). Pre-experiment soil moisture measurements did not vary much between treatments (Table 4) or between years and treatments (Supporting Information). The minimum soil moisture was on the low slope plots (0.8%) and highest on the logged only plots (2.1%).

Mean bulk density varied among treatments at both depths measured on the hillslope plots. There were similar values by treatment at the 0–5 and 5–10 cm depths and lower bulk densities were measured on both the control and logged only plots (Table 4). These less disturbed plots had bulk densities around 1.15 g cm⁻³ at both depths. All other plots had some degree of disturbance from the skidder traffic which resulted in higher bulk densities ranging from 1.26–1.38 g cm⁻³ at 0–5 cm depth and 1.31–1.39 g cm⁻³ at 5–10 cm depth. The bulk densities were greater in the more disturbed plots than the undisturbed controls and logged only plots except for the drop and lop at the 0–5 cm depth (Table 4).

3.1.2 | Ground Cover

In the first post-fire year, the control, logged only and drop and lop treatments had 40% or greater organic cover, with litter and wood being the major cover categories. The many pass plots had the least organic ground cover (9%), and the few pass, many pass subsoiled, and the low slope plots all had between 13% and 23% cover (Figure 2)—the remainder of which was soil and gravel and classified as ‘erodible’. In the second post-fire year all plots except logged only had more cover than in Year 1, and in the third post-fire year all treatments had 30% or more vegetation cover. The high slope many pass plots still had ~50% cover in Year 3 which was significantly more than the controls, logged only, drop and lop and few pass plots.

The many pass low slope and subsoiled low slope plots were statistically analysed separately due to the potential effect of gradient between the different slope classes. Both many pass and subsoiled plots had low percentages (13%–22%) of organic cover in the first post-fire year which at least doubled in the second year. By the third year, total organic cover was 65%–80% and the live vegetation cover (50%–70%) was significantly greater than in the first or second year in the low slope plots.

3.2 | Rill Runoff and Sediment Delivery

3.2.1 | Logging Equipment Disturbance

Mean runoff rates in the first post-fire year were higher on the many pass, few pass, and drop and lop plots (30 L min⁻¹) compared to the control and logged only plots (21 L min⁻¹; Figure 3a), though none of the differences were significant because of within-treatment variability. This trend generally held for each year, with a slight decrease over time for each treatment, with the control plots decreasing from 21 to 20 L min⁻¹. The logged only plots had a significant decrease in mean runoff rate to 16 L min⁻¹ in Year 3. There was no difference in runoff rate between the few pass and drop and lop plots in any year, although there was a steady decrease over time for both treatments (30 to 26 L min⁻¹).

Runoff velocities were higher on the many pass and few pass plots (0.29 and 0.28 m s⁻¹, respectively) than the logged only plots (0.15 m s⁻¹) in the first post-fire year (0.15 m s⁻¹) (Figure 3a). Results were somewhat more consolidated in the second post-fire year, with velocities ranging from 0.12 to 0.21 m s⁻¹, with no differences among the treatments. In the third post-fire year, velocities continued to decrease, though not significantly, across treatments while largely maintaining the same order, with the least disturbed plots (control and

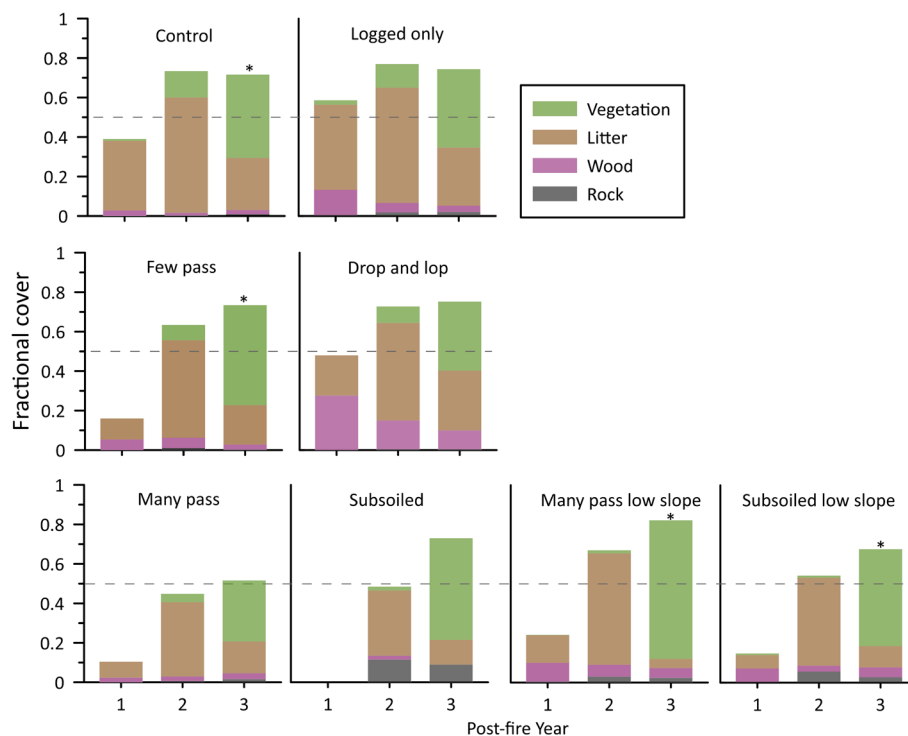


FIGURE 2 | Mean fractional cover by treatment and year. Less disturbed plots are in the top row; high slope few pass plots in the middle row; many pass and subsoiled high and low slope plots in the bottom row. The dashed line at 0.5 (50% cover) is a reference line for ease of interpretation among treatments. An asterisk indicates significantly more vegetation cover in the third post-fire year compared to the first ($p < 0.05$).

logged only) having the lowest velocity (0.08 ms^{-1}). Velocity on the few pass plots decreased from 0.28 to 0.20 ms^{-1} and by half (0.25 to 0.12 ms^{-1}) on the drop and lop plots over the 3 years, though there were no significant differences between treatments or among years (Figure 3b).

On the high slope plots in the first post-fire year, the many pass plots had higher sediment concentrations (31 g L^{-1}) than the less disturbed logged only or control plots (9.0 and 5.6 g L^{-1}) (Figure 3a). While still ~ 3 times higher than the other treatments, the sediment concentration on the many pass plots decreased significantly in the second post-fire year when there was no significant difference among the different treatments. By the third post-fire year, mean sediment concentration in the many pass plots was still at least twice as high as all other treatments. Sediment concentrations decreased across all treatments in all years, with the most significant decreases in the more disturbed plots in the second post-fire year, and lesser decreases in the third year. The decrease in sediment concentration over time was significant on the few pass and drop and lop plots (Figure 3b). Sediment concentration decreased from 19 in Year 1 to 3.3 in Year 2 then 2.0 g L^{-1} in Year 3 on the few pass plots, and 28 to 2.2 to 0.9 g L^{-1} on the drop and lop plots over the 3 years, respectively.

3.2.2 | Subsoiling Treatment

To assess the impact of subsoiling on many pass plots and investigate possible differences related to plot slopes, we evaluated the many pass high and low slope plots, with and without subsoiling separately (Figure 3c). The mean runoff rate decreased

from 30 to 27 L min^{-1} on the many pass high slope plots and from 28 to 24 L min^{-1} on the many pass low slope plots, with the subsoiled high and low slope plots also falling in this range. There were no significant differences in runoff rates between treatments or years.

Mean runoff velocities decreased significantly between Years 1 and 2 on the many pass plots (0.29 – 0.21 ms^{-1} ; Figure 3c) and nearly by half the original value (0.17 ms^{-1}) in Year 3, though the change from Year 2 to Year 3 was not significant. A similar pattern was observed on the many pass low slope plots with a significant decrease from 0.2 to 0.1 ms^{-1} between Years 1 and 3. The subsoiled plots fell within the ranges of their many pass slope class counterparts.

The sediment concentration from the many pass plots decreased significantly between Years 1 and 2 (31 – 12 g L^{-1}) and then non-significantly to 6 g L^{-1} in Year 3 (Figure 3c). Similarly, sediment concentrations from the many pass low slope plots decreased from 13 to 1.5 g L^{-1} between the first 2 years and to 0.3 g L^{-1} in Year 3. The low slope subsoiled plots showed the same trend between Years 1 and 2, and both the low and high slope subsoiled plots had sediment concentrations less than 0.5 g L^{-1} in Year 3.

4 | Discussion

Rilling can occur on hillslopes once surface runoff (sheetflow) concentrates (Bryan 2000) and can be the dominant soil erosion mechanism in areas burned at high severity (Moody and Martin 2001; Robichaud et al. 2010). Once formed, rills are an

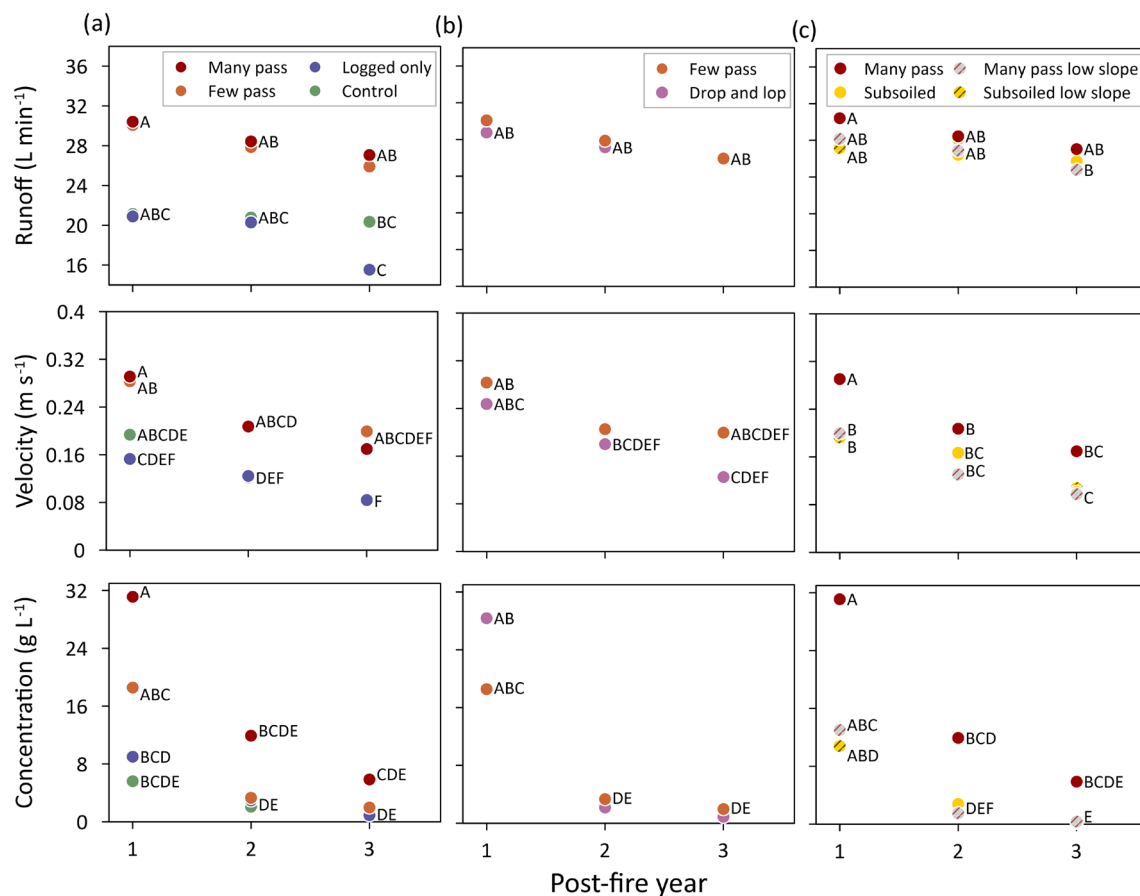


FIGURE 3 | Runoff and sediment delivery variables by treatment and year. Results are distributed among columns: (a) shows the impact of logging traffic with control, logged only, few pass and many pass plots; (b) shows the impact of adding logging slash by comparing drop and lop to few pass; and (c) shows the impact of slope and subsoiling by comparing high and low slope many pass plots, with and without subsoiling. Separate statistical comparisons were made among high slope treatments (columns a and b), and the many pass plus subsoil treatments which across slopes (column c). Different letters within a column represent significantly different means ($p < 0.05$) among treatment and post-fire year combinations.

important and efficient conduit for transporting eroded sediment to streams (Olsen et al. 2021). Rilling has also been attributed as one of the major mechanisms for post-fire debris flow initiation (e.g., Kean et al. 2019). Both the flow rates in rills and the upslope area needed to form rills depend on several factors, including the infiltration capacity of the soil, which itself depends on factors such as the parent material and disturbance condition, the rainfall or snowmelt rate, and the curvature along and perpendicular to the fall line of the hillslope (Moody and Kinner 2006).

4.1 | Drop and Lop Treatment

The sampling scheme of this study allowed for comparisons among multiple treatments, as well as across number of equipment passes and slopes. All treatments had an inherent paired treatment/control which are reflected in the organisation of Tables 3 and 4 as well as Figures 2 and 3. The drop and lop treatment was replicated on few pass skid trails and was designed to increase the ground cover and surface roughness across areas with some disturbance from heavy equipment. There was less bare soil and gravel in the drop and lop plots than on the paired few pass plots in the first post-fire year (Figure 2). However, there was no discernible difference in

cover between the drop and lop plots and the control or logged only plots in any year. Consequently, our implementation of this treatment did not provide a reduction in runoff rate, runoff velocity or sediment concentration relative to the few pass skid trails in any year or even compared to the many pass skid trails in the first post-fire year (Figure 3). Other studies have found that the presence of logging slash on skid trails decreased soil erosion (Wagenbrenner et al. 2015; Robichaud, Lewis, Brown, et al. 2020), and those results may have been a result of greater amounts of slash or even better contact between the slash and the soil. Robichaud, Lewis, Brown, et al. (2020) added logging slash to achieve at least 60% cover after a fire in eastern Washington and found the treatment to be effective at reducing sediment loss, while another study found 60%–80% slash cover was effective at reducing erosion after post-fire salvage logging in NW Spain (Fernández et al. 2021). We observed the rill path flowed under the slash in the drop and lop plot (Figure 4, left panel) and the slash did not appear to alter the flow path or otherwise increase flow path roughness which is the intended mechanism for reduced runoff velocity and sediment delivery potential. Drop and lop also is intended for application across hillslopes, where areas of heavy equipment traffic would be interspersed with areas of logging without traffic. These minor differences may affect the responses of the drop and lop treatment in a large scale implementation.

Several studies have related high post-fire sediment delivery rates to high proportions of exposed soil or gravel (Girona-García et al. 2021). Similarly, recent studies in areas affected by post-fire salvage logging have attributed lower sediment delivery rates at least partly to higher surface cover by litter or wood (Wagenbrenner et al. 2015, 2016; Prats et al. 2019, 2021; Cole et al. 2020; Olsen et al. 2021). In our study in the summer after salvage logging (first post-fire year), the logged only and drop and lop plots had at least 50% cover, which was largely litter and wood from the logging operation. These plots also had the highest ratio of organic cover to erodible cover (Figure 2), suggesting that litter and wood cover increased on the logged only plots as compared to the controls as an incidental part of the salvage logging operation, and resulted in similar wood and litter cover as the drop and lop plots after the addition of wood.

4.2 | Subsoiling Treatment

Statistically, our results were inconclusive in considering the effectiveness of the subsoiling treatment for reducing runoff or sediment delivery or increasing infiltration rates (Figure 3; Tables 3 and 4). The lack of statistical significance on the high slope plots can be attributed to variability in measured values between plots and years given the small number of subsoiled plots, as well as the fact that subsoiling on the two high slope plots had not yet occurred when we ran the experiments in the first post-fire year. From Figure 3, it is clear that time had a more significant impact on sediment concentration than treatment,

and both runoff rate and velocity decreased over time for all treatments and slopes. Missing the first year of subsoiled data in the high slope subsoiled plots made it impossible to say how the treatment may have impacted runoff characteristics in the first post-fire year. Still, we did observe some trends in the data based on mean values (Figure 3c). On the low slope subsoiled plots, the runoff rate and sediment concentrations were slightly lower than their paired many pass plots in the first post-fire year. There was an order of magnitude greater mean sediment concentration value on the high slope many pass plots compared to the subsoiled plots in the second and third post-fire years (Figure 3c). Although the mean runoff was high on the high slope subsoiled plots, indicating infiltration was not increased enough by subsoiling to affect runoff from the 4 m plot, the churned soil did not appear to promote sediment loss. The photo on the right in Figure 4 shows a typical low slope subsoiled plot. The soil surface was much rougher and rockier than the drop and lop plot shown in the left photo due to the subsoiling. There was 12% rock on the low slope subsoiled plots and 5% on the high slope subsoiled plots; neither number is large but compared with the 0%–1% present on all other treatments, this indicates the rock cover may have provided some armoring of the soil prior to being covered by litter or vegetation in Year 3. A study that directly compared how a similar amount of soil compaction (0.20 g cm^{-3} , or 25% greater bulk density) and surface cover from post-fire salvage logging affected runoff and sediment delivery showed that surface cover had a greater influence on both runoff rates and sediment delivery than soil compaction (Prats et al. 2021).



FIGURE 4 | The left panel shows the drop and lop treatment on a few pass skid trail after the rill experiment was completed. The wetted area is where the flow travelled down the skid trail and demonstrates the potential for incision that allows rills to pass under slash on the ground surface. The right panel shows the subsoiled treatment on a many pass low slope skid trail prior to the rill experiment. For reference, the flags are 1-m apart.

The infiltration rate on the low slope subsoiled plots was nearly 4× higher than the paired many pass plots (Table 3), but only in the first post-fire year. Furthermore, infiltration rates on the subsoiled plots were half of the control and logged only plots (2.6 mm min⁻¹ compared to 5 and 7 mm min⁻¹, respectively) in the first post-fire year. Soil bulk densities at both the 0–5 and 5–10 cm depths were uniform between the many pass and subsoiled pairs at both high and low slope sites (Table 4). Subsoiling increased infiltration for the first year and had a moderate effect on sediment loss in the high slope plots, but the drop and lop treatment, which increased cover without additional soil disturbance, was just as effective (Figure 3). Both mechanisms increase surface roughness, thereby decreasing velocity, but the drop and lop has the added benefit of cover which may hold soil in place and protect against raindrop impact under natural rainfall conditions (Prats et al. 2019, 2021; Wagenbrenner et al. 2015).

In all years, the subsoiled plots (both high and low slope) had statistically similar organic cover compared to their many pass counterparts (Figure 2). By the third year total organic cover was ~70% and there was 49%–52% vegetation cover on the subsoiled plots compared to 31% and 70% vegetation cover on the high and low slope many pass plots, respectively. We mentioned earlier that there was somewhat more rock (diameter > 75 mm) exposed on the subsoiled plots in the second post-fire year compared to any other treatment. In terms of cover alone, subsoiling did not appear to impact vegetation response.

4.3 | Slope Effects

Several studies have found that salvage logging on slopes greater than 20%–25% is prone to higher soil disturbance, rutting and increased bulk density as a measure of compaction (Naghidi et al. 2020; Labelle et al. 2022; Lewis et al. 2023). Given the experimental design and treatment distribution across the logging units, we were able to compare the many pass treatment and the subsoiling treatment across two slope classes. In the current study, there was no difference in runoff, but lower runoff velocity and sediment concentration on the low slope many pass plots as compared to the high slope plots (Figure 3). Given the lack of difference in the runoff rate, the differences in sediment concentration were probably related to the higher amounts of bare soil and higher velocities in the steeper plots. The 10% difference in slopes between these sites produced a three-times difference in sediment concentration in the first year and higher relative reductions in Years 2 and 3 (Figure 3c). Best management practises related to limiting impacts of post-fire salvage logging on steep slopes are generally targeted at slopes greater than the 20%–30% ‘high’ slopes in this study and results on steeper slopes would likely be different. Still, our results suggest that limiting equipment traffic to lower slopes would likely reduce sediment delivery and best management practises might be appropriate across a wider slope range than typical for skid trails in unburned forests.

4.4 | Logging Equipment Traffic Passes

There were no statistical differences in the soil bulk density, soil infiltration rate or the cover, runoff or sediment variables

between the many pass (> 6) and few pass (< 6) plots in any year (Figure 3a), suggesting similar impacts may occur with even a small amount of heavy equipment traffic (Wagenbrenner et al. 2016). In terms of sediment, in the first post-fire year the few pass plots had about half the sediment concentration as the many pass plots but more than twice the sediment concentration from the control plots. In the second and third post-fire years sediment concentration from the few pass plots was about the same as the control plots, while the many pass plots had relatively higher sediment concentration values. By the second and third post-fire years, the few pass plots had 38% and 28% bare soil and gravel, while the many pass plots had 57% and 50%, respectively. There was also more vegetation (51%) on the few pass plots than the many pass plots by the third year (31%). Despite the lack of differences among the many pass and few pass plots, these trends suggest a somewhat higher rate of vegetative recovery for the few pass plots, and this vegetation recovery likely helped further reduce the sediment concentration in the plots with less traffic.

Compounding soil disturbances (e.g., wildfire + logging traffic + subsoiling) have the potential to negatively impact soil and vegetation recovery (Cerise et al. 2013). There was significantly more bare soil and gravel on the many pass and subsoiled plots (54%–57%) compared to the control plots (28%) in the second year (Figure 2), and this result supports findings from a post-fire salvage logging study in southeastern Washington (Morgan et al. 2015). Our results also indicate more bare soil and gravel on the many pass plots (50%) compared to the few pass plots (30%) in Year 3. Despite a lack of significant differences, these results suggest increased logging traffic can negatively impact vegetation regrowth over multiple years.

4.5 | Vegetation Response

The rate of vegetation regrowth after the dual disturbance of fire and salvage logging can be site specific and dependent on the resilience of the site (Wagenbrenner et al. 2015; Knapp and Ritchie 2016). The additional soil disturbance of post-fire salvage logging has been found to influence species composition and, in some cases, increase the presence of undesirable or invasive species (Morgan et al. 2015; Leverkus et al. 2018). Malvar et al. (2017) found that soil erosion after salvage logging was positively related to rainfall intensity and negatively related to vegetation regrowth, more so than to the amount of disturbance caused by logging. Sediment loss decreased with time since disturbance, emphasising the importance of vegetation regrowth and the potential benefit of erosion mitigation measures such as cover augmentation by addition of wood or forest litter. We found the differences in vegetation over time as the recovery progressed were greater than the differences in vegetation across treatments (Figure 2). There was a significant increase in vegetation cover between the first and third years on all treatments except for logged only, while there was no difference in vegetation among treatments in any single year. The few pass, subsoil high and low slope, and the many pass low slope had ~50% vegetation cover by the third post-fire year which shows a positive vegetation response. Knapp and Ritchie (2016) had similar findings in a ponderosa pine forest in northeastern California, where bare ground decreased from

77% to 28% over 6 years but did not differ among treatments. Wagenbrenner et al. (2016) found that logging traffic impacted vegetation cover in Year 3, but not total organic cover. In this study, the vegetation growth coupled with the litter cover in the second and third post-fire years was partially responsible for the significant decrease in sediment loss over the same period (Figure 3).

4.6 | Comparisons to Similar Experiments

Several recent studies in the US and Canada used similar methods to assess runoff and sediment delivery responses in burned areas (Robichaud et al. 2010; Robichaud, Lewis, Brown, et al. 2020; Robichaud, Lewis, Wagenbrenner, et al. 2020; Wagenbrenner et al. 2016; Wagenbrenner and Robichaud 2011). We identified plots from these other experiments that generally matched the burn severity and slope of the Rim Fire plots and calculated the mean runoff ratio and sediment concentrations across treatments and post-fire years (Table 5). In this comparison, runoff ratio was the mean runoff rate for the plot divided by the mean inflow rate, as the inflow rates varied among the studies.

The runoff ratios in the current study declined over the first 3 years of the post-fire hydrologic recovery period (Figure 5a). Across the four treatments, the Rim Fire runoff ratios were generally higher than the comparable runoff ratios from the other sites. Differences in the experimental setup may have affected the runoff results, particularly the shorter plot length (4 m) at the Rim Fire and two other sites (Tower and North 25) as compared to the 9 m plot length at the other seven locations. The longer plot length provided greater opportunity for infiltration

as the runoff travelled down slope. All sites had runoff ratios that were much greater than those measured in unburned sites at Hayman (approximately 0.02, data not shown) (Robichaud, Lewis, Wagenbrenner, et al. 2020) or North 25 and Tower (combined runoff ratio 0.12) (Robichaud et al. 2010), which reflects the lost infiltration capacity in the burned or burned and compacted soils.

Like the runoff ratios, the mean sediment concentrations from the current study also decreased over time, suggesting the erosion rates declined as the soils recovered and fines were removed (Figure 5b). Unlike the runoff ratios, the sediment concentrations from the Rim Fire control plots were generally lower than the controls from the other sites. At first glance, this suggests the burned soils at the Rim Fire site were less erodible than the soils from the other sites. The high runoff ratios contributed to the low (diluted) sediment concentrations, as the sediment flux results from the Rim Fire sites were comparable to the other studies (Table S3). The first post-fire year sediment flux from the Rim Fire sites was 1.6 g s^{-1} , which was similar to the mean from the eight other sites with comparable data (1.7 g s^{-1}). The sediment concentrations from the wood-added (drop and lop), few pass and many pass plots were comparable to the concentrations from other sites across the western US. Given the higher runoff ratios at the Rim sites and assuming the soils are not source-limited (Rulli et al. 2006), this suggests the equipment traffic had a greater relative increase in total sediment delivery at the Rim Fire site than at the other sites.

Comparing the results across the 10 experimental sites allows us to put some additional context around the results from the current study. Generally, the Rim Fire plots had the highest

TABLE 5 | Number of plots and mean plot slope in % (in parentheses) of the current and previous rill simulation studies. Treatments varied across studies. Here, 'Control' plots are high burn severity with no other treatment; 'Few pass' has less than six passes from a skidder, feller buncher, or forwarder; 'Many pass' has six or more passes from a skidder or forwarder, except for Terrace Mountain, which has four or more; 'Wood' had wood added to the plot and includes the drop and lop treatment from this study (Rim). Plots were 9 m long except for Rim, Tower, and North 25, which were 4 m long.

Sites	Controls	Few pass	Many pass	Wood	Locations	Footnote references
Rim (2013)	5 (24)	5 (24)	5 (25)	5 (24)	California	This study
Tower (1996)	3 (25)		3 (26)		Oregon	^a
North 25 (1998)	3 (27)		3 (19)		Washington	^a
Hayman (2002)	8 (21)				Colorado	^b
Red Eagle (2006)	5 (41)	5 (40)	10 (37)	10 (38)	Montana	^c
School (2006)	5 (26)	5 (16)	5 (20)		Washington	^c
Tripod (2006)	5 (24)				Washington	^d
Columbia Complex (2007)	5 (22)				Washington	^d
Terrace Mountain (2009)	7 (43)		6 (27)		British Columbia	^c
North Star (2015)	7 (29)		7 (27)	7 (30)	Washington	^e

^aRobichaud et al. (2010).

^bRobichaud, Lewis, Wagenbrenner, et al. (2020).

^cWagenbrenner et al. (2016).

^dWagenbrenner and Robichaud (2011).

^eRobichaud, Lewis, Brown, et al. (2020).

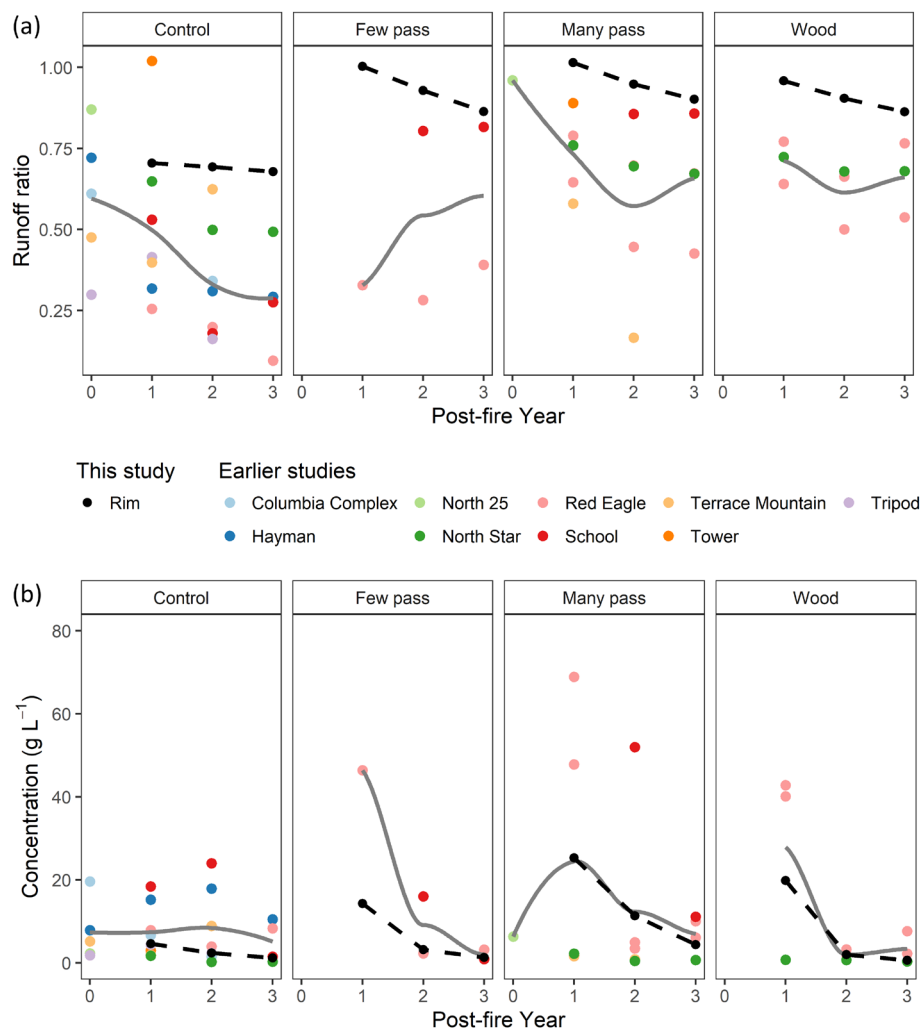


FIGURE 5 | (a) mean runoff ratio and (b) mean sediment concentration for rill experiments shown in Table 5. Solid lines in both panels show loess smooth fits to the non-Rim Fire sites and dashed lines show Rim Fire trends.

runoff ratios and among the lowest sediment concentrations of all the sites. Even with similar and highly controlled experiment methods across the sites, minor differences in implementation or soil conditions make drawing cross-site conclusions difficult. Still, these results help explain the high post-fire runoff and sediment delivery rates that have been measured around the western US (Moody and Martin 2009; Moody et al. 2013; McGuire et al. 2024).

4.7 | Management Implications

Recent work by the authors and others has shown that increasing ground cover can be an effective way to reduce sediment delivery following post-fire salvage logging (Robichaud, Lewis, Brown, et al. 2020; Wagenbrenner et al. 2023; Wagenbrenner et al. 2015; Prats et al. 2021). The drop and lop treatment did not reduce sediment delivery, and this result was probably due to the relatively low quantity of the cover added. Over all treatments and years, as litter accumulated and vegetation regrew, sediment concentrations decreased. This study adds to the growing understanding that post-fire erosion and downstream sediment delivery can be reduced when ground cover is added.

We also found that the subsoiling treatment had no real effect on sediment concentration. While there may be other justifications for subsoiling such as reducing competition during artificial regeneration or increasing infiltration rates in heavily compacted areas for a short period, subsoiling on the low slope class plots showed no benefit in reducing sediment delivery rates. Subsoiling on the high slope plots resulted in less sediment delivery in years two and three (Table S3), but there is also a greater risk of rill initiation following natural rainfall on steeper subsoiled hillslopes (Demirtas 2017). These results will help managers assess subsoiling as a treatment to mitigate potential erosion caused by the use of heavy equipment in burned areas.

There were no statistical differences in runoff or erosion rates between the many pass and low pass traffic levels in any year. However, the plots with fewer equipment passes allowed vegetation to recover more quickly, and vegetation and other organic soil cover increase surface roughness and can reduce erosion rates. Also, over all treatments and years, the control and logged only (no traffic) plots had the lowest runoff and sediment loss, confirming the correlation between soil disturbance and hydrologic impacts. These results suggest that minimising the extent of many pass skid trails may reduce the sediment delivery

following salvage logging within a watershed. Arranging skid trail networks in post-fire salvage logging units such that less-disturbed areas are interspersed and occur downslope of many pass skid trails may also reduce sediment delivery to the stream network (Olsen et al. 2021; Wagenbrenner et al. 2023). Fewer sediment impacts of salvage logging were seen on the lower slope plots compared to the high slope plots, which also suggests that choosing harvest methods that minimise traffic on steep slopes may reduce sediment delivery.

4.8 | End-User Tools

These data are also valuable for future development of predictive modelling tools to inform post-fire land management decisions. Similar experiments served as the foundation for earlier erosion modelling efforts (Elliot 2004; Nearing et al. 2011; Robichaud et al. 2007). The data from this study could be used to develop erosion modelling parameters (as in Dobre et al. 2022; Lew et al. 2022; Wagenbrenner et al. 2010) for post-fire salvage logging. Such model development would allow subsequent extrapolation of our results to different locations, soil and runoff conditions, and scales within the limitations of the modelling framework. Our controlled quantification of the runoff and sediment delivery effects of post-fire salvage logging and subsequent treatments like subsoiling and surface cover manipulation will facilitate modelling and evaluation of the effects of post-fire salvage logging and mitigation practises to support management objectives in burned forests.

4.9 | Limitations

In other studies, we observed evidence of rill formation in burned areas ranging from a few (<10) to hundreds of square metres (Wagenbrenner and Robichaud 2014; Olsen et al. 2021). The results from the current study focused on the relative responses among different soil conditions and mitigation treatments when a standardised set of runoff conditions were applied. We are confident in the extrapolation of the results about relative performance of the treatments to other settings and conditions, especially at spatial scales where rill formation may be important. An example would be comparing the relative sediment concentrations in runoff generated from skid trails to help select erosion mitigation treatments for a future post-fire salvage logging operation in another part of the Sierra Nevada. However, like most simulated runoff studies, application in absolute terms outside of our tightly controlled experimental methods, conditions and setting should only be done after thorough consideration of the target conditions in question.

5 | Conclusion

We ran comprehensive rill simulation experiments for 3 years after the 2013 Rim Fire and subsequent post-fire salvage logging, with and without treatments intended to reduce downstream sediment delivery. The results presented here improve our understanding of the effects of salvage logging, as well as post-salvage mitigation measures, on soil and water resources

and will allow managers to make informed decisions about implementing the drop and lop treatment or subsoiling along skid trails in future post-fire logging projects.

Overall, runoff and sediment delivery responses fell into two groups: responses in unlogged controls and logged only areas that had no heavy equipment traffic were generally lower than responses in plots impacted by heavy equipment traffic (few pass and many pass) even when mitigation treatments (subsoiling or drop and lop) were applied, though the differences between the groups were not always significant.

Infiltration rates in the burned area were reduced by logging equipment traffic due to compaction despite concomitant decreases in soil water repellency. Logging activities on steep slopes increased sediment delivery rates more than traffic on lower slopes. Compared to the many pass skid trails where subsoiling was applied, subsoiling increased infiltration in the first year but did not reduce runoff or sediment delivery. The drop and lop treatment did not reduce runoff velocities or sediment concentrations as expected, likely due to relatively low amounts of wood cover and the spatial arrangement of the hand-application of the wood.

Runoff and sediment delivery rates decreased over time on all sites as they recovered and vegetation regrew. Runoff ratios in all treatments were higher at the Rim Fire than in other sites with comparable plot conditions where similar experiments were conducted, while the sediment concentrations were lower or comparable to other sites. Reducing the extent of heavy equipment traffic during salvage logging would likely reduce sediment delivery rates. These findings will be useful in developing comparative modelling tools and in selecting mitigation strategies to reduce sediment delivery rates following post-fire salvage logging.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Infiltration and soil characteristics by year and treatment. WDPT is the median water drop penetration time test at 1 cm depth or 3 cm depth; Soil moisture was collected before wetting; Infiltration is the mean steady state value from the ring infiltrometer; Bulk density was measured at 0–5 cm and 5–10 cm depth and the means are reported. Less disturbed control and logged only plots are shaded. Different superscript letters within a measurement and depth (e.g., WDPT 1 cm across the 3 years) are significantly different at $p < 0.05$. High slope and low slope plots were evaluated separately and there were no significant differences among the low slope plots. **Table S2:** Soil fractional cover by treatment and year. Low slope plots were evaluated separately; different letters between treatments above and below the line indicate significantly different values ($p < 0.05$). **Table S3:** Rill runoff variables; mean values of each are shown by treatment and year. The table is organised by treatment pairs reflective of Figure 3. **Table S4:** Rill dimensions variables. Treatments are paired. In each rill, width and depth of flow were measured at 1 and 3 m downslope from the release point. The combined width and average depth of all rills at each downslope location were calculated and then averaged across the two locations for each flow rate. Different letters between treatments between each shaded section indicate significantly different values ($p < 0.05$)