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WILDFIRE AND HYDROLOGICAL PROCESSES

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Compaction and cover effects on runoff and erosion in post-fire salvage logged areas in the Valley Fire, California

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Abstract

Runoff and erosion processes can increase after wildfire and post-fire salvage logging, but little is known about the specific effects of soil compaction and surface cover after post-fire salvage logging activities on these processes. We carried out rainfall simulations after a high-severity wildfire and post-fire salvage logging to assess the effect of compaction (uncompacted or compacted by skid traffic during post-fire salvage logging) and surface cover (bare or covered with logging slash). Runoff after 71 mm of rainfall across two 30-min simulations was similar for the bare plots regardless of the compaction status (mean 33 mm). In comparison, runoff in the slash-covered plots averaged only 22 mm. Rainsplash in the downslope direction averaged 30 g for the bare plots across compaction levels and decreased significantly by 70% on the slash-covered plots. Sediment yield totalled 460 and 818 g m^{-2} for the uncompacted and compacted bare plots, respectively, and slash significantly reduced these amounts by an average rate of 71%. Our results showed that soil erosion was still high two years after the high severity burning and the effect of soil compaction nearly doubled soil erosion via nonsignificant increases in runoff and sediment concentration. Antecedent soil moisture (dry or wet) was the dominant factor controlling runoff, while surface cover was the dominant factor for rainsplash and sediment yield. Saturated hydraulic conductivity and interrill erodibility calculated from these rainfall simulations confirmed previous laboratory research and will support hydrologic and erosion modelling efforts related to wildfire and post-fire salvage logging. Covering the soil with slash mitigated runoff and significantly reduced soil erosion, demonstrating the potential of this practise to reduce sediment yield and soil degradation from burned and logged areas.

KEYWORDS
post-fire management, rainfall simulation, skid trail, soil compaction, soil erodibility, wildfire

1 | INTRODUCTION

Wildfires can greatly enhance the hydrological and erosive responses from forested mountainous areas (Johansen et al., 2001; Robichaud, 2000; Shakesby, 2011). The removal of the protective vegetation and litter cover as well as the heat-induced changes in soil properties, such as increased soil water repellency (Pierson et al., 2001), loss of soil organic matter (OM) and structure (De la Rosa et al., 2019; García-Orenes et al., 2017; Jiménez-Morillo et al., 2020), and changes in aggregate stability (Campo et al., 2008) are key factors in fire-induced runoff and soil losses (Badía & Martí, 2008; Benavides-Solorio & MacDonald, 2001). Beside wildfires, post-fire management such as the passage of heavy machinery during salvage logging of burned timber can have negative effects. The most important factors related to post-fire salvage logging are the compaction of soils (Croke et al., 2001; García-Orenes et al., 2017; Wagenbrenner et al., 2015) and loss of soil surface cover (Cole et al., 2020; García-Orenes et al., 2017; Lucas-Borja et al., 2019; Olsen et al., 2020; Wagenbrenner et al., 2015). Post-fire soil compaction has been associated with an increase in runoff and erosion (Malvar et al., 2017; Wagenbrenner et al., 2015), although opposite results have also been measured (James & Krumland, 2018).

Until recently there has been little research on the cumulative impact of compaction from logging equipment on burned soils. More information is available regarding soil compaction in unburned forests, especially related to unpaved roads, and we can use this body of research to help assess the potential impacts of compaction of burned soils on runoff generation and erosion. Although the network of forest roads—including skid trails, haul roads and landings—can constitute between 10% and 24% of the forest surface (Han et al., 2009; Kolka & Smidt, 2004; Olsen et al., 2020), it contributes to a large portion of basin-runoff and erosion, even in unburned forestland (Arnáez et al., 2004; Jordán et al., 2009; Sheridan et al., 2008). Forest roads with regular traffic and maintenance strongly reduce infiltration on the running surface through compaction, increase erosion by replenishing the supply of sediment, and hamper the establishment of vegetative cover (Foltz et al., 2009). Natural recovery of soil properties on closed forest roads is usually slow and can take decades, especially for bulk density and infiltration (Wert & Thomas, 1981).

Increasing ground cover is an effective method for mitigating soil erosion from a variety of scenarios such as burned areas (Badía & Martí, 2000, 2008; Prats, Gonzalez-Pelayo, et al., 2019), agriculture lands (Jordán et al., 2010) and forest roads (Sosa-Pérez & MacDonald, 2017). Mulch and other types of ground cover may influence the hydrologic and erosive responses, and mulch has been shown to influence modelling parameters such as saturated hydraulic conductivity (Ks) and interrill erodibility (Ki) (Foltz et al., 2009; Smets et al., 2008; Sosa-Pérez & MacDonald, 2017). However, the mechanisms affecting mulch effectiveness are not totally understood. In the complex case of post-fire salvage logging, some efforts have been made to mitigate the erosion response by adding slash or mulch (Fernandez & Vega, 2016; Wagenbrenner et al., 2015), but the results were not always consistent (Prats, Malvar, et al., 2019; Wagenbrenner et al., 2016). Three field studies indicate that slash can be effective at reducing rainsplash but not rilling (Fernandez & Vega, 2016; Wagenbrenner et al., 2015, 2016), and other studies indicate that the influence on rills might be improved if the slash had more contact with the soil surface (Han et al., 2009; Robichaud, Lewis, Brown, et al., 2020). Previous research isolating hydrologic (runoff, leaching, soil moisture) and erosive processes (splash, interrill and rill erosion) allowed the assessment of the performance of two types of cover and two levels of compaction under laboratory conditions (Prats, Malvar, et al., 2019). Shredded sequoia bark mulch significantly reduced rainsplash, interrill and rill erosion in uncompacted and compacted soils, whereas pine logging slash was less effective, despite its similar cover rate (60%). However, the application of slash to burned compacted soils deserves further research for several reasons: (1) it is immediately available in burnt forests in sufficient quantities to treat large surface areas, (2) it does not introduce invasive species, and (3) it can be a by-product of post-fire salvage logging and can be applied using log skidding equipment (Robichaud, Lewis, Brown, et al., 2020).

This study is the second of a two-part experiment whose main aim was to evaluate the effects of compaction and ground cover on post-fire hydrology and erosion. We designed this field study to validate a relationship found in the laboratory (Prats, Malvar, et al., 2019) with in-situ soils that were burned and later compacted by equipment in a post-fire salvage logging operation. The specific objectives of the present study were to: (1) determine the effects of soil compaction by machinery used for post-fire salvage logging on selected soil properties (bulk density, soil resistance, organic matter, aggregate stability, water repellency, cover and roughness); (2) determine the effects of soil compaction in the hydrologic (runoff, infiltration, soil moisture, runoff timing, Ks) and erosion variables (rainsplash, interrill erosion, Ki); (3) determine the effects of pine slash cover on the same variables; and (4) compare laboratory and field rainfall simulations for their ability to reproduce similar results.

2 | MATERIALS AND METHODS

2.1 | Site description

The study was conducted in the Boggs Mountain Demonstration State Forest (BMDSF), located in north-central California (38.81443° N, 122.67339° W). Precipitation and air temperature at BMDSF average 1400 mm and 12.2°C (PRISM, 2020). Vegetation is described as a Mediterranean California dry-mesic mixed conifer forest and woodland, with ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), sugar pine (*Pinus lambertiana* Douglas), manzanita (*Arctostaphylos* spp.), and oaks (*Quercus* spp.) (US-GAP, 2011). The soils are deep, well drained, have frequent lapilli (small, approximately spherical gravel formed from andesite rocks) and exhibit andic soil properties (Edinger-Marshall & Obeidy, 2016). The soil corresponds to the Whispering series loamy-skeletal, mixed, mesic, Ultic Haploxeralfs (Soil Survey Staff, 2016). Surface soil textures (0–5 cm) are gravelly to very gravelly sandy loams. Stones larger than 8 mm diameter constitute 15.4% of the Ah topsoil horizon, gravel (2–8 mm) is 19.8%, sand is 47.2% and silt and clay make up 17.6%. Clay content increases with increasing depth (Edinger-Marshall & Obeidy, 2016). Soil OM is very high, even after the high severity fire (0.13 g g^{-1}; loss-on-ignition 500°C for 4 hr).

The BMDSF was almost entirely burnt by the Valley Fire, which started 12 September 2015 and burned 30 000 ha (Figure 1). A northeast-aspect hillslope was selected for its high severity according to burned area reflectance (CAL FIRE, 2015; White et al., 1996) and field site inspection (Parson et al. (2010) and post-fire salvage logging history. The elevation of the site is 1100 m.a.s.l. and slope steepness 15–20°. The study site was salvage logged in September–October 2016. Trees were felled by chainsaws and skidded to landings by a Caterpillar 525B rubber-tired, grappled skidder (approximate weight

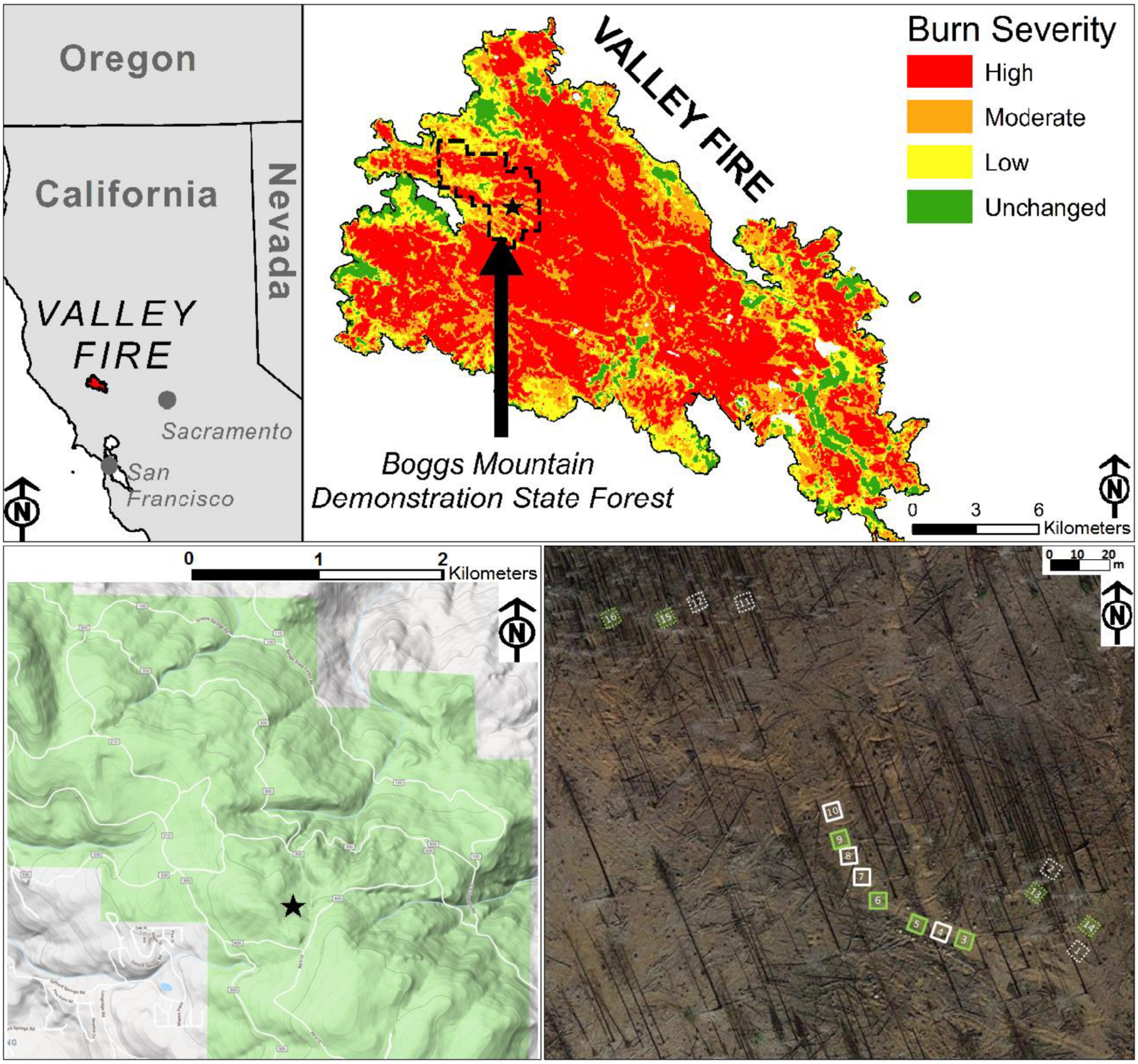

FIGURE 1 Top: Location of the 2015 Valley Fire and Boggs Mountain Demonstration Site Forest (BMDSF) in California. Bottom: Study site for the 16 rainfall simulations within the BMDSF (green shading). White and green-shaded squares in lower right panel correspond to bare and slash-covered plots, respectively, and dashed or bold lines correspond to uncompacted and compacted plots, respectively

16.2 Mg). The most-used skid trail (≈20 passes) was selected for simulations. The skid trail had an average width of 5 m, with two more-compacted wheel tracks, or shallow ruts, and a compacted centre between the ruts. Unlogged, uncompacted areas were also selected in the same site with similar burn severity, soils, slopes and aspects, such that any observed differences could be attributed solely to the compaction (Figure 1).

2.2 | Plot preparation and field measurements

A total of 16 plot frames were installed three days before the simulations, which were done 8–16 June 2017. Eight plots were installed in the uncompacted area (four each in two locations) and eight in the compacted area (four on the ruts and four between ruts) (Figure 1). Half of the plots in each compaction group were randomly selected to be covered with slash. The steel square plot frames of 70 × 70 cm (0.49 m^2) and 15 cm height were carefully hammered into the soil to a depth of 5–10 cm, and inside borders were filled with a bentonite-soil mixture in order to minimise edge effects. The downslope edge of the plot frame consisted of a lip connected to a detachable gutter where surface runoff was funnelled to a hose for collection (Robichaud et al., 2016). Installation of the plots on the skid trails was extremely difficult due to soil compaction. Specific locations were abandoned if the plot frames could not be inserted at least 5 cm into the soil, and all the plots in the compacted areas needed several tries in order to attain the installation described.

A short (5.5 cm long) soil moisture sensor (ECH2O 5-TM sensor, Meter Group, Pullman, WA, USA) was installed at 3 cm depth in a precut hole on the lower left corner of the metal plot frame. A handheld read-out device stored soil moisture every minute through the simulation and for 5 min after the rainfall stopped. Soil moisture in some of the compacted plots (2 bare and 2 slash) was not monitored due to the strong soil compaction which prevented proper sensor installation. Soil moisture, soil bulk density, and soil OM were measured on samples obtained with a bulk density core sampler (5 cm diameter × 5 cm height). The soil moisture and bulk density samples were gathered at 0–5 and 5–10 cm depths adjacent to each plot before the rainfall simulations and within each plot after the rainfall simulations. Soil OM samples were collected adjacent to the plots after the simulations. All samples were oven-dried at 105°C for 24 hr (ASTM, 2007) and the OM (0–5 cm) samples were incinerated to determine soil OM (loss-on-ignition; 500°C for 4 hr). Plot roughness was measured before treatment application with a 1-cm, 1-m long roller chain (Saleh, 1993) in three downslope lines (center, left and right sides). Plot roughness was the average difference (in cm) between the chain carefully placed on the soil surface following the depressions along the plot and the plot length (≈70 cm) measured using a ruler.

Eight horizontal transects were set out in June 2017 to further characterise the soils near the plot frames. Each transect consisted of 18 points at 0.5 m intervals, generally with nine points upslope and nine points downslope of the groups of plot frames. At each point we measured: (1) soil resistance (Kg cm^{-2}) at the soil surface with a hand penetrometer (Gilson Company, Inc., Lewis Center, OH, USA); (2) soil water repellency at the soil surface, 1 and 3 cm depths using the Water Drop Penetration Time test (WDPT), where 10 or more drops of water were placed on the soil and the seconds for the drops to infiltrate were measured (Letey et al., 2000); (3) soil moisture at 0–5 cm depth with the handheld ECH2O soil moisture sensor; and d) soil aggregate stability at the soil surface and 1 cm depth, by assigning a soil stability class (1–3, very unstable; to class 6, 75%–100% stable sample) by field observation of slaking time during immersion of soil samples in distilled water (Herrick et al., 2001).

Ground cover was described with the point-intersect method on a 5 cm grid at 100 points on each plot, prior to the rainfall simulations. We used the following cover categories: slash, the applied woody material; litter, mainly composed of leaves; herbs; moss; lapilli, small spherical gravel <2–6 mm which are frequent in this andesite-derived soil; stones, >6 mm and bare soil. Herb cover was very low (average ± standard deviation: 2 ± 2%) and aerial parts were cut from all the plots prior to measurement to avoid bias in the experimental design. Ground cover was the sum of all cover categories except bare soil. The logging slash was gathered from the site and was composed of stems and branches of ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) (diameter: 2.2 ± 0.8 cm; length: 39.7 ± 14.9 cm; n = 120). Slash was oven-dried (105°C, 24 hr) and applied by hand at a rate of 40 Mg ha^{-1} to each slash-treated plot. Actual slash cover was measured with point-counts on a 5 cm grid, and material was added or removed to achieve the nominal target of 60% slash cover (Table 1).

2.3 | Rainfall simulations

Each simulation was composed of two parts of 30 min rainfall (Dry and Wet runs), interrupted for approximately 1 hr, in order to test the responses of the treatments under different antecedent soil moisture. A portable Purdue-type rainfall simulator was covered with a wind-shelter and set at 3 m above the plot with three telescopic legs (Figure 2). The simulator head (about 10 Kg) contained a single Veejet 80 pressurised nozzle mounted on an oscillating-arm driven by a small electric motor controlled by a solenoid. The simulator was designed and fabricated at the USDA Forest Service Rocky Mountain Research Station. A water pressure of 55 kPa produced an initial drop velocity of approximately 8.8 m s^{-1} and an impact kinetic energy of 271 kJ ha^{-1} mm^{-1} (Paige et al., 2003). Prior to each run, the rainfall was collected in a calibration pan covering the plot and measured with a portable scale. The water pressure to the nozzle was adjusted as needed based on the calibrations to meet the target rainfall rate. After adjusting the rainfall rate to the plot projected horizontal area, we achieved a rainfall intensity of 71.4 ± 2.6 mm h^{-1}. This rate represents

TABLE 1 Plot, treatment and rainfall characteristics for the rainfall simulations carried out in un/compacted and bare/slash-covered soils

Compaction	Uncompacted		Compacted	
Cover	Bare	Slash	Bare	Slash
Plot properties				
Slope (°)	19.6 ± 3.5a	17.1 ± 2.7a	14.8 ± 2.3a	15.8 ± 3.1a
Plot projected area (m^2)	0.46 ± 0.01a	0.47 ± 0.01a	0.47 ± 0.01a	0.47 ± 0.01a
Treatment characteristics				
Slash application rate (Mg ha^{-1})	0 ± 0b	39.7 ± 2.9a	0 ± 0b	41.1 ± 3.5a
Slash cover (%)	0 ± 0b	61.3 ± 3.8a	0 ± 0b	60.3 ± 2.7a
Rainfall characteristics				
Rainfall intensity $_{Dry}$ (mm h^{-1})	73.3 ± 2.4a	71.3 ± 1.6a	71.1 ± 1.7a	72.3 ± 2.7a
Rainfall intensity $_{Wet}$ (mm h^{-1})	69.4 ± 2a	72.3 ± 2.2a	69.5 ± 2.3a	71.6 ± 4.6a

Note: Total plot cover includes stones, lapilli, litter and slash. Values are means ± one standard deviation. Different letters within a row correspond to significant differences between treatments (p ≤ .05). There were four replicates per compaction-cover combination.

FIGURE 2 (a) Portable rainfall simulator assembled over one plot on the skid trail, with wind-shelter in place and (b) detail of a compacted and slash-covered plot and the splash-collecting system. The gutter is located 3 cm below the splash fabric

a 100-year, 30-min return interval rainfall intensity at BMDSF (Perica et al., 2011). This rainfall intensity assured surface runoff in all the treatments (Foltz et al., 2009), and was in the range of other post-fire rainfall simulation studies (Robichaud et al., 2016).

Rainfall splashed material was collected along the downslope end of the plot for each Dry and Wet run. Oven-dried and pre-weighed fabric pieces were secured to the plot frame forming a splash collector (Prats, Malvar, et al., 2019). The porous geotextile fabric collected rain splashed material larger than the 0.21 mm opening sizes, while surface runoff passed through the fabric and down to the gutter (Figure 2).

The runoff start time was the time when runoff exceeded one drop per 3 s coming from the collection hose while runoff stop time was the time when runoff rate fell below one drop per 3 s. Timed runoff samples were collected in separate pre-labelled and pre-weighed bottles each minute during the period between the runoff start and stop times. After each simulation (Dry and Wet runs), the splash fabric and the sediment deposited in the gutter were removed and stored in separated pans. All runoff samples, splash fabrics, and sediment deposited in the gutter were oven-dried (105°C, 24 hr) and weighed to obtain runoff volume (mm), splash material (g), and dry sediment deposited in the gutter (g). Runoff coefficient was the runoff volume divided by the applied rainfall volume. The deposited sediments were integrated to each runoff sample and combined with the sample-sediment to make up sediment concentration (g L^{-1}) and total sediment yield (g m^{-2}) for each run. Runoff and sediment dry weights were divided by the horizontal projection of the plot area to produce unit-area runoff and sediment yields, respectively.

Saturated hydraulic conductivity (Ks, mm h^{-1}) was determined from the Wet run, as saturated conditions were a requirement for estimation of Ks (Foltz et al., 2009). The calculated Ks was estimated as the rainfall rate minus the average runoff rate over the five minutes prior to the end of rainfall. Interrill erodibility (Ki, kg s m^{-4}) was calculated from the Dry runs, as it represented the most erodible soil condition, following the equation:

$$K_\mathrm{i} = \frac{D_i}{IQ} \tag{1}$$

where D_i was the mean sediment yield rate for the Dry run runoff period (kg m^{-2} s^{-1}), I was the rainfall intensity (m s^{-1}), and Q was the mean runoff rate for the Dry run period (m s^{-1}) (Fangmeier et al., 2006).

2.4 | Statistical analysis

Statistical analyses were performed on the hydrologic and erosive response variables and on the independent variables listed in Tables 1 and 2. Three-way mixed-effects models (Littell et al., 2006) were constructed on the response variables with fixed effects of compaction (uncompacted or compacted), cover (bare or slash) and run (Dry or Wet) and plot as the random effect. Only three response variables (runoff start time, runoff end time and rainsplash) were 4th root transformed to achieve normally distributed model residuals. Variance components or autoregressive variance–covariance structures of the

TABLE 2 Soil properties assessed before slash application and rainfall simulations for un/compacted and bare/slash-covered soils

Compaction		Uncompacted		Compacted	
Cover	*n*	Bare	Slash	Bare	Slash
Bulk density $_{0–5\ cm}$ (g cm^{-3})	32	0.79 ± 0.06b	0.77 ± 0.04b	0.98 ± 0.05a	0.98 ± 0.04a
Bulk density $_{5–10\ cm}$ (g cm^{-3})	16	0.82 ± 0.04b	0.73 ± 0.07b	1.01 ± 0.11a	1 ± 0.07a
Plot roughness (cm)	16	3.5 ± 0.7a	2.6 ± 0.8a	2.4 ± 1a	3.1 ± 1.4a
Soil resistance (Kg cm^{-2})	144	1.4 ± 0.7b	1.1 ± 0.7b	5.2 ± 1.8a	6.2 ± 2.7a
WDPT $_{surface}$ (s)	126	0 ± 0a	0 ± 0a	0 ± 0a	0 ± 1a
WDPT $_{1\ cm}$ (s)	126	1 ± 5a	2 ± 5a	0 ± 0b	0 ± 0b
WDPT $_{3\ cm}$ (s)	126	17 ± 67a	43 ± 250a	0 ± 0b	0 ± 0b
Aggregate st. $_{surface}$ (class)	144	3.8 ± 1.6a	3.9 ± 1.8a	2.2 ± 1.6b	1.6 ± 1b
Aggregate st. $_{1\ cm}$ (class)	144	5.5 ± 1a	5.3 ± 1.3a	2.3 ± 1.3b	2.1 ± 1.2b
Soil OM $_{0–5\ cm}$ (g g^{-1})	15	0.14 ± 0.02a	–	0.13 ± 0.01a	–

Note: Values are means ± one standard deviation. Different letters within a row corresponded to significant differences ($p \le .05$) between treatments.

measurements were selected for each variable according to the smallest value of the restricted maximum likelihood criteria (Littell et al., 2006). Pre-simulation independent variables were evaluated for consistency of initial soil conditions using one- or two-way mixed models similar to the ones for the response variables. All interactions among factors were considered. The Tukey method was used for all pairwise comparisons. Results were reported using an $\alpha = 0.05$ level of significance. All statistical analyses were carried out using SAS version 9.3 (SAS Institute, 2016).

3 | RESULTS

3.1 | Soil properties and ground cover

Bulk density at 0–5 cm soil depth averaged 0.78 g cm^{-3} in the uncompacted treatments and 0.98 g cm^{-3} in the compacted ones, indicating a significant, 25% increase in bulk density from the skidder traffic (Table 2). At 5–10 cm soil depth, the increase in bulk density due to skidder traffic was 30% and also significant. There were no differences in bulk density between the compacted plots installed in the ruts or between ruts at either depth, and no distinction is made between these two plot conditions in subsequent results. Also, because the soil properties were measured before the slash was applied, there were no differences in soil properties between the slash-covered and bare plots.

The roughness in the compacted plots was 10% lower than the uncompacted plots. Skidder activity increased the soil resistance to penetration in the compacted soils (Table 2). Soil water repellency (WDPT) was generally low in all plots and depths (treatment averages 0–43 s). WDPT did not differ among treatments at the soil surface but it was significantly lower in the compacted plots than the uncompacted at both 1 and 3 cm soil depths. Aggregate stability was significantly higher in the uncompacted plots (3.8–5.3) and decreased by 40%–50% at both the soil surface and 1 cm soil depth as a result of compaction. Soil OM was similar among treatments (0.14–-0.13 g g^{-1}; Table 2).

The amount of stones, moss and litter cover was 18% for the uncompacted bare and compacted bare plots (Figure 3). Moss cover was only present in the uncompacted plots and averaged no more than 4%. Stones and especially lapilli cover were responsible for the higher total ground cover on the compacted plots (49%) as compared to the uncompacted plots (32%). After covering half of the plots with slash, the mean total ground cover was 74% on the uncompacted slash plots and 79% on the compacted slash plots.

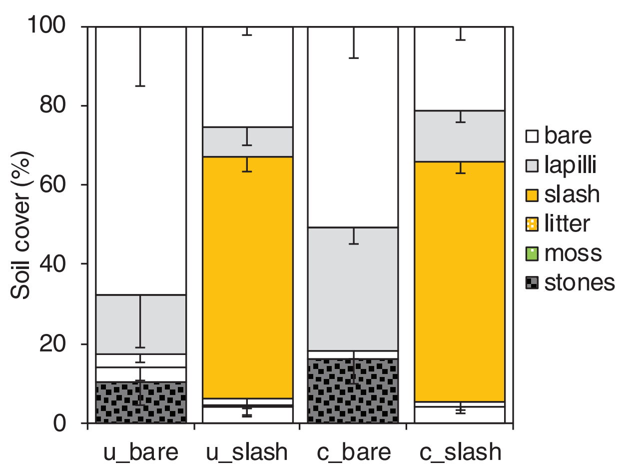

FIGURE 3 Mean soil cover for the four treatments. Cover categories included: added slash, litter (mainly leaves and small roots), mosses and two stone categories: lapilli (small spherical gravel <6 mm diameter) and stones (>6 mm). Vegetation was trimmed from the plots before measurements occurred. Upward error bars (one standard deviation) were removed for clarity. u, uncompacted; c, compacted; bare, bare soil; slash, 60% slash cover added

3.2 | Rainfall simulation results

3.2.1 | Hydrologic results

Runoff in the Dry simulations started after 134–225 s without differences among treatments (Table 3). The onset of runoff was somewhat delayed on the slash plots (191–225 s). Runoff start times consistently and significantly decreased for the Wet runs, with no differences among treatments (Figure 4). Runoff ended, on average 150 s after the rainfall stopped, without differences among treatments or runs (Table 3).

Runoff coefficients during the Dry run were similar between compaction conditions, although somewhat higher on the compacted plots than the uncompacted plots (Figure 4). The responses differed for the wet runs, where the runoff rates in the uncompacted plots decreased at the end of the wet run whereas the runoff rates in the compacted plots continued increasing through the end of the wet run. The runoff coefficients on the slash-covered treatments followed the same patterns as the bare plots, but with lower magnitudes.

The combined runoff for the uncompacted bare plots during the Dry and Wet runs represented 38% of rainfall. In comparison, the combined runoff on the uncompacted slash plots was 18% of the rainfall. Runoff amount only differed significantly for the uncompacted slash (13 mm) as compared to the compacted bare treatment (39 mm; Table 3), and this difference occurred in the Wet run and the combined total.

The initial soil moisture from the 0–5 cm depth core samples did not vary among treatments and was 11% on average (Table 3). After the Dry and Wet runs, soil moisture significantly increased by factor of 2.5 to 4.2 for all treatments. Soil moisture at the 0–5 cm depth in

TABLE 3 Hydrologic and erosive responses for the uncompacted and compacted treatments

Compaction	Uncompacted		Compacted	
Cover	Bare	Slash	Bare	Slash
Runoff start time (s)				
Dry	134 ± 70a	225 ± 53a	173 ± 74a	191 ± 206a
Wet	74 ± 38a	96 ± 5a	65 ± 12a	62 ± 31a
Mean	104 ± 52a	160 ± 28a	119 ± 43a	127 ± 3a
Runoff end time (s)				
Dry	128 ± 24a	108 ± 30a	149 ± 47a	144 ± 39a
Wet	129 ± 19a	122 ± 31a	214 ± 74a	207 ± 59a
Mean	129 ± 20a	115 ± 30a	181 ± 60a	175 ± 118a
Runoff (mm)				
Dry	12 ± 4a	5 ± 1a	14 ± 3a	9 ± 2a
Wet	15 ± 2ab	8 ± 2b	24 ± 5a	20 ± 3ab
Total	27 ± 5ab	13 ± 3b	39 ± 7a	30 ± 4ab
Soil moisture (% vol.)				
Pre-dry $_{0\text{-}5cm}$	13 ± 2a	10 ± 2a	11 ± 4a	9 ± 2a
Post-wet $_{0\text{-}5cm}$	33 ± 2b	42 ± 2a	29 ± 4b	31 ± 2b
Post-wet $_{5\text{-}10cm}$	38 ± 6ab	45 ± 5a	33 ± 3b	32 ± 2b
Splash (g)				
Dry	17 ± 8a	4 ± 2b	16 ± 9a	3 ± 1b
Wet	13 ± 4a	2 ± 0b	13 ± 5a	2 ± 1b
Total	30 ± 8a	6 ± 2b	29 ± 14a	5 ± 2b
Sediment concentration (g L^{-1})				
Dry	19 ± 5a	14 ± 7a	21 ± 12a	13 ± 5a
Wet	16 ± 3a	7 ± 4a	22 ± 4a	7 ± 2a
Mean	17 ± 3ab	9 ± 5b	22 ± 7a	9 ± 3b
Sediment yield (g m^{-2})				
Dry	216 ± 59ab	69 ± 36b	289 ± 132a	116 ± 50ab
Wet	244 ± 72bc	58 ± 46c	529 ± 83a	136 ± 20c
Total	460 ± 123 ac	127 ± 80b	818 ± 165a	252 ± 58bc

Note: Values are means ± one standard deviation. Different letters correspond to significant differences between treatments within a run (row). Differences between runs within the same treatment are significant if highlighted differently (plain text or underlined). Treatment means or totals are provided for times, runoff, and erosion responses. Significance level was .05.

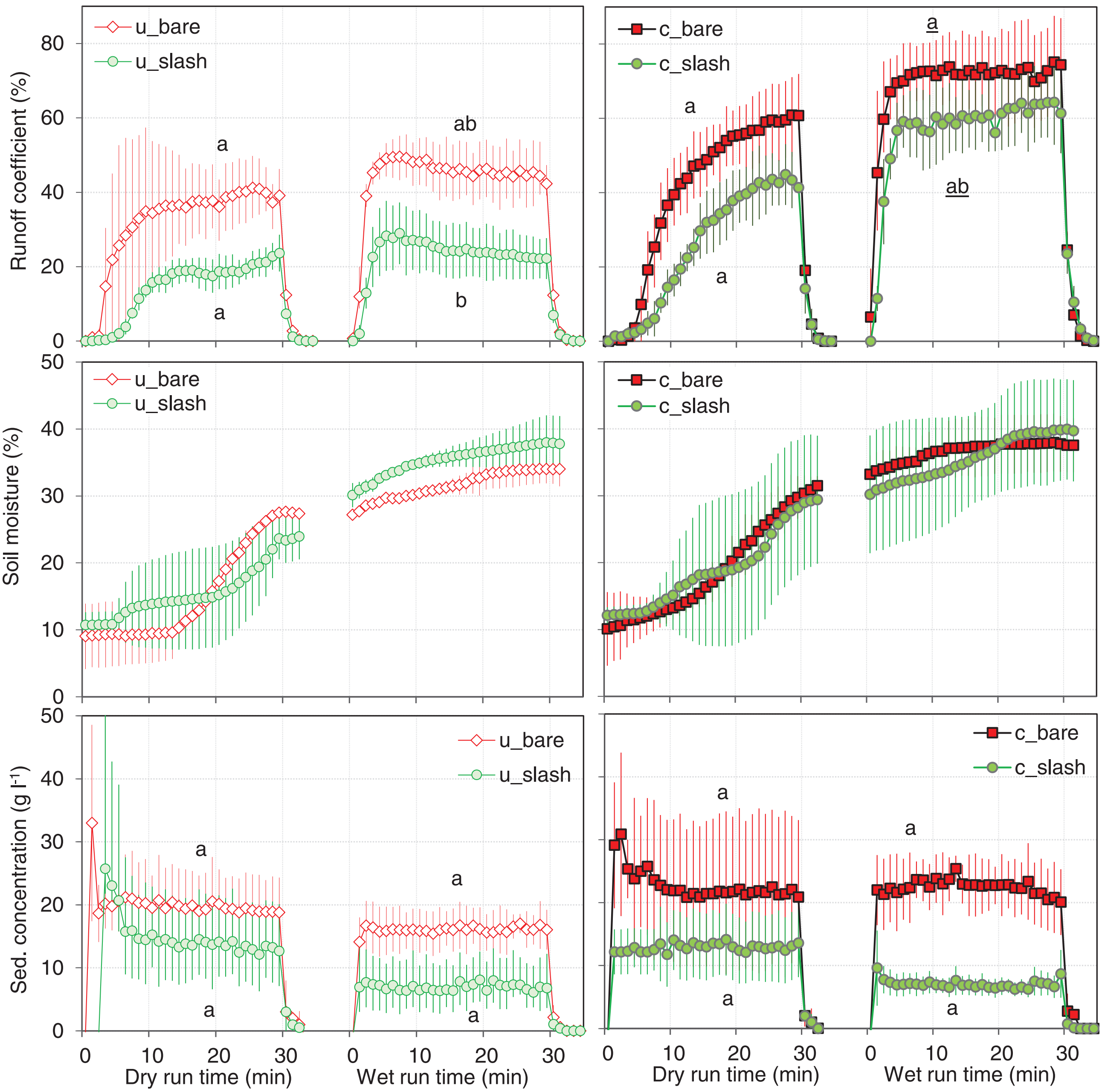

FIGURE 4 Mean runoff coefficient (% of rainfall rate), soil moisture at 3 cm depth (% volume) and sediment concentration (g L^{-1}) for the four treatments at 1-minute intervals for the Dry and Wet runs. Overall means of treatments within the same run were statistically different when followed by different letters. Differences between runs for a given treatment were significant when letters are highlighted differently (plain text vs. underlined). u_, uncompacted; c_, compacted; bare, bare soil; slash, slash

the uncompacted slash plots (42%) was significantly higher than all other treatments (29%–33%), and the same pattern generally held for the 5–10 cm depth (Table 3). The soil moisture sensors showed an increase only after 15 minutes in the uncompacted bare plots (Figure 4), and after 5 min in the uncompacted slash plots. After the initial response, soil moisture increased sharply in the uncompacted bare plots, while the increase was more gradual in the uncompacted slash plots. For the Wet run both uncompacted treatments showed similar patterns, and the uncompacted slash plots had a higher soil moisture. The soil moisture patterns for the compacted treatments were very similar to the pattern in the uncompacted slash pots, without differences due to slash cover. The three-factor mixed-effects models which assessed the relative strength of compaction, cover and run indicated that run exerted the strongest control on all the hydrologic variables (Figure 5). Both run and compaction factors exerted a stronger control on the hydrologic variables than the cover factor. Consequently, saturated hydraulic conductivity (Ks) was higher for the uncompacted treatments (averaging 38 and 56 mm h^{-1} for uncompacted bare and slash plots, respectively) than for the compacted treatments, which were about 50% lower (Table 4).

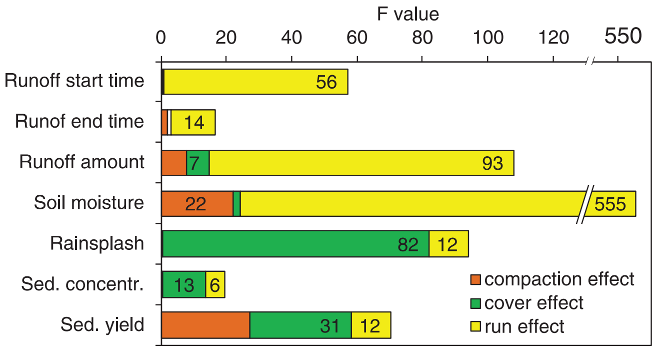

FIGURE 5 *F* values for the three-way mixed-effects statistical models comparing the impact of compaction (uncompacted/compacted), cover (bare/slash) and rainfall run (dry/wet) on dependent variables of runoff start and end times (s), runoff amount (mm), soil moisture (% volume), rainsplash (g), sediment concentration ("Sed. concentr.;" g L^{-1}) and sediment yield ("Sed. yield"; g m^{-2}). Runoff start and end times and rainsplash were fourth-root transformed prior to analysis. *F* values are shown for the corresponding factor when they were significant at $p \leq .05$

3.2.2 | Erosion results

The uncompacted bare plots produced nearly the same amounts of rainsplash as the compacted bare plots (Table 3). Slash significantly reduced rainsplash from the uncompacted soils by 76% and 85% for the Dry and Wet runs, respectively, and the same applied for the compacted soils.

The sediment concentration was similar for all the treatments and runs (Table 3). However, the mean sediment concentration was significantly lower in the compacted slash plots (9 g L^{-1}) than in the bare compacted bare plots (22 g L^{-1}) (Table 3).

Sediment yields were similar for the Dry run and significantly increased by a factor of 2.2 for the Wet runs in the compacted bare plots. Slash significantly reduced the total sediment yield by 72% for the uncompacted soils and by a similar amount for the compacted soils, and the reduction was larger for the Wet runs. The mixed-model *F* value analysis showed that the erosion variables were all significantly controlled firstly by cover and followed by run (Figure 5). Furthermore, interrill erodibility coefficient (Ki) was the lowest for the slash treatments (0.68 and 0.62×10^6 kg s^{-1} m^{-4}; respectively for uncompacted and compacted slash plots) and higher for the bare treatments (0.91 and 1.01×10^6 kg s^{-1} m^{-4}; respectively for uncompacted and compacted bare plots) (Table 4).

4 | DISCUSSION

4.1 | Compaction effect on soil properties

Soil compaction by salvage logging equipment significantly increased bulk density by 25% and 30% at 0–5 and 5–10 cm soil depths, respectively. Other researchers have reported increases after logging traffic in unburned or burned forests with sandy loam soils of 9%–17% (Olsen et al., 2020), 20%–37% (Croke et al., 2001; Han et al., 2009; Sosa-Pérez & MacDonald, 2017) and 44%–58% (Sheridan et al., 2008; Wagenbrenner et al., 2016). In these studies, the compaction effect increased with soil moisture, traffic load and traffic levels of logging equipment, especially wheeled skidders. The consistently higher compaction of the deeper soil layers was probably due to their lack of lateral displacement, especially as compared to the more detachable superficial topsoil layer.

Additionally, we found that skidder traffic significantly reduced soil aggregate stability (Table 2). Soil compaction can reduce soil aggregation due to the reduction of pore spaces and macroporosity (Menon et al., 2015), and it is exacerbated by low soil OM content, which binds the soil particles (Hamza & Anderson, 2005). Soil aggregation depends in part upon soil biota and soil OM (Six et al., 2004), and some authors have shown that burned soils covered with litter or forest residues have higher aggregate stability (Campo et al., 2008; Prats, Gonzalez-Pelayo, et al., 2019). Consequently, soil aggregation has been widely described as a function of soil OM. However, the lack of soil OM differences among our treatments indicate that the reduction in aggregate stability was likely not related to OM. The extent to which soil compaction or lower soil OM control the reduction in soil aggregation needs to be further studied.

Although there was generally low to moderate soil water repellency in the uncompacted areas in our study, soil compaction eliminated the soil water repellency completely (Table 2). Pierson et al. (2001) had suggested that repellency can break down in the field by wetting/drying or freeze thaw cycles, both of which occur at BMDSF. Bryant et al. (2007) also demonstrated that pressure on the soil, such as that imparted by heavy equipment traffic, can lower roughness and increase contact area between water drops and soil surface, which provide increased opportunities for surface wetting mechanisms. We suspect the ground pressure was the primary cause for the difference in soil water repellency between our compacted and uncompacted soils.

4.2 | Compaction and cover effects on hydrology

Runoff was lower from uncompacted areas than from the compacted skid trails, irrespective of cover. This phenomenon has been observed in past studies in both burned and unburned forests and typically attributed to the increase in soil compaction, which reduces soil porosity and infiltration capacity (Foltz et al., 2009; Prats, Malvar, et al., 2019; Sheridan et al., 2008; Sosa-Pérez & MacDonald, 2017).

The hydrographs for the uncompacted plots (Figure 4) showed that runoff coefficient decreased at the end of the wet run, which suggests that infiltration capacity slightly increased. This could be attributed to increased hydraulic conductivity, possibly by activation of larger pores, reduced soil water repellency, or a combination of the two factors, as soil moisture increased (Pierson et al., 2001; Robichaud, 2000). In contrast, the hydrographs from our skidder-compacted soils (Figure 4) showed a gradual approach toward steady state runoff at the end of the wet run, very similar to hydrographs

TABLE 4 Rainfall simulations grouped by Burning (U, unburned; B, high severity burning), Logging (U, unlogged; L, salvage logged) and Compaction factors (U, uncompacted; C, compacted))

Treatment name (year since fire)	Factor (U/B; U/L; U/C)	Cover %	Plot surface; slope m^2; °	Rainfall intensity; duration mm h^{-1}; min	Bulk density g cm^{-3}	Runoff mm	Sed. Yield g m^{-2}	Ks mm h^{-1}	Ki $x10^6$ kg s m^{-4}	Reference
Undisturbed forest										
Undisturbed	U–U–U	58	0.5;11	100;60	—	30	5	75	0.01	Larson-Nash et al. (2018)
Undisturbed	U–U–U	87	0.5;31	100;60	—	55	39	72	0.03	Larson-Nash et al. (2018)
Undisturbed	U–U–U	91	0.6;23	100;60	0.44	53	7	50	0.005	Robichaud et al. (2016)
Undisturbed	U–U–U	97	32;2	60;60	—	12	0	30	0.000	Johansen et al. (2001)
Undisturbed	U–U–U	99	1;5	44;45	1.28	16	3	28	0.01	Sosa-Pérez and MacDonald (2017)
Undisturbed	U–U–U	99	1;12	74;60	—	43	23	31	0.03	Benavides-Solorio and MacDonald (2001)
Undisturbed	U–U–U	100	1;26	94;30	—	10	na	64	—	Robichaud (2000)
Mean						31	13	50	0.01	
Burned forest										
Burned (2)	B–U–U	1	0.5;31	100;60	—	67	2532	56	1.36	Larson-Nash et al. (2018)
Burned (2)	B–U–U	2	0.5;11	100;60	—	81	1698	16	0.75	Larson-Nash et al. (2018)
Burned (1)	B–U–U	5	1;16	82;60	—	50	342	32	0.30	Benavides-Solorio and MacDonald (2001)
Burned (2)	B–U–U	17	0.6;23	100;60	0.46	62	391	37	0.23	Robichaud et al. (2016)
Burned (0)	B–U–U	23	1;17	86;60	—	57	428	29	0.32	Benavides-Solorio and MacDonald (2001)
Uncompacted bare	B–U–U	0	0.5;18	72;30	0.91	10	180	24	0.86	Prats, Malvar, et al. (2019)
Uncompacted bare	B–U–U	18	0.5;20	73;30	0.79	12	216	38	0.91	This study
Burned (0)	B–U–U	35	1;30	94;30	—	16	—	43	—	Robichaud (2000)
Burned (1)	B–U–U	37	1;21	80;20	1.1	13	100	67	0.35	Robichaud et al. (2013)
Burned (1) + wood	B–U–U	73	1;21	80;20	1.1	10	30	70	0.14	Robichaud et al. (2013)
Burned (1) + straw	B–U–U	75	1;21	80;20	1.1	10	30	70	0.14	Robichaud et al. (2013)
Uncompacted GHA	B–L–U	50	45;14	122;30	1.14	1	17	58	0.77	Croke et al. (2001)
Uncompact. mulch	B–U–U	63	0.5;18	72;30	0.89	8	65	28	0.41	Prats, Malvar, et al. (2019)
Burned (6)	B–U–U	90	1;18	77;60	—	28	27	49	0.05	Benavides-Solorio and MacDonald (2001)

TABLE 4 (Continued)

Treatment name (year since fire)	Factor (U/B; U/L; U/C)	Cover %	Plot surface; slope m^2; °	Rainfall intensity; duration mm h^{-1}; min	Bulk density g cm^{-3}	Runoff mm	Sed. Yield g m^{-2}	Ks mm h^{-1}	Ki x10^6 kg s m^{-4}	Reference
Uncompacted slash	B–U–U	67	0.5;17	71;30	0.77	5	69	56	0.68	This study
Mean						29	438	45	0.52	
Compacted forest roads (truck, skidder & ATV roads)										
Reopened no-track	U–U–C	0	1;4	100;30	—	38	304	17	0.29	Foltz et al. (2009)
Reopened track	U–U–C	0	1;4	100;30	—	39	624	17	0.58	Foltz et al. (2009)
Ungravel low traffic	U–U–C	0	3;8	100;30	2.07	42	348	15	0.30	Sheridan et al. (2008)
Ungravel trafficked	U–U–C	0	3;5	100;30	2.19	43	998	10	0.84	Sheridan et al. (2008)
Gravel low traffic	U–U–C	0	3;5	100;30	2.44	46	398	10	0.31	Sheridan et al. (2008)
Gravel trafficked	U–U–C	0	3;5	100;30	2.45	45	254	8	0.20	Sheridan et al. (2008)
Roadbed	U–U–C	8	0.6;6	90;30	—	26	154	37	0.23	Jordán et al. (2009)
Road (closed)	U–U–C	14	1;3	44;45	1.75	39	43	5	0.09	Sosa-Pérez and MacDonald (2017)
Trafficked ATV	U–U–C	12	1;3	44;45	1.79	40	130	4	0.27	Sosa-Pérez and MacDonald (2017)
Ripped	U–U–C	32	1;3	44;45	1.54	35	72	9	0.17	Sosa-Pérez and MacDonald (2017)
Roadbed	U–U–C	48	0.1;10	75;30	—	17	14	40	0.04	Arnáez et al. (2004)
Ripp. + strand mulch	U–U–C	66	1;5	44;45	1.52	24	16	20	0.05	Sosa-Pérez and MacDonald (2017)
Brushed-in no-track	U–U–C	95	1;6	100;30	—	32	70	15	0.08	Foltz et al. (2009)
Brushed-in track	U–U–C	98	1;5	100;30	—	38	84	11	0.08	Foltz et al. (2009)
Mean						36	251	16	0.25	
Burned and salvage Logged and skid-Compacted										
Compacted bare	B–L–C	0	0.5;18	72;30	1.09	15	341	16	1.15	Prats, Malvar, et al. (2019)
Compacted bare	B–L–C	18	0.5;15	71;30	0.98	14	289	19	1.01	This study
Compacted mulch	B–L–C	63	0.5;18	72;30	1.06	18	166	14	0.46	Prats, Malvar, et al. (2019)
Compacted slash	B–L–C	61	0.5;18	72;30	1.07	18	225	14	0.62	Prats, Malvar, et al. (2019)
Compacted snig	B–L–C	35	76;14	125;30	1.36	5	142	13	0.82	Croke et al. (2001)
Compacted slash	B–L–C	66	0.5;16	72;30	0.98	9	116	26	0.62	This study
Mean						13	213	17	0.78	

Note: The four groups are: Undisturbed forest (U–U–U); Burned forest (B–U–U); Compacted forest roads (U–U–C) and Burned + salvage Logged + skid-compacted areas (B–L–C). The ground cover (GC;%) threshold for bare/covered discretisation is highlighted by a dotted line at 30%. Year since wildfire is indicated between brackets.

Abbreviations: BD, bulk density; Ki, interrill erodibility coefficient following Equation (1); Ks, saturated hydraulic conductivity; R, runoff; SY, sediment yield.

from rainfall simulations on roads (Foltz et al., 2009; Sheridan et al., 2008). These compacted soils were not water repellent, and the compaction would have eliminated any macropores.

Mulching with various types of organic residues can mitigate post-fire runoff (Badía & Martí, 2000; Prats, Malvar, et al., 2019) and reduce runoff velocities (Jordán et al., 2010; Robichaud, Lewis, Wagenbrenner, et al., 2020), but most mulches are not locally produced. In our study, the runoff response in both levels of soil compaction was reduced by covering the plot with pine slash. Slash also significantly increased soil moisture in the uncompacted plots (Table 3), indicating more rainfall was able to infiltrate in the slash-covered plots.

These effects may not be consistent at broad scales, once overland flow concentrates into rills and some gaps between the soil and the slash can allow runoff to pass unimpeded under the slash (Wagenbrenner et al., 2016). Still, the effect at the smaller spatial scale of our study suggests that adding slash may be an attractive practise to reduce runoff rates in burned or burned and logged forests. The capacity of slash to mitigate the hydrologic responses at larger spatial scales is generally unknown and larger-scale experiments should be considered. Similarly, the relative impacts and spatial arrangement of compacted areas on soil hydrology and runoff generation may differ across larger areas (Sheridan et al., 2008), and should be further investigated.

4.3 | Compaction and cover effects on erosion

The strong reduction that ground cover exerts on rainsplash has been extensively explained by the protection of the soil against detachment by rainfall drops, such as in studies assessing post-fire mulching (Badía & Martí, 2000, 2008; Jordán et al., 2010; Robichaud et al., 2013, 2016). Rainsplash was consistently lower during the Wet runs for all the treatments, which can be attributed to the smaller extent of detachable soil exposed to splash after reaching some degree of surface water impoundment (Bryan, 2000).

Compared to other rainfall simulation studies carried out in areas burned at high fire severity and with similar soil properties, our mean sediment yield from uncompacted soils in the second post-fire year (460 g m^{-2}) was higher than the corresponding value for the Valley Complex Fire in Montana (391 g m^{-2}; Robichaud et al., 2016) and also higher than the sediment yield immediately after the Bobcat Fire (428 g m^{-2}) or in the first year after the Lower Flowers prescribed fire (342 g m^{-2}) in Colorado (Benavides-Solorio & MacDonald, 2001). On the other hand, other research measured extremely high sediment yields in the second year after the Hot Creek Fire in Idaho (1698 g m^{-2}) (Larson-Nash et al., 2018). The differences are mostly attributed to the higher rates of understory cover that intercepted rainfall (Table 4), as the rainfall simulator, rainfall conditions, plot size, slope, and soil texture were similar. Our results demonstrate that soil erosion risk in severely burned areas can still be high two years after wildfire (Robichaud, Lewis, Wagenbrenner, et al., 2020).

As in other post-fire and post-fire salvage logging field studies (Malvar et al., 2017), our results have shown increases in soil loss due to compaction by skidding of 1.8 times the uncompacted rates (Table 4). Higher relative increases in soil erosion of 10–100 times relative to burned, unlogged areas have been measured in wider plots and attributed to skidding in burned areas, although those rates also included rilling (Croke et al., 2001; Wagenbrenner et al., 2015).

Slash cover reduced soil erosion by 69% in skid-compacted soils in this study and in other studies monitoring soil erosion by natural rainfall (Cole et al., 2020; Wagenbrenner et al., 2015). However, added slash did not reduce rill erosion in a runoff experiment (Wagenbrenner et al., 2016), where the lack of effect was attributed to the smaller relative difference in slash ground cover between groups (40–50% in controls vs. 70% in slash-added condition) and to the relative lack of contact between the slash and the soil. Alternative methods for incorporating slash into the soil (e.g., applying logging slash over the skid trail prior to or during equipment traffic) may increase its effectiveness at mitigating erosion and may reduce the effect of machine traffic on soil compaction (Han et al., 2009). Robichaud, Lewis, Brown, et al. (2020) observed that 60% slash cover can be attained on skid trails used for whole-tree yarding in a post-fire salvage logging operation with no extra trips by moving the logging slash to the skid trail during the return of the skidder from the landing.

4.4 | Ks and Ki modelling parameters

Saturated hydraulic conductivity (Ks) in our uncompacted bare plots (38 mm h^{-1}) fit well with rainfall simulation studies (Table 4) carried out in undisturbed (50 mm h^{-1}) as well as burned areas (45 mm h^{-1}; Table 4). Ks decreased to 19 mm h^{-1} in our compacted bare plots, and this was similar to results for compacted forest roads in unburned areas (16 mm h^{-1}) and burned, salvage logged and skid-compacted sites (17 mm h^{-1}). The lowest Ks values were attributed to a higher degree of soil compaction (Foltz et al., 2009). Interestingly, the presence of at least 30% vegetative or mulch cover in those studies did increase the reported Ks values in both compacted soils (14 vs. 19 mm h^{-1} for low and high cover, respectively) and uncompacted burned soils (34 vs. 50 mm h^{-1} for low and high cover, respectively).

Interrill erodibility coefficient (Ki) in undisturbed forests was very low (0.01×10^6 kg s m^{-4}; Table 4). Ki increased to a mean value of 0.68×10^6 kg s m^{-4} for uncompacted bare plots that had burned at high severity, and decreased to 0.34×10^6 kg s m^{-4} in the case of uncompacted covered burned plots, including our results (Table 4). Ki values from bare road surfaces compacted by truck, skidder or all-terrain vehicles in Australia (Sheridan et al., 2008), Spain (Arnáez et al., 2004; Jordán et al., 2009) and USA (Foltz et al., 2009; Sosa-Pérez & MacDonald, 2017) decreased, on average, to 0.25×10^6 kg s m^{-4} (Table 4). The combination of burning and skidder-traffic resulted in the highest Ki values, averaging 1.08×10^6 kg s m^{-4} for plots with no added cover, which was very similar to the average Ki of our compacted bare soils (1.01×10^6 kg s m^{-4}). These results highlight the extreme vulnerability of burned and salvage logged skid-compacted soils. These high Ki values can be somewhat mitigated by adding surface cover to the burned compacted areas, which reduced the Ki values to an average of 0.63 x10^6 kg s m^{-4} (Table 4). As with the Ks calculations, the Ki, a modelling soil parameter, should not change substantially with the addition of surface cover, and the differences because of the slash or mulch probably reflect the calculation method for Ki. The addition of slash or other cover to burned or compacted soils does typically reduce the sediment yield, but the mechanism is most likely an increase in roughness (Robichaud, Lewis,

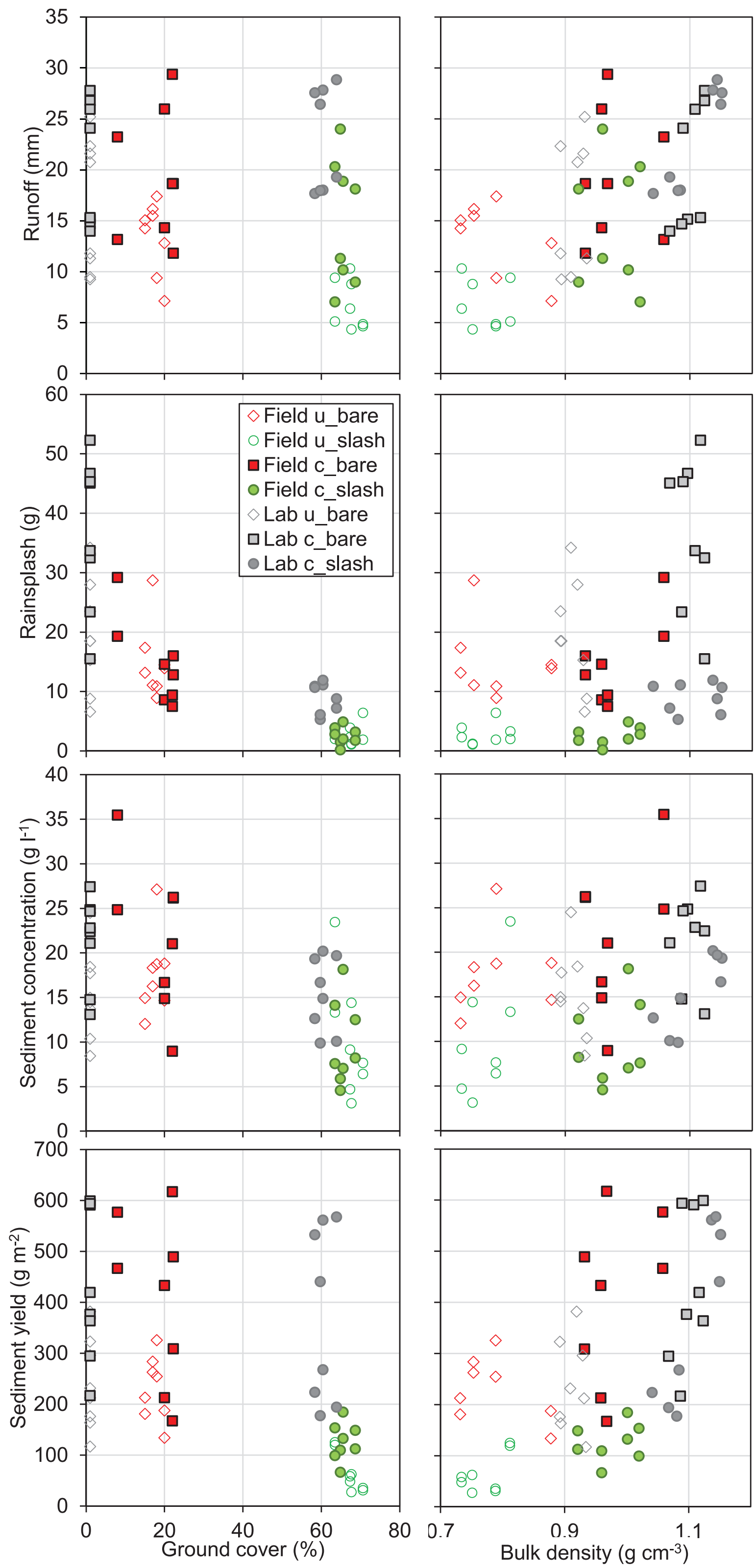

FIGURE 6 Runoff (mm), rainsplash (g), sediment concentration (g L^{-1}) and sediment yield (g m^{-2}) vs. soil ground cover (left panels) and bulk density (right panels) for the Dry and Wet runs from the field (coloured symbols) (this study) and laboratory rainfall simulations (grey symbols) of Prats, Malvar, et al. (2019). Note that symbols are empty for bare, filled for 60% slash cover, light line weight for uncompacted and heavy line weight for compacted. u_, uncompacted, c_, compacted; bare, bare soil; slash, pine slash

Wagenbrenner, et al., 2020) and resultant partitioning of some of the shear stress to the covering elements (Knapen et al., 2007), leading to less soil detachment and transport in the interrill flow.

4.5 | Comparing laboratory and field rainfall simulations

The setup in the related laboratory study (Prats, Malvar, et al., 2019) allowed the calculation of leaching and soil water balances that are not readily measured in the field, particularly in compacted soils. The laboratory study as well as other experiments showed that ash, stone, charcoal or slash cover increase leaching, especially in the case of uncompacted soils (Prats et al., 2018; Prats, Malvar, et al., 2019). Soil cover by mulch or slash enhanced the infiltration process by increasing leaching more than increasing the soil water storage, and this is probably due to the ability of the surface cover to reduce sealing and thus maintain the contribution of larger pores in conducting water while the soil is near saturation (Six et al., 2004). In contrast, compacted soils exhibited very low leaching (Prats, Malvar, et al., 2019), and soils remained unsaturated through Dry and Wet laboratory simulations, most likely because of the lower hydraulic conductivity caused by the compaction. Across the two studies, the plot runoff was more closely related to the bulk density than the soil cover (Figure 6).

Runoff differences between the Dry and Wet runs for the uncompacted plots were more pronounced in the laboratory (60% increase in the Wet relative to the Dry) than in the field (30% corresponding increase). Across both studies, the runoff rate was more correlated to the bulk density than to the surface cover (Figure 6). The presence of the relatively low soil water repellency in the uncompacted plots in the field may have initially reduced infiltration and increased runoff in the Dry run (Figure 4), although on average the effect was very subtle. In a similar way, the rise of soil moisture at the 3 cm depth in the field experiment was probably also affected by soil water repellency. During the Dry run in the uncompacted plots soil moisture rose slowly and less pronounced (starting at around 15 minutes to a maximum of 25%) (Figure 4) as compared to the laboratory (starting at around 5 min to a maximum of 40%) (Prats, Malvar, et al., 2019). The soils used in the laboratory were sieved and lacked both water repellency and macroporosity, and thus, the hydrologic response was larger and faster.

Rainsplash was higher in the laboratory than in the field (Figure 6), which is likely related to the 10%–20% higher soil cover in the field. The difference in cover arose from two aspects. First, the soil sieving (6.3 mm sieve) for the laboratory simulations resulted in a lack of stones, soil roughness and macroaggregates. Second, the soil in the field had been subjected to erosion from natural rainfall during the 20 months since the fire and eight months since the post-fire skidding operations. Given the high soil erosion rates measured at BMDSF in an associated study (Cole et al., 2020), this resulted in a preferential removal of fines and soil armoring by lapilli in the field experiment (Shakesby, 2011) (Figure 3). Furthermore, the relationship of rainsplash with surface cover was stronger than with bulk density across the two studies (Figure 6).

The overall mean sediment concentration was very similar between the laboratory and field experiments on the uncompacted bare (16 vs. 17 g L^{-1}, respectively) and compacted bare treatments (23 vs. 22 g L^{-1}, respectively), but not for the compacted slash treatment (16 vs. 9 g L^{-1}, respectively) (Figure 6). These results suggest the laboratory scenario was more erosive, since the infiltration was almost totally hindered due to the artificially sieved soils and to the higher bulk densities that resulted from the compaction method. Also, the availability of easily transported soil particles was greater in the laboratory since those plots had not been subject to erosion from natural rainfall and winnowing of the smaller soil particles. Still, the total sediment yield from the uncompacted bare soil in the laboratory (497 g m^{-2}) compared well with the value in the field (460 g m^{-2}) and the same applied for the compacted bare treatments (902 vs. 818 g m^{-2}, respectively). Laboratory experiments allowed the detailed assessment of hydrologic and erosion processes under more controlled conditions while the field experiments provided results more relevant to natural conditions. The field experiments also allowed direct comparison of different in-situ soil conditions using the same rainfall inputs, thus eliminating the variation in the results due to precipitation identified in an associated field experiment (Cole et al., 2020).

5 | CONCLUSIONS

We assessed the effects of soil compaction by logging machinery and the effects of increasing ground cover with logging slash on runoff, rainsplash and sediment yield using rainfall simulations on Dry and Wet soils in a severely burned area in the 2015 Valley Fire in north-central California. Saturated hydraulic conductivity (Ks) and interrill erodibility (Ki) modelling parameters were calculated and compared to values from previous research.

- The treatments had less impact on runoff relative to impacts on sediment yield. The runoff coefficient for the combined Dry and Wet runs was similar for all the plots, although it was lower for the uncompacted bare plots (38%) than for the compacted bare plots (55%). Adding slash also did not significantly reduce the overall runoff coefficients, even though the values were 19%–41% lower than the comparable conditions without slash.
- Ks for the uncompacted bare plots was 38 mm h^{-1}. On average, Ks was reduced by compaction by 63% and increased by soil cover by 11%. Our calculated Ks values were comparable to others previously reported in burned soils and along compacted road surfaces.
- Rainsplash was not affected by compaction, but the addition of slash significantly reduced rainsplash by 80% as compared to the bare soil conditions. Compaction increased total sediment yields from 460 g m^{-2} in the uncompacted bare plots to 818 g m^{-2}, in the compacted bare plots. Slash significantly reduced sediment yields by 69%–72% as compared to the bare plots.

- The mean Ki values were highest on the compacted bare soils (1.01×10^6 kg s m^{-4}), which were similar to those reported from compacted road surfaces. The high erodibility highlights the relative vulnerability of burned and skid-compacted soils to interrill erosion.

These results help explain the mechanisms that control the runoff and sediment yield responses from soils impacted by post-fire salvage logging equipment. Slash appears to be an effective method for mitigating the increased runoff and erosion associated with post-fire salvage logging, and because it uses locally available materials, adding slash may be a feasible forest management practise to carry out during or after salvage logging operations to reduce sediment yield.

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DATA AVAILABILITY STATEMENT

Data Availability The data that support the findings of this study are available from the corresponding author Dr. S.A. Prats upon reasonable request.

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