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Hydrologic and erosion responses to compaction and added surface cover in post-fire logged areas: Isolating splash, interrill and rill erosion

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1. Introduction

Runoff and soil erosion can increase substantially after wildfires, especially in severely burned areas (Benavides-Solorio and MacDonald, 2001, 2005; Moody et al., 2013). These increases have been associated with negative on-site and off-site effects such as soil fertility losses (Shakesby, 2011), stream water pollution (Emelko et al., 2011; Lewis et al., 2018) and sedimentation (Shakesby, 2011; Robichaud et al., 2016). Soil compaction by machinery used during post-fire logging activities has been shown to affect soil roughness, bulk density and shear strength, and it can increase post-fire runoff and erosion (Croke et al. 1999a, 1999b, 2001; McIver and McNeil, 2006; Silins et al., 2009; Emelko et al., 2011) which may greatly exacerbate the detrimental effects of the wildfire itself. Some post-fire field studies have shown that unlogged areas exhibited lower runoff and erosion volumes as compared to soils impacted by logging equipment (Wagenbrenner et al., 2015, 2016; Malvar et al., 2017). In contrast, other experiments have shown that compaction or disturbance related to post-fire logging led to lower soil erosion rates (Adekalu et al., 2006; Ekwe and Harrilal, 2010; James and Krumland, 2018).

Soil surface cover, such as litter, stones, char, ash and vegetation cover are known to inhibit surface runoff (Arnau-Rosalen et al., 2008; Ruiz-Sinoga and Martinez-Murillo, 2009; Prats et al., 2017, 2018) and soil erosion (de Figueiredo and Poesen, 1998; Cerda and Doerr, 2005; Prats et al., 2012), but the effects of added cover on runoff and erosion from burned and compacted soils are not well understood. Post-fire soil erosion rates have been directly linked to low ground cover rates (Larsen et al., 2009), and mulch application rates have been determined for several materials for agriculture (Smets et al., 2008), post-fire hillslopes (Robichaud et al., 2010b) and roads (Burroughs and King, 1989). It is widely assumed that mulching at rates above 60% ground cover can significantly reduce soil erosion (Burroughs and King, 1989; Robichaud et al., 2000; Smets et al., 2008; Robichaud et al., 2010b; Moody et al., 2013). Different materials can be used as mulches, and the main differences among mulch materials relate to density, application rate and resistance to physical degradation on the ground surface. Application rates ranged from 1-11 Mg ha^{-1} with straw and forest residue mulches for post-fire unlogged environments (Robichaud et al., 2010b; Prats et al., 2016), while slash application rates for reducing soil erosion in skidder-compacted soils can be more than 10 times higher (28-165 Mg ha^{-1}) (Cambi et al., 2015; Jourgholami and Abari, 2017). Because of its larger particle size, slash is not always effective in reducing erosion from surface runoff. For example, Wagenbrenner et al. (2016) found that manually adding harvest residues to attain at least 50% cover on skidder-compacted soils resulting from post-fire salvage logging did not affect sediment flux rates. The researchers also suggest that specific best management practices are needed to mitigate the hydrologic impacts of post-fire salvage logging. Besides ground cover other factors such as soil properties (soil moisture, soil texture, slope angle), skidder characteristics (ground pressure), and rainfall characteristics such as rainfall intensity (Cambi et al., 2015) can have important roles in soil erosion.

In spite of a number of studies assessing the mitigation of post-fire soil erosion with mulching (e.g., Bautista et al., 1996; Wagenbrenner et al., 2006; Robichaud et al., 2010b; Fernandez et al., 2011; Robichaud et al., 2013a; Prats et al., 2016), very little is known about the reasons why mulch is a relatively effective treatment. Mulch seems to be effective due to three components: (i) increasing interception of raindrops and associated reduction in rain splash detachment; ii) reducing soil surface sealing and crusting which thereby increases infiltration and reduces surface runoff rates (Bautista et al., 1996); and (iii) increased surface roughness and obstruction of overland flow that results in lower soil detachment by sheetflow and rilling (Pannkuk and Robichaud, 2003; Giménez and Govers, 2008). The increase in surface roughness by mulch promoted infiltration and lowered runoff velocities in areas treated with mulch, and this reduced sediment transport (Robichaud et al., 2013c). Foltz and Wagenbrenner (2010) observed that overland flow is often temporarily stored upslope of mini debris dams that form when strands of mulch and litter interlock, and these small ephemeral ponds may increase infiltration. However, it is difficult to determine the proportion of erosion reduction that can be attributed to protecting the soil from raindrop impact as opposed to slowing overland flow velocity or increasing detention storage (Robichaud et al., 2013c). In general, the mulch success is often attributed to the increase in ground cover without identification of a specific process change.

It has been very difficult to isolate the runoff (i.e., saturation excess vs. infiltration excess) and erosion mechanisms (i.e.; splash, sheetwash or rill). For example, Flanagan and Nearing (1995) described sheetwash (or interrill) erosion as the combination of soil detachment resulting from the impact of water drops directly on soil particles (rainsplash) and the associated transport of the detached particles by shallow overland flow (sheetwash). Most of the past laboratory research studied combinations of processes, such as splash and sheetwash (De Figueiredo and

Poesen, 1998), only sheetwash (Foltz et al., 2009), sheetwash and rill erosion (Foltz and Wagenbrenner, 2010), sheetwash and rill erosion (Croke et al., 2001). There have been more studies addressing solely rill erosion (Nearing et al., 1999; Robichaud et al., 2010a; Wagenbrenner et al., 2010; Wagenbrenner et al., 2016) but studies independently assessing each of the three mechanisms are generally lacking. Understanding the relative magnitudes of splash, sheetwash and rill erosion on total soil losses will help us to determine the mechanism(s) affected by mulch that lead to reductions in erosion, and also help refine specific measures for post-fire management scenarios.

The main aim of this study is to evaluate the effects of compaction and the presence and type of ground cover on post-fire runoff and soil erosion. Our specific objectives were to: 1) determine if soil compaction affects hydrologic responses (runoff, leaching, soil moisture, and runoff timing); 2) determine the effects of compaction on rainsplash, sheetwash and rill erosion; and 3) determine if adding sequoia bark strand mulch or logging slash changes these hydrologic or erosional responses. We used laboratory rainfall and flow simulations to isolate each hydrologic and erosion processes.

2. Materials and Methods

The effects of two levels of soil compaction (uncompacted and compacted), and two levels of ground cover (0%and 60% sequoia bark mulch cover) on runoff, leaching, soil moisture, runoff timing, rainsplash sheetwash and rilling were tested with a rainfall simulator. The 60% cover rate was chosen as it is generally considered the minimum amount of cover for erosion control in different environments (Smets et al., 2008; Robichaud et al. 2010b; Burroughs and King, 1989) and widely used as a coverage target in operational post-fire mulching. The study used a replicated, full factorial, completely randomized design with four replications of the four combinations of the two factors (treatments). A fifth treatment with compacted soil and 60% cover of logging slash was also included. The plot preparation and subsequent simulations were randomly ordered among the treatments. The simulations were done indoors in McKinleyville, California, USA between January and April 2017. Each simulation was comprised of three parts (Dry, Wet and Flow) in order to test the responses of the treatments under different antecedent soil moisture (Dry and Wet) and to test the treatments under rill initiation (Flow). Splash erosion was also measured during the Dry and Wet runs.

2.1. Plot preparation

Soil was collected from the Boggs Mountain Demonstration State Forest (BMDSF), located in north-central California (38.81443°N, 122.67339°W) which was burned by the Valley Fire in 2015. A separate research project assessing hydrologic and erosional responses to post-fire forest management was underway at this location, and several experiments are still ongoing. As part of the ongoing experiments, soil bulk density was measured using a bulk density sampler with a 5 x 5 cm cylindrical core in uncompacted areas and in areas where skidder traffic had caused compaction. Bulk density at 0-5 cm soil depth was 0.76±0.08 g cm^{-3} (mean± standard deviation; n=13) in the uncompacted soil and 0.96±0.05 g cm^{-3} in the compacted soil (n=13), indicating an increase in bulk density from the skidder traffic of 26%.

The soil for the simulations was gathered from a hillslope burned at high severity, 1100 m.a.s.l. and a steepness of 12° where no equipment had passed since the fire. These soils were deep, well drained, formed from igneous rocks and exhibited andic soil properties (Edinger-Marshall and Obeidy, 2016). The soil corresponded to the Whispering series loamy-skeletal, mixed, mesic, Ultic Haploxeralfs (Soil Survey Staff, 2003). Stones larger than 8 mm diameter constituted 15.4% of the bulk soil mass, gravel (2 to 8 mm) was 19.8%, sand was 47.2% and silt and clay made up 17.6% of the mass. Soil organic matter determined by loss-on-ignition from 15 replicates (550 °C at 4h) was very high (0.182 g g^{-1}). In preparation for the rainfall simulations, stones and gravel greater than 6.3 mm were removed by sieving, resulting in a gravelly sandy loam texture with a gravel content of 17%.

Steel square plots, 70 cm wide by 70 cm long (0.49 m^2), and 15 cm deep had a 1 cm metal grid bottom that we covered with a porous geotextile fabric that allowed water to permeate. This water was funneled to a hose for the measurement of the leaching volume (Figure 1). The plots were gently filled with uncompacted air-dried soil. A single pass of a straight-edged blade was used to produce a flat surface with a uniform soil depth, as confirmed with a rigid steel needle inserted in the soil at 6 locations (Table 1). The downslope edge of the plot consisted of a metal lip at a height of 5 cm, which corresponded to the top of the soil (Figure 1). This lip was connected to a detachable gutter where surface runoff was funneled to a hose for collection (Robichaud et al., 2016). Mean bulk density for the uncompacted soil in the laboratory was higher than measured in the field, and this was attributed to the absence of large aggregates, which were destroyed by sieving before plot preparation. For the compacted treatment, additional dry soil was added to the plot (Table 1) and the soil was compacted with a 5 kg hammer to a plate that covered the full plot during roughly 1 hour. The dry soil was compacted to a similar soil depth and resulted in a bulk density that was 20% higher than the uncompacted condition. Three soil cores were used to sample bulk density and soil moisture within each plot (Table 1) and the three holes were gently refilled with a proportional amount of soil. Some plots were discarded if the bulk density was greater than 0.91 g cm^{-3} in the uncompacted treatment or lower than 1.04 g cm^{-3} in the compacted treatment. After carrying out the simulations, another three bulk density samples were gathered in areas undisturbed by the Flow run and these samples were also used to measure gravimetric soil moisture. All bulk density samples were dried at 105° C for 24 h (ASTM, 2007).

A soil moisture sensor (ECH2O 5-TM, Meter Group, Pullman, WA) was installed at 3 cm depth in the lower left corner of the plot. A handheld read-out device stored soil moisture every minute during the simulations and for 5 minutes after rainfall stopped. Initial and final soil moisture for each run was also recorded for statistical analysis.

Sequoia (*Sequoia sempervirens* (D. Don) Endl.) bark shreds and strands were sieved through a 4 cm screen to remove the smaller portion (Foltz and Wagenbrenner, 2010; Prats et al., 2017), dried at 105 °C for 24 h and applied at a rate of 200 g m^{-2} to the “mulched” plots to obtain a target surface cover of 60% cover (Table 1). For the slash plots, logging slash was gathered from BMDSF after wildfire and logging activities, and was composed of either ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson) or Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stems and branches of 1.9±0.6 cm diameter and 34.1±10.6 cm length. Oven-dried slash was applied by hand at a rate of 3400 g m^{-2} to each slash-treated plot to achieve the nominal target of 60% cover (Table 1). Actual mulch or slash cover was measured with point-counts on a 5 cm grid, and material was added or removed to achieve the target cover amount (Table 1). We measured the saturated water retention capacity of the mulch and slash by subtracting the oven dried mass (105° C, 24 h) from the saturated mass, yielding an average water retention capacity of 2.6±0.4 g water per g of mulch and 1.4±0.3 g water per g of slash.

2.2. Rainfall and inflow simulations

A portable Purdue-type rainfall simulator (Bertrand and Parr, 1961) with a single oscillating Veejet 80100 S.S.CO.H3/8U pressurized nozzle (Spraying Systems Co., Wheaton, IL) was set at 3 m above the center of the plot. This oscillating-arm rainfall simulator was designed and fabricated at the USDA-Forest Service Rocky Mountain Research Station following similar designs (Paige et al., 2003). The water pressure was set at 55 kPa which produced an initial velocity of approximately 8.8 m s^{-1} (Meyer and Harmon, 1979), which closely approximated the terminal velocity of natural raindrops of this size (van Dijk et al., 2002) and produced an impact kinetic energy of 271 kJ ha^{-1} mm^{-1} (Paige et al., 2003). The rainfall intensity was set by the number of oscillations, which was controlled with a small fixed-speed motor and a solenoid (Norton and Savabi, 2010). We achieved a rainfall intensity of 72±1.5 mm h^{-1} using a run time of 97%. Rainfall of this intensity over a 30-minute duration would occur on average less than every 100 years at BMDSF, but this high application rate assured the rainfall rate exceeded the infiltration capacity of the soil and assured surface runoff from each treatment (Foltz and Wagenbrenner, 2010), and the rate was on the low end of the range of intensities used in other post-fire rainfall simulation studies (Robichaud et al., 2016).

The plot was inclined to 18° to simulate the average slope of the BMDSF study sites and centered below the nozzle (Figure 1). Prior to each Dry run, the rainfall rate was tested and the applied rainfall was collected in a calibration pan that covered the top of the plot frame.. Three to five 1-minute samples were collected from the outlet of the calibration pan and weighed with a portable scale. If necessary, the nozzle run time was adjusted to achieve the target rainfall intensity.

Rainfall splashed material was collected along the downslope end of the plot for each Dry and Wet run using a 60 cm by a 40-cm piece of geotextile. The Skaps GT-140 needle-punched nonwoven geotextile fabric was porous (136 g m^{-2}, Skaps Inc., Athens, GA, USA) allowing water to permeate and retaining sediments larger than the 0.21 mm opening sizes. Prior to installation, the splash fabric pieces were numbered, dried (105° C, 24 h) and weighed. The fabric was secured to the plot frame at the outlet 2 cm above the soil surface with clips and wood posts forming a 70 cm wide, 20 cm high, and 20 cm deep splash collector above the detachable gutter (Figure 1) (de Figueiredo and Poesen (1998). The splash fabric collected rain splashed material coming from the upslope direction while surface runoff passed beneath the fabric to the gutter and funnel.

After 30-min of rainfall on the dry soil (Dry run), the simulation was interrupted for approximately 1 hour. During this break, the splash fabric was removed and stored in a pan, the sediment deposited in the gutter was removed and stored in a separate pan, a new piece of splash fabric was installed, and the rainfall intensity was re-calibrated. The Wet run was also 30 min, and after the Wet run we again removed and stored the splash fabric and deposited sediment.

Approximately 1 hour after the Wet run, ruts were simulated on the bare and mulched plots and inflow was delivered in four short pulses at the top of each plot to simulate overland flow from upslope (Nearing et al., 1999). To simulate the ruts, a small toy truck with rubber wheels was passed diagonally over the plot with uniform hand-pressure in order to introduce depressions on the soil surface (Figure 1). These simulated ruts were not scaled to field conditions, and were intended only to simulate the effects of ruts or tracks on concentrating runoff and inducing the formation of rills (Wagenbrenner et al., 2016). The size of the wood pieces prevented introduction of the simulated ruts in the slash-treated plots. Each pulse consisted of 1.1 l of clear water that was instantaneously gravity fed at the upslope center of the plot via a 10 cm wide flow box (Figure 1). The four pulses resulted in an overall flow rate of 4.3±0.8 l min^{-1}, equivalent to a total of 10.3±0.6 mm in each Flow run (Table 1), which was comparable to rates used in other rill experiments (Foltz and Wagenbrenner, 2010; Robichaud et al., 2010a; Prats et al., 2017, 2018). Sediment deposited in the gutter during the Flow run was also collected and stored separately from the sediment deposited during from the Dry and Wet runs.

Runoff start time for the Dry and Wet runs was the time between the initiation of rainfall and the time when runoff at the outlet of the plot was more than 1 drop per 3 seconds. For the Flow run, the start time was the period between the release of the runoff pulse and the instant when the runoff reached the bottom of the plot. Runoff end time was the time between the cessation of rainfall (or runoff pulses) and the time when runoff at the outlet of the plot was less than 1 drop per 3 seconds. Timed runoff samples were collected in separate pre-labeled and pre-weighed bottles each minute between the runoff start and stop times. The runoff produced by each runoff pulse during the Flow run was collected in a single bottle. Leaching for each run was the volume of water that permeated the bottom of the plot.

All runoff samples, splash fabrics, and sediment deposited in the gutter were weighed, oven-dried (105° C, 24 h) and re-weighed to obtain runoff volume (mm), sediment concentration (g l^{-}

^{1}), splash material (g), and dry sediment deposited in the gutter (g). The deposited sediment was included in the total sediment yield (g m^{-2}) for each run. Runoff, leaching and sheetwash and rill sediment dry weights were divided by the horizontal projection of the plot area (0.474 m^2) to produce unit-area runoff, leaching, and sediment yields, respectively. Runoff coefficients were the runoff volumes divided by the applied rainfall or inflow volumes. Ratios were calculated to demonstrate the effect of compaction (compacted value/uncompacted value) and addition of cover (mulch or slash value/bare value) for runoff, leaching, splash, and sediment yield.

2.3. Statistical analysis

Analyses were performed using three-way mixed effects models on the response variables (surface runoff, leaching, initial and final soil moisture, runoff start time, runoff end time, splash, sediment yield and sediment concentration). In each model, "compaction" (uncompacted and compacted soils), "cover" (bare, mulch and slash) and "run" (Dry, Wet and Flow) were the fixed effects, and plot was the random effect. We also ran the same model excluding the slash treatment because it was only present on the compacted soils, which resulted in two simpler mixed-effects models: one with two levels of compaction, two levels of cover and three levels of run; and another with only two levels of run (Dry and Wet). These two reduced models were constructed in order to assess the weight of compaction and cover factors on the hydrologic and the erosive response variables in balanced statistical models. All interactions among fixed factors were also considered.

All dependent variables except runoff and final soil moisture were 4^{th} root-transformed to achieve normally distributed model residuals. Autoregressive variance-covariance structures were selected for the mixed-effects models (Littell et al., 2006). Multiple pair wise comparisons were computed on all significant treatment and interaction effects using the Tukey-Kramer procedure (Kramer, 1956).

Simple linear regressions with intercept set to the origin were calculated for splash versus sheetwash sediment yields for the Dry and Wet runs and, similarly, for the combined Dry and Wet run splash sediment yield versus the rill sediment yield for the Flow run. All the statistical assumptions used $\alpha = 0.05$, and all statistical analyses were carried out using SAS 9.3 (SAS, Institute, Inc., 2016).

3. Results

3.1. Hydrologic results

Runoff in the Dry run started after 276 s in the uncompacted bare plots as compared to 213 s for the compacted bare plots, but this difference was not significant (Table 2). The mulch significantly delayed the onset of runoff in the uncompacted plots (487 s), but mulch and slash had no significant effect in the compacted plots (Table 2). Runoff start times consistently and significantly decreased for the Wet runs (52– 90 s) for each treatment, and there were no differences among treatments in either the Wet or Flow runs.

Runoff end times averaged 189 s for the uncompacted bare Dry runs, and none of the other treatments had a significantly different mean runoff end time (Table 2).The mean runoff end time for the uncompacted bare Wet runs was 175 s, and this did not differ from the value from the Dry run. The compaction and cover treatments generally increased the Wet run end time, but only the compacted mulch plots produced a significantly longer end time relative to the uncompacted bare value (Table 2). The compacted mulch plots also had a longer mean run time for the Wet run than for the Dry run. For the Flow runs, the mean end time was 177 s for the uncompacted bare plots, and all of the other treatments had significantly greater runoff end times than this (Table 2).

From the onset of runoff, runoff coefficients progressively increased within each run and between runs (Figure 2). The runoff coefficients exceed 50% by the end of each Dry run and exceeded 60% for most of each Wet run and for all of the Flow runs. The runoff coefficient approached 100% on the Flow run for the bare plots. There were no significant differences in mean runoff coefficients for any run among the treatments (Figure 2).

Runoff from the uncompacted bare plots averaged 10 mm during the Dry run, 22 mm from the Wet run, and 10 mm from the Flow run (Table 2). The mean plot total runoff for the uncompacted bare treatment (43 mm) represents 54% of the water volume applied to the plot. Runoff volumes for all treatments increased significantly from the Dry to the Wet run (Table 2). Compaction did not significantly increase the runoff for the bare plots as compared to the uncompacted bare plots in any of the runs (Table 2). Mulching did not affect the runoff rate for any of the runs as compared to the uncompacted bare plots. Similarly, there were no differences in runoff due to mulch or slash for a given run among the compacted plots (Table 2).

Leaching from the uncompacted bare plots averaged 1 mm in the Dry run, 6 mm in the Wet run, and 0 mm in the Flow run, totaling 7 mm for the simulation, or 9% of the total amount of water applied to the plot (Table 2). Soil compaction significantly decreased leaching regardless of the cover treatments, and only the bare compacted plot produced any leachate (Table 2). The leaching from the uncompacted mulch plots was greater for each run than uncompacted bare plots and totaled 12 mm (18%), but none of the apparent differences (Figure 3) were significant.

The initial soil moisture from the laboratory measurements was 7% for the uncompacted bare plots and none of the other treatments significantly varied from this (Table 1). The soil moisture from the sensor at 3 cm below the soil surface started at 3% for the uncompacted bare plots and the initial value for the uncompacted mulch plots was not significantly different (Table 2). The compacted plots all had initial soil moisture of 9%. The soil moisture increased significantly for each treatment during the Dry run (Table 2). The soil moisture in the uncompacted treatments increased for the first 20-25 minutes of the Dry run and then leveled off. The relatively rapid increase in the uncompacted plots resulted in 40% soil moisture in the uncompacted bare plots and 44% soil moisture in the uncompacted mulched plots at the end of the Dry run (Figure 2), and these values were not significantly different (Table 2). The soil moisture for the uncompacted plots decreased slightly before the start of the Wet run, and then increased to a relatively constant value within about 5 minutes (Figure 2), and remained at or near the values measured at the end of the Dry run through the rest of the simulations (Table 2; Figure 2). In contrast, the soil moisture in all the compacted treatments increased more gradually (Figure 2), and the compacted bare plots averaged only 22% at the end of the Dry run, which was significantly less than the uncompacted bare plots (Table 2). Neither the compacted mulch nor the compacted slash plots had a different soil moisture than the compacted bare plots at the end of the Dry run (Table 2). The gradual increase in soil moisture in the compacted plots continued through the Wet run (Figure 2) and the increase in the soil moisture at the end of the Wet run was significant for the compacted bare plots (Table 2). At the end of the flow run none of the treatments had a significantly different soil moisture than the uncompacted bare plots (Table 2).

3.2. Erosion results

The uncompacted bare plots on average produced 21 g of splash erosion in the Dry run and 17 g in the Wet run (Table 2). The compacted bare plots produced nearly double these amounts (Figure 3a), 42 g in the Dry run and 32 g in the Wet run, although the differences were not significant (Table 2). Mulching significantly reduced rainsplash in the uncompacted soils by 73% and 78% for the Dry and Wet runs, respectively. Similarly, the mulch and slash on the compacted soils both significantly reduced rainsplash by 72% to 79% for the Dry and Wet runs (Table 2). In all the treatments rainsplash was slightly higher on the Dry run than on the Wet run, and the difference was significant for the compacted mulch plots.

The mean sediment concentration in the uncompacted bare plots was 18 g l^{-1} in the Dry run, 14 g l^{-1} in the Wet run, and 89 g l^{-1} in the more erosive Flow run (Table 2). Soil compaction increased sediment concentration during the Dry (23 g l^{-1}) and Wet (22 g l^{-1}) runs on the bare plots, but neither of these values were significantly different than the uncompacted bare plot values (Table 2). In contrast, the Flow run of the compacted bare plots had a significantly lower sediment concentration (28 g l^{-1}) than the comparable concentration in the uncompacted bare plots (Table 2). The mulch cover reduced the sediment concentrations in all runs as compared to the bare plots with comparable level of compaction, and the reductions were significant in the Flow run (Figure 2; Table 2). The slash plots produced somewhat lower sediment concentrations than the compacted bare plots in the Dry and Wet runs, but the differences were not significant (Table 2). The sediment concentration in the Flow run of the compacted slash plots, which did not have simulated ruts, increased relative to the compacted bare plots, but this difference also was not significant (Table 2).

Mean sediment yields for the uncompacted bare plots were 180 g m^{-2} for the Dry run, 317 g m^{-2} for the Wet run, and 858 g m^{-2} for the Flow run (Table 2). Soil compaction in the bare plots produced not significant increases in sediment yields, despite compaction ratios for sediment yield of 1.90 and 1.77 for the Dry and Wet runs, respectively (Figure 3a). However, the mean sediment yield in the Flow run in the compacted bare plots was only 28% of the value for the uncompacted bare plots (Figure 3a), and this was a significant decrease (Table 2). Mulching significantly reduced sediment yields by 64% for the Dry run, 62% for the Wet run, and 95% for the Flow run relative to the uncompacted bare plots (Table 2; Figure 3b). The sediment yield on the compacted mulch plots was about half the yield on the compacted bare plots for the Dry and Wet runs (Figure 3b), and for the Flow run the reduction was 78% (Figure 3b), which was significant. The compacted slash plots produced slightly lower sediment yields for the Dry and Wet runs than the compacted bare plots, and greater sediment yields for the Flow run (where no ruts were introduced in the plots), but none of these differences were significant (Table 2).

The three-factor statistical models which assessed the relative strength of compaction, mulch cover, and run, indicate that compaction was a stronger control for the hydrologic variables of runoff, leaching, and soil moisture, while cover exhibited a stronger control on runoff start and end times (Table 3). The F-values for all the hydrologic variables except for runoff start and end times decreased slightly when the Flow run data were included in the analysis, but the same overall results were produced (Table 3). The mulch cover factor was a stronger control for splash, sediment concentration, and sediment yield. The F-value for splash stayed the same and the F-values for sediment concentration and sediment yield increased when the Flow run was included (Table 3).

4. Discus on

4.1. Compaction effects on runoff

We increased the bulk density in our sandy loam soil by 20% with the compaction treatment. The significantly lower infiltration and leaching in the compacted plots was attributed to decreases in micro-porosity (Ares et al., 2005; Schäffer et al., 2007). During the Dry run, uncompacted soils were able to store 18-19 mm and leached 1-3 mm of the rainfall, while the compacted soils stored only 8-12 mm of rainfall, and produced negligible leaching (Figure 4). As a consequence of the lower infiltration, compacted soils produced 41% and 127% more runoff under dry soil conditions for compacted bare and mulched plots, respectively, relative to their uncompacted counterparts (Figure 3a). The increase in runoff was less pronounced for the Wet run, and this result was similar to results from rainfall simulations on native surface roads (Foltz and Burroughs, 1990). Lower increases in bulk density (2-14%) on agricultural sandy loam soils also led to 8-33% more runoff (Adekalu et al., 2006; Ekwue and Harrilal, 2010). On the other hand, compaction of finer-textured soils led to lower increases in bulk density (4-6-%), but greater increases in runoff than we measured (25-70%), irrespective of laboratory or field conditions (Ekwue and Harrilal, 2010). These comparisons illustrate that the relationship between runoff response and bulk density is not linear. The impact of compaction on bulk density depends on soil texture, soil organic matter, soil moisture, and the compaction method, and these dependencies can explain some of the differences in the changes in observed bulk density among these studies. Also, as demonstrated in our study and the previous studies (Adekalu et al., 2006; Ekwue and Harrilal, 2010), it is difficult to simulate an increase in bulk density that replicates field conditions.

In the uncompacted plots, the soil moisture at 3 cm and runoff generation were delayed until about 5-8 minutes into the dry run, and we attribute this to filling of the interception and surface storage capacity. These results were similar to other rainfall simulation studies (Groen and Woods, 2008; Robichaud et al., 2016) where this early period was identified as having the highest infiltration capacity. This initial delay in runoff was followed by a period (5-25 minutes in the Dry run (Figure 2) when both soil moisture and runoff generation rapidly increased. The runoff during this period was generated by infiltration excess, as concomitant increases in soil moisture resulted in lower infiltration capacity in the plots from about 5-25 minutes in the Dry run (Figure 2). After about 25 min into the dry run, the soil moisture was relatively stable and near its maximum, and this is likely when the wetting front reached the soil moisture sensor. From 25 min through the remainder of the Dry, Wet and Flow runs the runoff was approximately steady (Figure 2), and still generated by infiltration excess, but the infiltration was at a minimum. Saturation never occurred in the uncompacted plots because they were able to freely drain, and there were no impeding interfaces within the soil profile.

In the compacted plots, the increase in soil moisture at 3 cm depth was much slower than in the uncompacted plots, and we attribute the reduced rate to lower porosity and lower unsaturated soil hydraulic conductivity. The lower porosity also reduced the total water storage capacity of compacted plots. Even though the storage capacity was lower than in the uncompacted plots, it took longer to wet up because of the lower conductivity in the compacted soil. In this sense, the compaction effect on infiltration (and hence runoff) would be similar to that of other processes that impede infiltration such as soil sealing (Smets and Poesen, 2009) or soil water repellency (Shakesby and Doerr, 2006).

4.2. Compaction effect on erosion

The Dry, Wet, and Flow runs produced different results for each erosion process. Rain splash was slightly higher for the Dry run than for the Wet run (Table 2), and this was attributed to a higher depth of surface water in the Wet run because of the increase in overland flow during that period, which provided more protection from raindrop detachment (Sander et al., 1996). During the Dry run, soil compaction doubled rain splash as compared to the uncompacted plots. We attribute this increase to the destruction of the remaining aggregates on the surface of the soil by the pressure we applied via the plate to compact the soil. In contrast, the uncompacted plots retained small aggregates and a higher soil roughness (Schäffer et al., 2007; Julião et al., 2011). The fewer number of small aggregates and the pressure in the compacted plots resulted in a lower soil roughness, and rainsplash has been shown to increase on as soil surface roughness decreases (Roth and Helming, 1992).

Sheetwash, measured by sediment yield, increased across all the treatments from the Dry to the Wet run. The increase in sheetwash yield was a consequence of greater runoff volumes in the Wet runs and similar sediment concentrations between the Dry and Wet runs. Compaction doubled the amount of sheetwash sediment delivery, and this result is consistent with earlier studies. For example, post-fire soils compacted by heavy logging machines exhibited increases in soil losses of 7 to 17fold, as compared to uncompacted burned and logged (Wagenbrenner et al., 2016) or unlogged soils (Malvar et al., 2017).

The sediment yield compaction ratios (compacted/uncompacted) in previous studies were higher for dry soils (2 to 6) than for wet soils (1 to 1.8) (Burroughs and King, 1989; Foltz and Burroughs, 1990; Wilson, 1999; Croke et al., 2001). The compaction ratio for our bare plots in the Dry run (1.9) was close to the corresponding range from the previous works, and our ratio for the Wet run (1.7) was in the range from earlier studies (Figure 3a). In contrast to our findings and the compaction ratios from earlier research, some earlier studies have shown that compaction decreased soil loss by 19 to 54% as compared to uncompacted soils (Adekalu et al., 2006; Ekwue and Harrilal, 2010). Those results were attributed to greater soil strength resulting from compaction and were determined on soils with less compaction (10-14% increases in bulk density) than in our experiment. Some evidence of these contrasting findings were apparent in our Flow run, where compaction and simulated rutting decreased rill sediment delivery by 72% on the bare plots. We attribute this to both the higher erodibility of the uncompacted bare soils, and the confinement of the runoff in the simulated ruts. Ruts have been found to increase erosion as compared to unrutted areas (Foltz and Burroughs, 1990), but here again it is difficult to separate the effect of the higher bulk density (and presumably greater soil strength) and the effect of flow concentration within the ruts. Prototype experiments without ruts resulted in rill sediment delivery rates of 390 g m^{-2} (data not shown), whereas the mean sediment delivery with ruts in our uncompacted bare plots was 2.2 times this value and 3.6 times the sediment delivery from the compacted soil with ruts. In summary, ruts were very effective in concentrating runoff (Figure 1), but deeper rilling and greater sediment delivery happened only as a result of both rutting and low bulk density on the uncompacted bare soils (Figure 6).

4.3. Cover effect on hydrologic responses

Neither mulch nor slash led to significant runoff reductions in the uncompacted or compacted plots, and these results were consistent with some other research using rainfall simulations (Pannkuk and Robichaud, 2003; Robichaud et al., 2013c) and natural rainfall (Robichaud et al., 2013a, b). However, some studies have reported decreases in runoff rates when mulch was tested using rainfall simulations in laboratory (Adekalu et al., 2006; Ekwue and Harrilal, 2010; Foltz and Wagenbrenner, 2010) and field settings (Groen and Woods, 2008), as well as in field settings under natural rainfall (Prats et al., 2012; Jourgholami and Abari, 2017). Conceptually, the differences among these results may be related to the soils, the amount and rate of rainfall applied, the interception storage capacity of the mulch, the plot dimensions, or the analytical technique. However, the results in both categories spanned a wide range of simulated rainfall intensities (34-65 mm h^{-1} in the no mulch effect group, 51-100 mm hr^{-1} in mulch effect group) and similar plot sizes (0.5 to 4 m^2 no effect and 0.5-4.8 m^2 for the mulch effect group). Unfortunately insufficient details are provided across the different soils regarding permeability and about the water storage potential of the mulches to draw any general conclusion. Future research may answer the question about why mulching sometimes reduces runoff.

Similarly, in our study, neither mulch nor slash led to changes in leaching for the timescale of the simulation (Table 2), but some differences are noticeable in the time series data (Figure 2). Previous research on surface cover materials such as mulch, ash, and stones has shown that the presence of these materials can increase leaching (Ruiz-Sinoga and Martinez-Murillo, 2009; Prats et al., 2017, 2018). Changes in leaching have been related to the water volume storage of the surface components. For example, our mulch and slash water storage capacities were 0.5 and 5 mm, respectively (Figure 4). Until the time the storage was filled, this surface storage would reduce runoff volume and therefore runoff velocity and erosivity. More importantly, the wet mulch or slash layer may also increase the water contact at the soil surface, thereby promoting infiltration through larger pores that are only conductive near saturation (Woods and Balfour, 2010). These differences were not enough to affect the plot-scale runoff or leaching rates, but they can be observed in the differences in the hydrographs of the uncompacted plots (Figure 2). The mulched plots show slightly higher rates of soil moisture increase and lower runoff rates in the uncompacted plots. In the compacted plots, the pores were smaller, and the difference in porosity (Schäffer et al., 2007), explains the lack of observable impact of mulching on the soil moisture after the Dry run (Figure 2) and the lack of difference in runoff among the bare, mulch, and slash plots. Thus, in our study, the mulch and slash stored water on the compacted soils, which was also shown in the longer runoff start and end times, but this effect was countered by the loss of larger pores due to compaction, resulting in infiltration primarily via capillarity and therefore a much lower hydraulic conductivity and hence total infiltration rate.

4.4. Cover effects on erosion

Mulching resulted in higher reductions of splash erosion (73-78%) than sheetwash erosion (51-64%) as compared to unmulched plots. We attribute the changes in splash to reduced energy as the drops hit the soil due to mulch interception, which is reflected in the longer runoff start times in the uncompacted mulched plots during the Dry run as the mulch absorbed much of the first 0.5 mm of rainfall. The runoff start times for the Wet and Flow runs in the mulch and slash plots were nearly double their counterparts in the bare plots for both the uncompacted and compacted conditions, although none of these differences were significant. The tendency toward longer start times, after the storage capacity of the mulch was filled during the Dry runs, reflect the increased surface roughness and resultant reduced runoff velocity and erosive power of the runoff (Robichaud et al., 2013c; Foltz and Wagenbrenner, 2010) .

Shredded sequoia bark mulch, applied at a rate of 2 Mg ha-1 and 60% cover reduced the overall sediment yield by 84% for the uncompacted soils and by 61% for the compacted soils. Similar reductions in sediment yields have been shown for straw mulch at comparable rates of surface cover on native surface roads (Burroughs and King, 1989). Mulching provides surface cover and thereby serves the same role as a natural soil cover of litter or vegetation, absorbing rain drop energy and reducing splash detachment and soil (de Figueiredo and Poesen, 1999; Larsen et al., 2009). Mulch of different types including agricultural straw, wood shreds, and shredded bark has been shown to reduce erosion after wildfires due to these reasons (Badía and Martí, 2000; Wagenbrenner et al., 2006; Kim et al., 2008; Prats et al., 2012; Robichaud et al., 2013a, 2013b, 2013c).

The slash reduced splash erosion as efficiently as the mulch, but there was only a slight reduction in sheetwash, and this occurred only in the Dry run. The sharp increases in sediment concentration from the Dry to Wet to Flow runs (12, 20 and 40 g l^{-1}, respectively) indicated that the splash-detached particles were not stored by the slash, and that they were available for transport by overland flow. Further, because the slash cover was made up of larger pieces of material than the mulch, there was less contact between the slash and the soil surface and therefore a smaller increase in surface roughness for the same amount of surface cover (Figure 7), resulting in ample transport capacity to deliver the particles to the outlet of the plot. Other research using different slash materials found striking differences in erosion mitigation, possibly due to the wide application rates, length and contact of slash pieces and possibly also due to differences in wildfire severity or other plot or soil characteristics. Shakesby et al. (1996) found that 80% cover of pine slash only reduced erosion by 50%, while 89% cover of eucalypt slash reduced erosion by 91%. In contrast, Prats et al. (2012) found that 76% cover of eucalypt slash only reduced erosion by 16%.

Although other research has suggested that achieving 60-70% ground cover in burned areas can significantly reduce soil erosion, our results suggest that increasing both the amount of surface cover and the degree of contact of the cover with the soil surface are important (Paningbatan et al., 1995; Wagenbrenner et al., 2016). Slash seemed to reduce sediment delivery while the soil was relatively dry, even though the splash detachment from the dry soil was greater, because the runoff generation and transport capacity were low. But because the slash was not as continuously in contact with the soil as the mulch, it allowed sheet flow to travel underneath with less impedance. In contrast, mulching locally slowed the runoff, allowing some sediment to deposit without resuspension. Some studies concluded that slash needs to be in contact with the soil surface to maximize erosion reduction (Cambi et al., 2015; Wagenbrenner et al., 2016). Slash added to the soil before the passing of machinery reduced soil compaction (Eliasson and Wästerlund, 2007) and will probably reduce sediment yields due to increased contact with the soil. This aspect of slash remains to be tested under controlled or natural runoff conditions.

5. Conclusions

We assessed soil compaction (uncompacted or compacted) and the presence (0% or 60% cover) and type of ground cover (bark mulch or logging slash) on the hydrologic and erosion responses of a burned soil using laboratory rainfall simulations (30 min of rainfall at 72 mm h^{-1}) on dry and wet soil followed by concentrated flow pulses on wet soil.

The runoff coefficients (runoff/rainfall) for the combined Dry and Wet runs were 48% for the uncompacted bare plots and 60% for the compacted plots, reflecting the apparent but not significant increase in runoff due to compaction. Mulching of these plots slightly reduced the runoff coefficient on the uncompacted plots (42%), but there were no differences in runoff after the addition of mulch or slash cover on the compacted plots. Leaching accounted for 10% of the incident rainfall on the uncompacted bare plots and this decreased significantly to 0% due to compaction. Mulching again resulted in not significant increases in leaching (16% of rainfall) on the uncompacted plots, but had no effect on the compacted mulch or slash plots. Soil compaction also increased rainsplash from 38 g in the uncompacted plots to 74 g in the compacted plots, and sediment delivery by sheetwash (496 uncompacted, 902 g m^{-2} compacted) but these differences were not significant. Rill sediment delivery in the Flow run decreased from 858 in the uncompacted bare plots to 237 gm^{-2} in the compacted bare plots, and we attribute this significant decrease to the greater energy needed to detach soil particles in the compacted plots.

The mulch significantly reduced rainsplash by 72%, sheetwash by 63%, and rill sediment delivery by 95% as compared to the uncompacted bare soil. Mulching of the compacted soils significantly reduced splash by 78%, sheetwash by 52%, although not significantly, and rill sediment delivery by 78% as compared to the bare, compacted soils. Slash cover on the compacted plots also significantly decreased rainsplash erosion by 75%, but had no significant effect on sheetwash or rill sediment delivery as compared to the compacted bare plots. While the reductions in rainsplash in the mulched plots were attributed to the reduced energy imparted to the soil by rain drops, the reductions in sheetwash and rilling were assigned to the increase in roughness and high degree of contact between the mulch and soil surface, which combined resulted in less energy available for particle detachment and transport by overland flow. Like the mulch, slash provided enough areal cover to reduce rainsplash erosion, but unlike the mulch, its lack of surface contact did not affect soil detachment or transport capacity of either sheetwash or concentrated flow.

Our results suggest that soil compaction that can occur during post-fire logging with ground-based machinery may increase runoff and significantly increase erosion rates at small spatial scales. Increasing surface cover using mulch from the shredded bark of *Sequoia sempervirens* or from logging slash did not reduce runoff rates but both types of cover reduced rainsplash, and the mulch also reduced sediment delivery by flowing water. Post-fire logging slash placed on bare, compacted soil lacked contact with the soil and did not affect interrill or rill sediment delivery rates. The potential reduction capacity of adding slash as a post-fire logging erosion mitigation practice may increase by either shredding the slash to make the pieces smaller prior to application or by applying the slash before or during the use of heavy machinery so that the slash is better incorporated in the soil.

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TABLES CAPTIONS

Table 1. Characteristics of the soils, treatments and simulations. Values are means ± one standard deviation of three soil samples on each of four replicates per treatment. Different letters within a row correspond to significant differences ($p \leq 0.05$) among treatments.

Table 2. Hydrologic and erosion responses for each treatment and run. Values are means ± one standard deviation. Soil moisture values were gathered with the soil moisture sensor. All variables except runoff were 4th root-transformed prior to statistical analysis to achieve normally distributed model residuals. Different letters within a row correspond to significant differences in the transformed run means between treatments. Differences in transformed means between sequential runs (Dry-Wet and Wet-Flow) within a treatment (column) are significant if the type face differs (plain text, bold or underlined). For all comparisons, $\alpha = 0.05$.

Table 3.F values of reduced three-ways mixed-effects statistical models comparing the impact of soil compaction and mulch cover. Data from the compacted slash treatment were excluded from these statistical models. The two sets of models pool the Dry and Wet runs (D+W pool) and the Dry, Wet and Flow runs (D+W+F pool).All data except runoff and final soil moisture were fourth-root transformed prior to analysis. Bold text indicates significance at $p \leq 0.05$.

FIGURES CAPTIONS

Figure 1. Photographs of the two uncompacted treatments (a, b), the three compacted ones (d, e, f) and a detail of the experimental set up (c). The inflow distributor box, splash fabric, and leaching and runoff collection apparatus are highlighted with yellow arrows in c).Treatment abbreviations are: “u_” for uncompacted and “c_” for compacted; and “bare”, “mulch” or “slash” correspond to uncovered (0%), mulch-covered (60%) or slash-covered (60%) soils, respectively.

Figure 2. Mean runoff coefficient (% of rainfall or flow volume), soil moisture (% volume) and sediment concentration (g l^{-1}) for the five treatments at 1-minute intervals for the Dry and Wet runs and for each pulse event for the Flow run. The sediment concentration axis is in logarithmic scale. Abbreviations are described in Figure 1.Treatments followed by different letters within the same run are statistically different, and runs followed by different text format (lowercase, uppercase or underlined) within the same treatment are statistically different at $p \leq 0.05$.

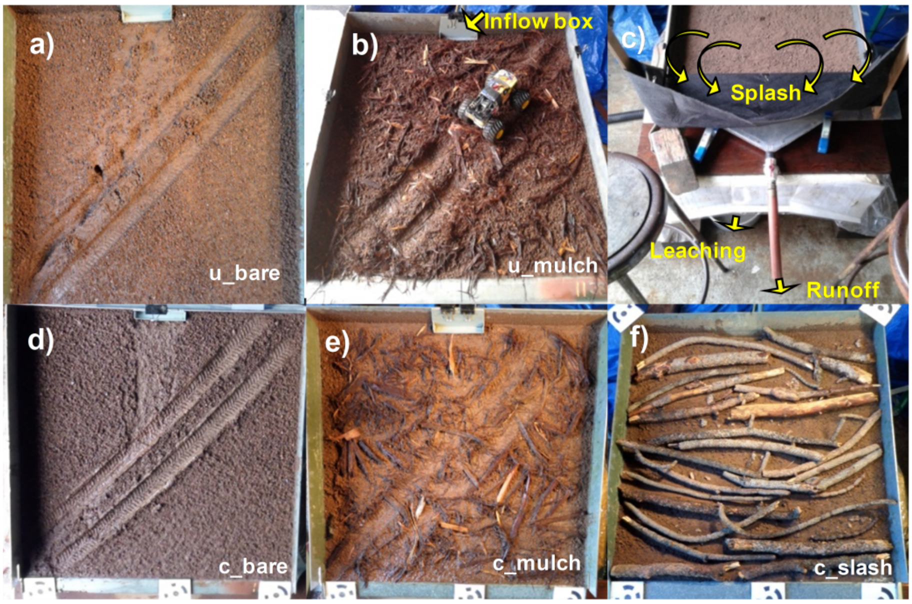
Figure 3.a) Compaction ratios -compacted value/uncompacted value- and b) cover ratios -(mulch or slash value)/bare value- for runoff, leaching, splash and sediment yield for each run. Abbreviations are described in Figure 1.

Figure 4. Water budget for each treatment and run. Cover and soil water volumes were calculated using mulch/slash water retention capacities, initial/final soil moisture, soil weight and bulk density. All water volumes (in mm) corresponded to the increments due to each simulation. Error bars represent the difference of the water budget to the average incident rainfall or flow volumes (in mm).

Figure 5. Splash erosion rate (g per m^2 of projected area) versus sheetwash erosion rate(g m^2) for each treatment for the Dry run (a) and Wet run (b) and splash erosion rate (average for Dry and Wet runs)versus rill erosion rate (g m^2)for the Flow run (c). Lines represent simple linear regressions with 0 intercept, and r values are correlation coefficients.

Figure 6. Combined overland flow (a), splash (b), sheet wash erosion (c) and sediment concentration (d) for the Dry and Wet rainfall simulations, and the rill flow (e) and rill erosion (f) for the Flow runs.

Figure 7. Photographs of compacted slash (a) and compacted mulch (b) plots after the Flow run, and the same plots with the cover materials removed which reveals the contact areas (c and d).


a)
u_bare
b)
Inflow box
u_mulch
c)
Splash
Leaching
Runoff
d)
c_bare
e)
c_mulch
f)
c_slash

Treatments Compaction	Uncompacted		Compacted		
Cover	Bare	Mulch	Bare	Mulch	Slash
Soil characteristics					
Soil mass (Kg)	21±0a	21±0a	31±0b	31±0b	31±0b
Soil depth (cm)	4.6±0.1a	4.6±0.3a	5.4±0.1b	5.1±0.3b	5.3±0.3b
Bulk density (g cm^{-3})	0.91±0.02a	0.89±0.04a	1.09±0.02b	1.06±0.03b	1.07±0.02b
Soil moisture (% vol.)	7±1a	6±3a	9±1a	7±2a	7±1a
Treatment characteristics					
Cover material	None	Shredded sequoia bark	None	Shredded sequoia bark	Logging slash
Application rate (Mg ha^{-1})	0±0a	2±0b	0±0a	2±0b	34±1c
Ground cover (%)	0±0a	63±3b	0±0a	63±2b	61±2b
Simulation characteristics*					
Dry run rainfall (mm)	34±1a	34±0a	34±1a	34±1a	34±0a
Wet run rainfall (mm)	34±1a	34±1a	34±1a	34±1a	34±0a
Flow input (mm)	11±0a	11±0a	10±1a	10±1a	11±0a
Flow input (l min^{-1})	4±1ab	5±0a	4±0b	4±1ab	5±0a

* Treatments and runs had n=4 except uncompacted bare, mulch and compacted bare on the Flow run (n=3).

Compaction	Uncompacted		Compacted		
Cover	Bare	Mulch	Bare	Mulch	Slash
Runoff start time (s)					
Dry	276±63b	487±200a	213±47b	191±28b	200±20b
Wet	**52±9a**	**90±24a**	**58±3a**	**85±12a**	**81±5a**
Flow	4±0a	8±0a	3±1a	8±1a	6±2a
Runoff end time (s)					
Dry	189±27a	185±25a	124±12a	155±16a	149±13a
Wet	175±17b	235±62ab	216±59ab	**341±113a**	249±41ab
Flow	177±16c	406±86ab	306±91bc	588±173a	**440±140ab**
Runoff (mm)					
Dry	10±1bc	8±5c	15±1abc	18±2a	18±1ab
Wet	22±2ab	21±5b	26±2ab	27±1a	28±1ab
Flow	**10±0a**	**8±1a**	**9±1a**	**9±1a**	**9±0a**
Soil moisture (% vol.)					
Dry at t_0	3±1a	5±1ac	9±1b	9±1b	9±1bc
Dry at t_{30}	**40±8ab**	**44±8a**	**22±10c**	**28±6bc**	**22±7c**
Wet at t_0	**37±8a**	**41±5a**	**28±5a**	**31±3a**	**27±2a**
Wet at t_{30}	**40±6a**	**46±3a**	40±5a	**37±3a**	**32±2a**
Flow at t_0	**39±8a**	**44±0a**	38±7a	40±3a	**34±2a**
Flow at t_{30}	**41±6a**	**45±1a**	39±2a	40±2a	**35±1a**
Leaching (mm)					
Dry	1±1ab	3±2a	0±0b	0±0b	0±0b
Wet	**6±2a**	**8±3a**	1±0b	0±0b	0±0b
Flow	0±0a	2±1a	0±0b	0±0b	0±0b
Splash (g)					
Dry	21±11ab	6±2c	42±13a	**12±3bc**	9±3bc
Wet	17±9ab	4±2c	32±12a	7±3bc	9±3bc
Sediment concentration ($g\ l^{-1}$)					
Dry	18±6ab	9±5b	23±6a	9±2b	12±2ab
Wet	14±4ab	6±2b	22±5a	10±1ab	20±2a
Flow	**89±21a**	5±2c	28±13b	6±1c	**40±14b**
Sediment yield ($g\ m^{-2}$)					
Dry (sheetwash)	180±49a	65±34b	341±94a	166±27ab	225±41a
Wet (sheetwash)	317±74a	119±49b	561±121a	264±30ab	**549±61a**
Flow (rill)	**858±236a**	**43±23c**	**237±100b**	**53±10c**	**371±145b**

Response	Variable	D+W pool Compaction	D+W pool Cover	D+W+F pool Compaction	D+W+F pool Cover
Hydrologic responses	Runoff start time (s)	**8.9**	**10.1**	**8.7**	**21.3**
	Runoff end time (s)	0.0	**9.4**	**5.3**	**35.4**
	Runoff (mm)	**14.2**	0.0	**10.4**	0.1
	Moisture initial (%)	4.0	1.6	1.6	1.6
	Moisture final (%)	**12.4**	1.2	**7.0**	0.8
	Leaching (mm)	**70.6**	0.1	**65.0**	0.1
Erosion response	Splash (g)	**8.9**	**36.9**	**8.9**	**36.9**
	Sediment conc. (g l^{-1})	**18.5**	**29.1**	3.5	**75.9**
	Sediment yield (g m^{-2})	2.6	**24.5**	0.0	**74.7**

Declaration of interests

X The authors declare that they have no known competing financial interests or personal relationships
that could have appeared to influence the work reported in this paper.

X The authors declare the following financial interests/personal relationships which may be considered
as potential competing interests:

Highlights:

- Runoff was 40% higher and leaching 95% lower in compacted than uncompacted plots
- Soil compaction increased rainsplash and sheetwash, but not rill erosion.
- Mulch and slash did not affect soil hydrology, but strongly reduced rainsplash.
- Mulch cover, but not slash cover, reduced sheetwash and rill erosion.
- Compaction and soil cover contact were drivers of hydrologic and erosive variables.