FINAL REPORT

Title: Experimental investigation of slope and precipitation intensity on post-fire mulching effectiveness

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Research Supporting Sound Decisions

Experimental investigation of slope and precipitation intensity on post-fire mulching effectiveness

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CU: Christiansen's Uniformity

Acknowledgements

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Abstract

Mulch application following wildfire is increasingly being used to mitigate hillslope runoff and erosion. A mulch coverage of 70% has been proven to be effective in reducing sediment losses; however, most previous studies test only a single slope and rainfall regime when evaluating mulch type and coverage. Experimental studies across a wider range of slopes and rainfall intensities are needed to help identify hillslopes that will respond best to mulching at this coverage. The purpose of this study is to experimentally investigate the percent reduction of runoff and sediment yields with mulching for a wide range of slopes and rainfall intensities using slope-model rainfall simulations. We conducted experiments on a 1 m^2 inclined plot with a full cone nozzle lifted 3 m above the plot. We tested two slopes (20% and 40%) at three different rainfall intensities (30, 60, 90 mm/h for 20 min) for 0% and 70% mulch coverage. Mulch was effective at all tested slopes and intensities, reducing 76-100% of the unmulched simulations' sediment yields. Mulch reduced sediment losses 12% more on the higher slope (40%) compared to the lower slope (20%). Although there was not a large difference between sediment reduction percentages across rainfall intensities, mulch reduced sediment yields the most during the lowest rainfall intensity of 30 mm/h. Runoff was not reduced between the mulched and bare soil conditions, which we attribute to pre-wetting the plot to saturation. Our study supplements previous research demonstrating that mulch effectively reduces sediment yield at the plot scale across the range of rainfall intensities. We recommend prioritizing mulch on steep slopes (> 40%) expected to experience 20-minute rainfall intensities greater than 30 mm/h, along with shallower slopes where downstream values may be at risk.

Objectives

The objectives of this study are to (1) determine the effects of mulch coverage on runoff amounts and sediment yields for different slopes and rainfall intensities using slope-model rainfall simulations; (2) establish relationships of runoff and erosion as functions of slope, rainfall intensity and duration, and presence/absence of mulch; (3) compare the results to past studies and observed field conditions.

Background

Numerous studies have shown runoff and erosion rates to increase by as much as one to three orders of magnitude after wildfire (e.g. Helvey, 1980; Robichaud et al., 2000; Benavides-Solorio & MacDonald, 2001). Consequently, mulch is often applied to burned soils as a layer of erosion protection. Studies have shown mulch to provide immediate ground cover, protection from raindrop impact, and increased hillslope roughness thereby reducing overland flow and stabilizing hillslopes (Foltz and Wagenbrenner, 2010; Robichaud et al., 2010a; Wagenbrenner et al., 2006). Of the various mulch types, wood strand mulch is widely used since it can be derived from native forest materials, is easily transported, and persists on hillslopes for up to 10 years (Robichaud et al., 2020). A mulch coverage of 70% has been proven to be most effective (Foltz and Copeland, 2009; Prats et al., 2017); however, it is often challenging and expensive to apply mulch to such coverage. Studies of wood strand mulch done in the lab sought to understand the optimum coverage for a single slope and rainfall regime (Foltz and Dooley, 2003; Yanosek et al., 2006; Foltz and Copeland, 2009; Foltz and Wagenbrenner, 2010; Prats et al., 2017). These studies proved the effectiveness of wood strand mulch in reducing sediment yields by up to 100% at 30-40% slopes and 20-25 min of rainfall at an intensity of ~50 mm/h. Field studies documenting intense localized storms on slopes between 18-62% indicate more variability in mulch effectiveness (Robichaud et al., 2013a; Fernandez et al., 2011; Prats et al., 2016). This may be due to a spatial scale disconnect in mulch research as well as differing site-specific variables. More testing of wood strand mulch at various slopes and rainfall intensities is needed to help identify hillslopes that will respond best to the 70% coverage treatment.

Prior to this study, we began a field study evaluating geomorphic change on paired mulched and unmulched watersheds in the 2020 Colorado Cameron Peak burn scar (Hayter, 2023). We flew drone surveys before and after a Colorado monsoon season to map erosion and deposition across 6 small watersheds (0.5 – 1.5 km^2): 3 were partially mulched and 3 were unmulched. We found mulch to have little impact on hillslope erosion 2 years after the fire. Instead, we found hillslope erosion to be most influenced by watershed attributes such as vegetation recovery, hillslope length, and rainfall intensity. It is important to note that only about ~30% of the mulched watersheds' footprints were mulched, and within the mulched areas, coverage was measured to average ~22%. Significant erosion was found on steep hillslopes (40%+) despite mulching; however, high erosion also occurred at lower slopes (20-30%) (Figure 1).

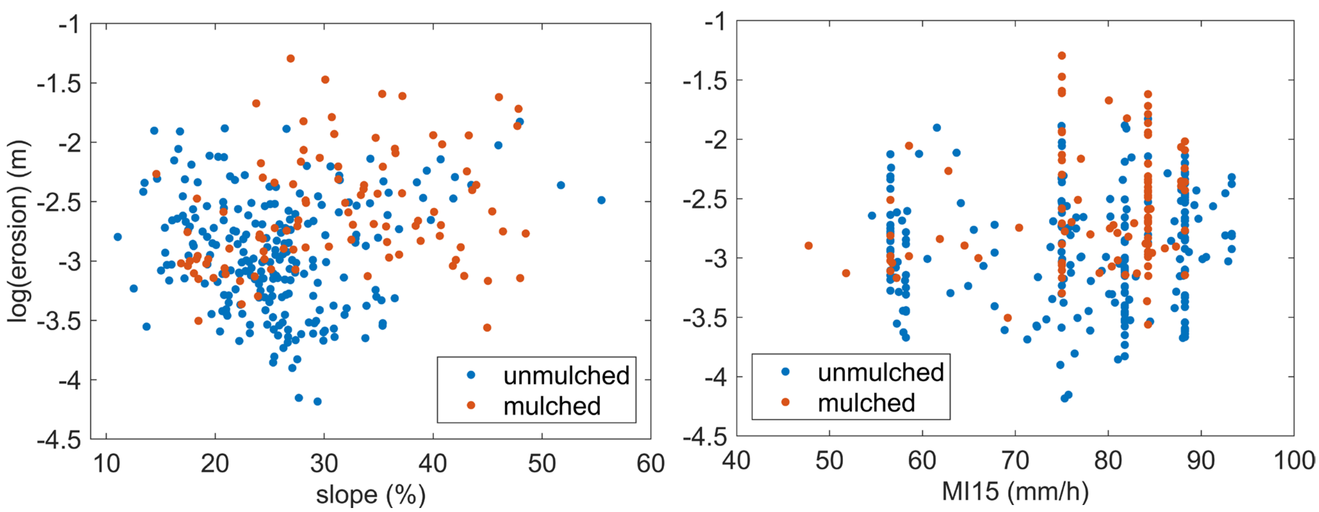

Figure 1. The erosion-slope relationship for the Bennett Creek field study indicates significant erosion occurring at both the high and low slope range (left). The erosion-intensity relation indicates a wide range of observed maximum 15-min rainfall intensities and erosion responses (right). Metrics were calculated over delineated watershed subunits. Erosion volume was summed over the subunit and divided by subunit area while slope and intensity (derived from NOAA MRMS estimates) were calculated by averaging values across each subunit.

From our field study findings, we ask the following question: if mulch had been applied to the desired coverage of 70%, would we have seen a greater impact of mulch, and for which hillslopes and rainfall rates would the impact have been greatest? Few lab studies have tested mulch effectiveness within the range of slopes and rainfall intensities we have seen in the field. Therefore, in this study we test slopes and intensities representative of field conditions (Figure 1), to broaden our understanding of the effectiveness of mulch on reducing runoff and erosion.

We conduct tests with an indoor rainfall simulator over a 1 m^2 sloped plot. Our purpose is to understand runoff and erosion response as a function of slope, rainfall intensity, and presence/absence of mulch.

Materials and Methods

Rainfall simulations were conducted on indoor soil plots during the summer of 2023 at the Hydraulics Laboratory, Colorado State University. Experiments were conducted in a steel-framed flume 92 cm wide, 278 cm long, and 28 cm deep. The test bed consisted of a sandy loam topsoil representative of that found on typical Colorado Front Range hillslopes. The soil had a grain size distribution as shown in Figure 1 with D_{16}, D_{50}, and D_{84} particle sizes of 0.4, 1.8, and 3.7 mm respectively.

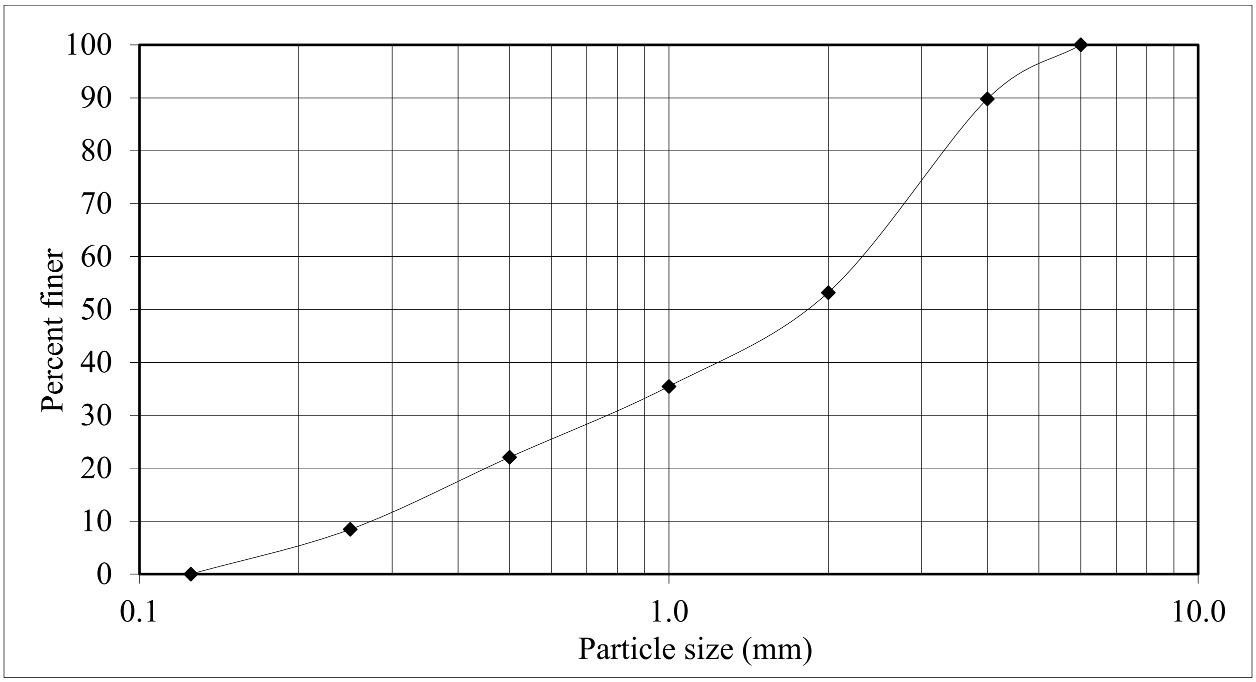

Figure 2. Grain size distribution of test soil

The flume and rainfall simulator setup is presented in Figure 3. The lowest 1 m^2 of the flume was filled with the soil and leveled with a straight edge blade to produce a uniform soil depth of 20 ± 0.2 cm. In this flume, subsurface drainage can seep through a 12 mm metal grid covered by a non-woven, 3 mm thick geotextile fabric at the downstream end of the steel framed plot, while surface runoff is directed through a tapered funnel. The slope of the flume is adjustable by rotating it about a center pivot and locking the flume in place with steel pins. A sprinkler-type rainfall simulator was set up 3 m above the flume on adjacent scaffolding. The simulator consisted of a FullJet 1/8 G1.5 full cone nozzle attached to a hose connected to the laboratory's water supply via a pressure-regulating valve. Salem and Meselhy (2021) found this nozzle type to achieve uniform rainfall distribution and yield Christiansen uniformity coefficients ranging from 89 to 95%. Spatial variability of the rainfall was tested by placing 16 evenly spaced cups on the plot and applying 90 mm/h rainfall for 5 min, and Christiansen's uniformity coefficient (CU) (Christiansen, 1942) was calculated for each test. Drop size distribution was determined using the Flour Pellet Method (Laws and Parsons, 1943, Chapman, 1948).

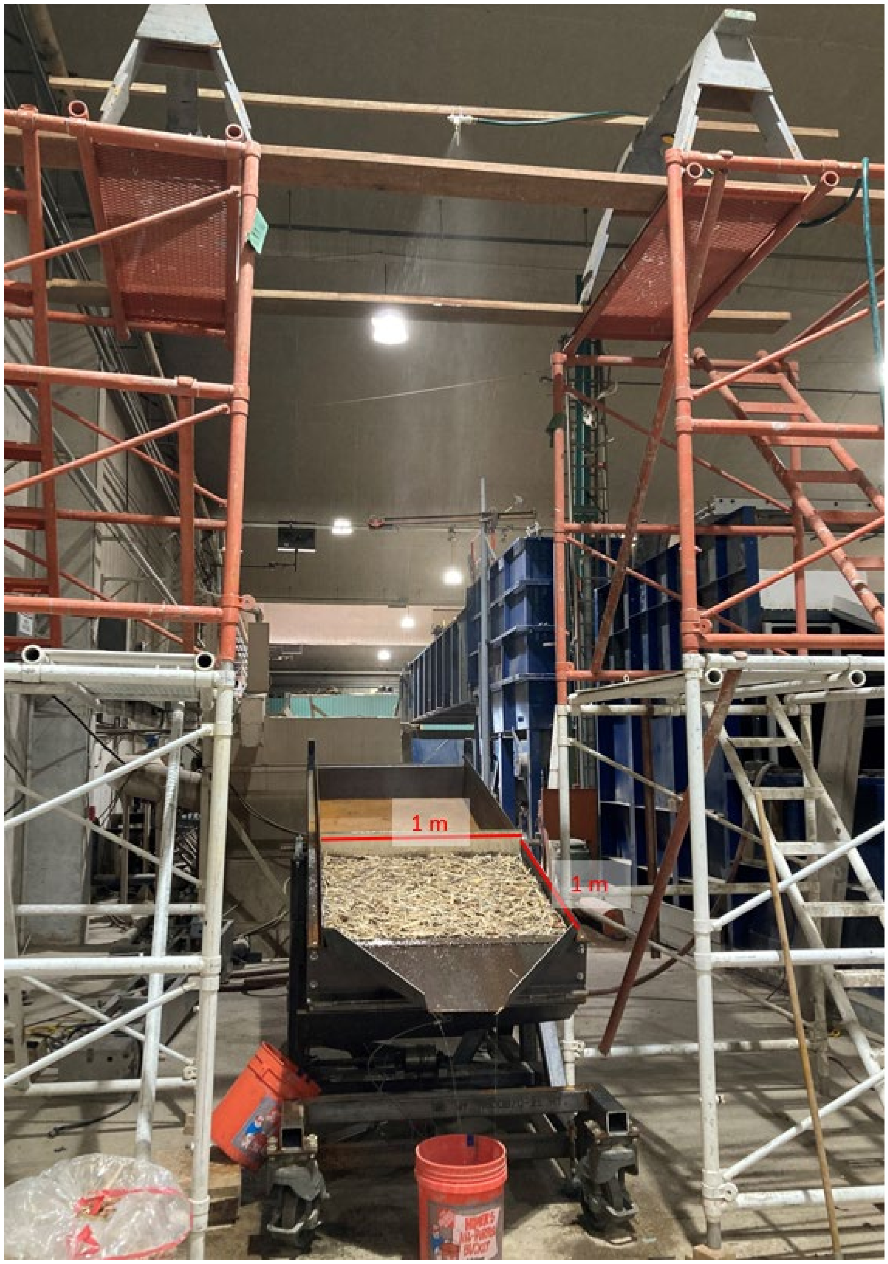

Figure 3. Flume setup with mulched soil filling the lower 1 m length of the tilt table.

Three rainfall intensity rates (30, 60, and 90 mm/h) and two slopes (20% and 40%) were tested on mulched and unmulched pre-wet plots, yielding a total of 12 simulations. The rainfall intensities of 30, 60, and 90 mm/h were obtained by varying water pressure and were chosen to represent summer storm conditions over the Bennett Creek field study site (Figure 1). Before each experiment, the plot was pre-wet using a rainfall intensity of 60 mm/h for 5 min until the soil became saturated without ponding. For experiments with mulch, wood shred mulch was applied by hand to the plot at 70% coverage. Coverage was confirmed using a photo taken above the plot overlain with a point intercept grid of 100 points. Coverage was adjusted by removing or adding shreds to a consistent spacing.

Each experiment lasted 20 min. During each simulation, runoff samples were collected during the last 10 seconds of each minute. Sediment concentration was determined by filtering the runoff, drying the filter (105℃ for 24 h; ASTM, 2007), and then prorating the runoff volume and sediment weight for the whole minute. Photos were also taken before and after simulations to document changes in mulch coverage and plots. After each experiment, soil was added to the plot surface as needed to return to the planar initial state and tamped down by hand before pre-wetting for the ensuing simulation.

To calculate percent reduction, total runoff volumes and sediment masses were computed across the 20 min simulation; then the difference between the bare-soil and mulched values was divided by the bare-soil value and multiplied by 100 to give percent reduction. A negative percent reduction indicated a percent increase.

Results and Discussion

Simulator Performance

The simulator produced a rainfall distribution yielding an average Christiansen coefficient of 47% (n=3). Rainfall can be considered uniform when CU is higher than 80% (Moazed et al. 2010), although CU is highly dependent on the sampling methodology employed (Green and Pattison, 2022). Variables affecting CU include resolution and spatial layout of samplers, area and time studied, as well as sprinkler intensity and pressure consistency. For example, Green and Pattison (2022) found CU to range from 45-81% for the same rainfall event. For our study, we prioritized a consistent intensity for the full area rather than fine spatial uniformity, so we considered a CU of 47% sufficient. Drop size for the nozzle was rated to be between 500 – 5000 µm, with specifications for drop size to decrease with increasing pressure at the nozzle. We visually verified this reduction in drop size with our increasing intensity simulations, as intensity was controlled by pressure. We measured a median drop size of 1440 µm for the 90 mm/h intensity. For recent northern Colorado events, disdrometers have measured a majority of droplets to be small to medium sized (median diameters < 1500 µm) (Friedrich et al., 2016), and so our droplet sizes are comparable to field conditions.

Hydrologic Response

Simulations indicated no significant decrease in runoff with mulching or slope increase (Figure 4). Mulch on the 20% slope reduced average runoff by about 3% for the 30 mm/h intensity, while average runoff slightly increased with mulch for the other intensities. On the 40% slope, mulching more noticeably reduced average runoff by 15, 3, and 9% for respective 30, 60, and 90 mm/h intensities. No large difference in runoff was observed from the 20% slope to the 40% slope. This is most likely due to the soil being saturated during the pre-simulation pre-wetting. Thus, the infiltration was fairly constant for the same rainfall intensities and mulch had little effect. Correspondingly, the hydrograph reached its peak flow in the first few minutes and sustained for the remainder of the simulation. Average runoff rates doubled from the 30 mm/h simulations to the 60 mm/h simulations. The 90 mm/h simulations did not experience the same scale of increase between intensities, which indicates a higher infiltration rate.

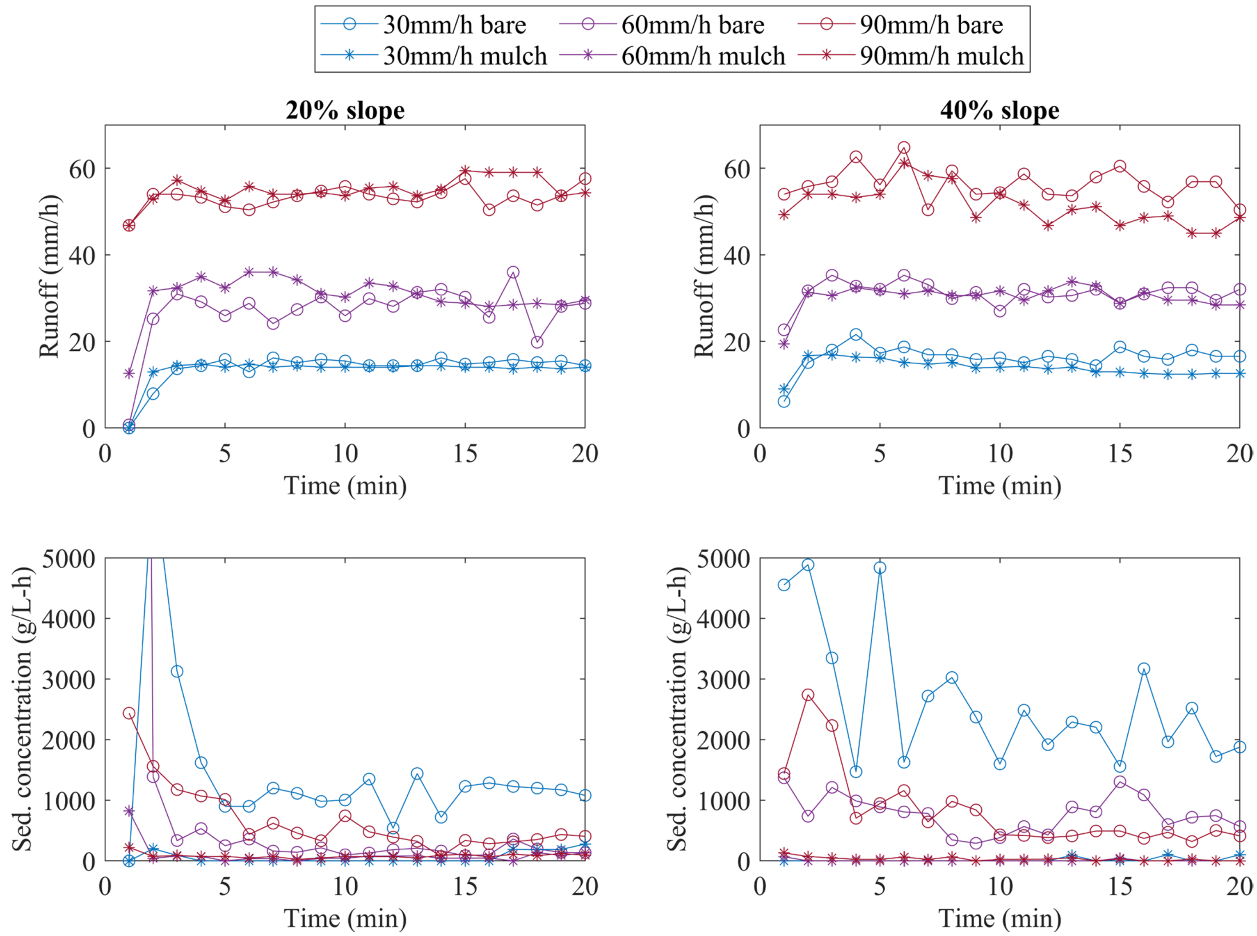

Figure 4. Runoff and sediment concentration measurements over time for 20% and 40% slopes

Erosion Response

Figure 4 shows the highest sediment concentrations occurred during the bare 30 mm/h simulations for both slopes. Visual observation indicated rainsplash erosion to dominate the 30 mm/h simulations while sheetwash erosion dominated the 90 mm/h intensity simulations. Erosion for the bare 90 mm/h case was overall greater per unit runoff compared to the bare 60 mm/h simulation. The 60 mm/h simulations yielded the least eroded sediment which may be attributed to the smaller droplet sizes than the 30 mm/h simulation and less rainfall volume than the 90 mm/h simulation. This simulation's rainfall characteristics seemed to offer the best balance for mitigating both rainsplash and sheetwash erosion. For all slopes and intensities, mulch was very effective, reducing 76-100% of the bare simulations' sediment yields. Very little mulch migration was found on both the 20% and 40% plots after simulations. Mulch was overall more effective at the lower rainfall intensities. Mulch reduced total erosion to similar masses for both slopes despite the bare 40% slope eroding more (Figure 5). Average percent reduction in sediment mass for the 40% simulations was 12% greater than the 20% simulations. Figure 5 shows the greatest sediment yields occurred during the 90 mm/h intensity and 40% bare slope, due to the volume of water flowing through the flume inducing sheetwash erosion. Even for the high-slope, high-intensity run, little evidence of rilling was observed, and post-simulation plots showed more pockmarks rather than flow paths.

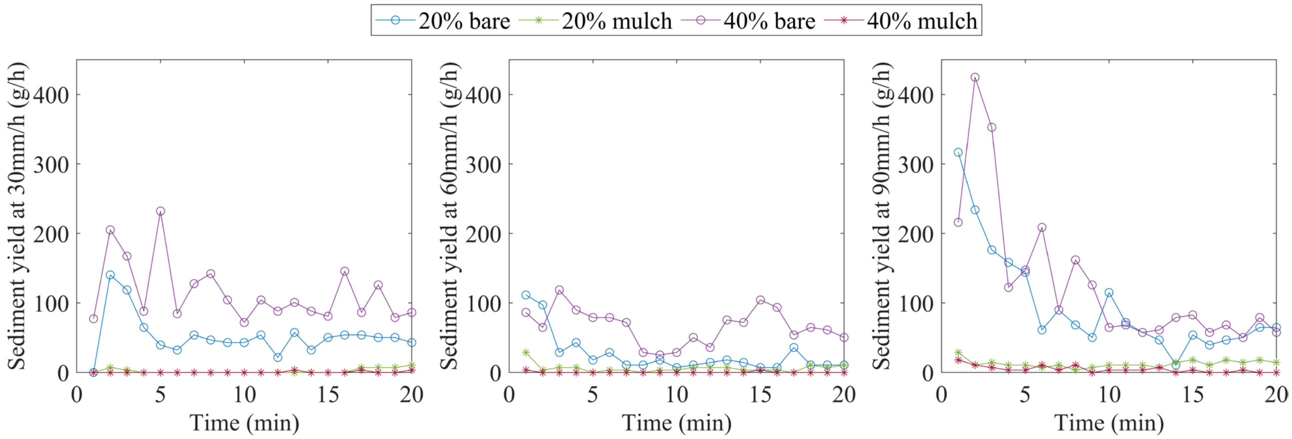

Figure 5. Sediment yield for 30, 60, and 90 mm/h intensities (left to right)

Comparison to Past Studies

Overall, mulch was effective at reducing sediment yields on the 20% and 40% slopes for all rainfall intensities tested. Mulch was most effective at the 40% slope since bare soil yields were initially higher. Past studies have found 70% mulch coverage to mitigate erosion up to 100% for different slopes and rainfall intensities (Table 1), which is similar to our results. Table 1 reviews previous literature testing the effectiveness of wood mulch on the plot-scale. Several of the studies listed included an overland flow analysis in their experimental set-up, which we excluded to allow for cross-comparison. Studies done by Foltz & Dooley, Foltz & Copeland, Yanosek, and Foltz & Wagenbrenner showed a decrease in runoff with added mulch. We instead report runoff reductions more similar to Prats et al., 2017 and 2019 where runoff did not significantly change and sometimes increased with added mulch. This discrepancy may be due to the prewetting methodology and soil saturation. Khan et al. (2016) conducted an in-situ experiment on burned soils and found that the slope contribution on water and sediment losses decreased with increasing rainfall intensity and slope steepness under both un-mulched and mulched soil. We also found intensity drove sediment losses but its influence was related to droplet size and sheer volume of water hitting the slope. Our study supplements previous literature demonstrating that mulch continues to be effective at both the high and low range of rainfall intensities on the plot scale.

Comparison to Field Observations

Our simulations were dominated by rainsplash and sheetwash erosion, so we cannot accurately scale our results to large-scale field conditions where more erosion processes are at play. For example, we saw little rilling on the test plots, but Bennett Creek field conditions showed widespread rilling on hillslopes and gully incision as deep as 0.5 m. Bennett Creek results also indicated erosion to increase with hillslope length up to ~240 m when it ultimately declined thereafter. This spatial scale disconnect, site-specific variables, and the fact that Bennett Creek mulch coverage was fairly low provide explanations as to why mulch had little impact at Bennett Creek. Future work should be done at a larger scale to understand the plot-hillslope-watershed scale erosion relationship.

Study	Scale	Soil	Slope	Mulch type	Coverage	Rainfall	Runoff reduction (%)	Sediment reduction (%)
Foltz & Dooley (2003)	indoor lab (5 m^2)	unburned gravely loam	30%	wood strands	70%	50 mm/h for 15 min	100	98
Yanosek et al. (2006)	indoor lab (5 m^2)	unburned sandy loam	30%	wood strands	30%	50 mm/h for 15 min	94	66
					50%		98	93
					70%		100	100
Foltz & Copeland (2009)	indoor lab (5 m^2)	unburned sandy loam	30%	wood shreds	30%	50 mm/h for 15 min	93	74
					50%		100	100
					70%		100	100
Foltz & Wagenbrenner (2010)	indoor lab (5 m^2)	burned sandy loam	40%	wood shreds	50%	50 mm/h for 15min pre-wet	77	82
							65	73
							88	76
					70%		81	95
							85	84
							82	87
Prats et al. (2017)	indoor lab (0.81 m^2)	unburned loamy sand	40%	bark strips (1 m length)	50%	56 mm/h for 20 min pre-wet	-25	81
					70%		-13	94
Prats et al. (2019)	indoor lab (0.81 m^2)	burned gravely sandy loam uncompacted	33%	shredded sequoia bark	60%	72 mm/h for 30 min pre-wet	5	62
							-4	53
Diaz et al. (2022)	Spain, plot (0.25 m^2) with simulator	burned sandy loamy	30%	wood shreds	50%	320 mm/h for 300 s	30	47
			50%		47%		6	57
Hayter & Nelson (2023)	indoor lab (1 m^2)	unburned sandy loam	20%	wood shreds	70%	30 mm/h for 20 min	4	96
						60 mm/h for 20 min	-13	76
						90 mm/h for 20 min	-3	87
			40%			30 mm/h for 20 min	15	100
						60 mm/h for 20 min	3	99
						90 mm/h for 20 min	9	96

Table 1. Reported mean runoff and erosion reductions for wood-mulch testing on plot-scale rainfall simulations

Conclusions and Implications for Management/Policy and Future Research

Mulch was effective at reducing sediment losses for all tested slopes and intensities. It was most effective at high slopes under low rainfall intensities, although not by an appreciable amount. Under bare soil conditions, the high-intensity simulation (90 mm/h) produced the most sediment mass. However, sediment concentration was greatest for the low-intensity simulation, which we attribute to the low intensity's larger droplet size. With mulch, both sediment masses and concentrations were greatly reduced for all simulations, indicating mulch to be effective at mitigating both rainsplash and sheetwash erosion. As expected, the bare 40% slope simulations eroded more than the 20% simulations, and mulch reduced sediment yields by 12% more on the 40% slopes. Runoff was not reduced between the mulched and bare soil conditions which we attribute to pre-wetting the plot to saturation. Our study expands the range of rainfall intensity and slope under which rainfall simulations have been conducted, and demonstrates that mulch can be effective under conditions we observed in the field if it is applied at 70% coverage. Due to time constraints, we were not able to validate our dataset with duplicate or triplicate simulations. Thus, we recommend future work be done to reproduce simulations and verify results. We also recommend adjusting the rainfall set up to allow for a more uniform distribution of rainfall and droplet size. Other variables such as burned soil, varying mulch coverage, and higher slopes could be tested to develop a more detailed relationship between slope, rainfall intensity, mulch coverage, and erosion.

Overall, our study along with prior rainfall simulations suggest that mulching at 70% coverage can be an effective tool to reduce hillslope erosion and sediment yields in high-risk burned areas. The greater effectiveness shown for steeper slopes in particular suggests that managers should continue to prioritize mulching steep slopes that experience intense storms, as well as mulch shallower slopes where downstream values at risk are present.

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Appendix A: Contact Information for Key Project Personnel

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Graduate thesis:

Hayter, L.A. (2023). Evaluating Post-Fire Geomorphic Change on Paired Mulched and Unmulched Catchments Using Repeat Drone Surveys. M.S. Thesis, Colorado State University, Fort Collins, CO.

Conference or symposium abstracts:

Hayter, L.A. and P.A. Nelson (2023), Evaluating Post-Fire Geomorphic Change on Paired Mulched and Unmulched Watersheds using Repeat Drone Surveys, SEDHYD, St. Louis, 8-12 May.

Posters:

Hayter, L., P. Nelson, and S. Kampf (2023). Evaluating post-fire geomorphic change on paired mulched and unmulched watersheds using repeat drone surveys, SEDHYD, St. Louis, 8-12 May.

Summary Guide:

We have created a one-page summary guide providing the primary findings of the simulation experiments along with field observations, and use those to suggest guidance for decision-making on future post-fire mulching projects.

Appendix C: Metadata

The metadata for this project describe the measured runoff and sediment yield volumes collected during each rainfall simulation experiment. Runoff volume and sediment yield were collected every 1-minute interval of each 20-minute experiment, so the data consist of time series of each of these variables. The metadata adhere to the Federal Geographic Data Committee's Content Standard for Digital Geospatial Metadata – Biological Data Profile.

The data and metadata will be uploaded to the US Forest Service Research Data Archive (USFS-RDA), as well as Hydroshare. The Data Management Plan for this proposal originally stated that the data would be stored in the USFS-RDA and the CSU Library online repository, but since the proposal submission CSU Libraries has stopped accepting new submissions, so we have elected to upload to Hydroshare instead. The data may be accessed in Hydroshare at the following link:

Hayter, L., P. Nelson (2023). Rainfall simulation data associated with JFSP Project 22-1-01-17, HydroShare, http://www.hydroshare.org/resource/edd53ec50edf4a4da44a4005c4687111