EVALUATING THE POTENTIAL IMPACTS OF STEEP SLOPE LOGGING ON HILLSLOPE HYDROLOGY AND EROSION

by

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of

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ABSTRACT

Bark beetle outbreaks in high-elevation mountain forests in the Western United States have increased in extent and severity in recent decades, motivating land managers to log beetle-killed forests to reduce canopy fuel loads and mitigate safety hazards from dead standing trees. Current slope policies restrict logging on slopes greater than 40%. Cut-to-length tethered logging provides an option for treating forests with slopes greater than the current limit because it is cable-assisted, exerting less force on the ground surface compared to untethered ground-based methods. To evaluate erosion potential of cut-to-length tethered logging, and slash application as an erosion mitigation strategy, we investigated runoff and soil erosion after a cut-to-length tethered logging project on a steep hillslope (10 - 80%) on Monarch Pass, Colorado. The site had severe infestation levels and tree mortality from spruce beetle (*Dendroctonus rufipennis*) and Western balsam bark beetle (*Dryocoetes confuses*) outbreaks, providing potentially inadequate slash supply consisting of dead timber. For three summer field seasons, we measured soil erosion that accumulated in 39 sediment fences. We additionally measured runoff and erosion during rainfall simulations of 10 and 100-year local rainstorm intensities on 20, 40, and 60% slopes. We evaluated erosion on tether roads (pathways equipment creates up and down the hillslope) with bare soil patches, tether roads covered with slash, and cut hillslope areas in between tether roads. Runoff per unit rainfall was 2x higher on bare tether roads compared to tether roads with slash. There was strong evidence that erosion was greater on bare tether roads than slashed tether roads. Sediment yield was 91% less on slashed tether roads relative to bare tether roads when we measured sediment accumulation in sediment fences after natural rainfall and 81% less on slashed tether roads relative to bare tether roads when we simulated high-intensity rainfall. The low to moderate erosion rates we observed (0 – 2 t/ha/yr) in a steep-sloped system with dead-timber slash indicate this logging method may have a reasonable erosion risk for logging on slopes greater than 40%.

CHAPTER ONE

INTRODUCTION

Forests cover about one-third of land in the Western United States and are estimated to generate 72% of surface water supply (Liu et al., 2022), motivating land management for a range of biotic and abiotic disturbances such as insect disease, windthrow, and fire. In the West, forest disturbances have increased in extent and severity in recent decades and are projected to continue to increase (McGinley et al., 2023). This is of particular concern from a forest hydrology perspective because water is very limited in the Western United States (Dettinger et al., 2015), and the increasing extent and severity of disturbances have broad water supply (Goeking and Tarboton, 2020) and quality (Shah et al., 2022) ramifications. Bark beetle infestations are a primary forest disturbance in the Western United States and have affected 59.2 million acres of coniferous forest in the region (Paschke, 2021). Bark beetle impacted forests are of particular concern because of post-disturbance damage to the landscape. Beetle-killed standing trees are much more susceptible than healthy trees to windthrow and can create more safety hazards for public use of the forest or potential wildfire management.

Many of the forests that land managers aim to treat are steep forests, however, much of these areas cannot be treated because current slope policies restrict logging on slopes greater than 40%. Cut-to-length tethered logging offers an option for managing steep-sloped forests. Tethered logging systems can treat steep forests because the equipment is stabilized on the hillslope with a tether system as a cable is attached to the ground-based equipment and an upslope anchor. Cut-to-length tethered logging systems process the trees in the forest and operate on slash mats that cover the bare ground surface of the tether roads. Operating on slash mats reduces the amount of

equipment tire contact with forest soils, providing more protection to the ground surface (Ring et al., 2021). Additionally, slash application can reduce erosion after logging (Vinson et al., 2017).

This research occurred on Monarch Pass, which is a high-elevation mountain pass in Central Colorado that has experienced epidemic levels of spruce beetle (*Dendroctonus rufipennis*) and Western balsam bark beetle (*Dryocoetes confuses*) infestations in recent decades. Many stands in this area had nearly 75% tree mortality (U.S. Forest Service, 2018). The extent of tree mortality and beetle infestation prompted land managers to log 346 acres (140 hectares) of a steep hillslope on Monarch Pass in 2019 and 2020 to reduce overstory canopy fuels and windthrow hazards that threatened infrastructure as well as firefighter safety. The slash at this site is unique because it is slash from dead timber consisting of woody, non-commercial material that is pole-sized, and lacked green tree tops and branches that are traditionally used as slash from healthy forests. In this study, we investigated erosion rates on Monarch Pass for three years after logging. For three summer field seasons, after natural rainstorms, we measured soil erosion that accumulated in 39 sediment fences that we installed across the hillslope. During the most recent field season (2023), we simulated 18 high and extremely high intensity rainstorms on a range of slopes and ground covers. The goal of this study is to evaluate the erosion potential in a forested system that may have inadequate slash supply due to a lack of slash supply and a type of slash that is primarily woody material. Additionally, this study investigates how ground cover influences overland flow (hereafter runoff) and erosion by observing runoff and erosion rates under natural and simulated rainfall with low to extremely high rainfall intensities on a range of slopes.

CHAPTER TWO

EVALUATING THE POTENTIAL IMPACTS OF STEEP SLOPE LOGGING ON HILLSLOPE HYDROLOGY AND EROSION

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Manuscript(s) in Chapter(s): 1

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Contributions: Advising, guidance, editing of manuscript

Co-Author: Tim Fegel

Contributions: Field work, lab work, editing of manuscript

Co-Author: Chuck Rhoades

Contributions: Initial project conceptualization, advising, editing of manuscript

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Evaluating the potential impacts of steep slope logging on hillslope hydrology and erosion

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Abstract

Bark beetle outbreaks in high-elevation mountain forests in the Western United States have increased in extent and severity in recent decades, motivating land managers to log beetle-killed forests to reduce canopy fuel loads and mitigate safety hazards from dead standing trees. Current slope policies restrict logging on slopes greater than 40%. Cut-to-length tethered logging provides an option for treating forests with slopes greater than the current limit because it is cable-assisted, exerting less force on the ground surface compared to untethered ground-based methods. To evaluate erosion potential of cut-to-length tethered logging, and slash application as an erosion mitigation strategy, we investigated runoff and soil erosion after a cut-to-length tethered logging project on a steep hillslope (10 - 80%) on Monarch Pass, Colorado. The site had severe infestation levels and tree mortality from spruce beetle (*Dendroctonus rufipennis*) and Western balsam bark beetle (*Dryocoetes confuses*) outbreaks, providing potentially inadequate slash supply consisting of dead timber. For three summer field seasons, we measured soil erosion that accumulated in 39 sediment fences. We additionally measured runoff and erosion during rainfall simulations of 10 and 100-year local rainstorm intensities on 20, 40, and 60% slopes. We evaluated erosion on tether roads (pathways equipment creates up and down the hillslope) with bare soil patches, tether roads covered with slash, and cut hillslope areas in between tether roads. Runoff per unit rainfall was 2x higher on bare tether roads compared to tether roads with slash. There was strong evidence that erosion was greater on bare tether roads than slashed tether roads. Sediment yield was 91% less on slashed tether roads relative to bare tether roads when we measured sediment accumulation in sediment fences after natural rainfall and 81% less on slashed tether roads relative to bare tether roads when we simulated high-intensity rainfall. The low to moderate erosion rates we observed (0 – 2 t/ha/yr) in a steep-sloped system with dead-timber slash indicate this logging method may have a reasonable erosion risk for logging on slopes greater than 40%.

1. Introduction

Forests cover about one-third of land in the Western United States and are estimated to generate 72% of surface water supply (Liu et al., 2022), motivating land management for a range of biotic and abiotic disturbances such as insect disease, windthrow, and fire. In the West, forest disturbances have increased in extent and severity in recent decades and are projected to continue to increase (McGinley et al., 2023). This is of particular concern from a forest hydrology perspective because water is very limited in the Western United States (Dettinger et al., 2015), and the increasing extent and severity of disturbances have broad water supply (Goeking and Tarboton, 2020) and quality (Shah et al., 2022) ramifications. Changes to forest health and extent in subalpine and alpine environments impact how water is cycled from precipitation to forest soils in mountain headwaters. High-elevation subalpine and alpine forests in the West are dominated by spring snowmelt and summer monsoon hydrologic regimes. Forest disturbances affect how mountain watersheds respond to the short, frequent, and high intensity rainstorms in the summer months, changing how runoff and soil erosion are generated. After forest disturbances that reduce the amount of tree cover and increase bare soil exposure, reduced soil infiltration rates and increased overland flow velocities (Moody et al., 2013), can lead to mobilization of sediment and soil erosion in response to high intensity rainstorms (Hartanto et al., 2003), and can ultimately lead to increased sediment delivery into streams (Croke and Hairsine, 2006).

Bark beetle infestations are a primary forest disturbance in the Western United States and are estimated to have affected 59.2 million acres of coniferous forest in the West since 2000 (Paschke, 2021). Forests that are impacted by bark beetles are of particular concern because of post-disturbance impacts on the landscape. Beetle-killed standing trees are much more susceptible than healthy trees to windthrow and can create more safety hazards for public use of the forest or potential wildfire management. Additionally, land managers aim to treat forests with severe beetle-kill to reduce overstory canopy fuel loads.

Many of the forests that land managers aim to treat are steep forests, however, much of these areas cannot be treated because current slope policies restrict logging on slopes greater than 40%. Tethered logging offers an option for managing steep slopes. Tethered logging systems can treat steep forests because the equipment is stabilized on the hillslope with a tether system as a cable is attached to the ground-based equipment and an upslope anchor. These systems are winch-assisted, reducing tire slip and exerting less force on the ground (Visser and Stampfer, 2015). Additionally, the equipment creates less of a traction footprint because it is able to maintain consistent travel paths (Green et al., 2020). The equipment creates tethered roads up and down the hillslope, perpendicular to the contour of the hillslope, as the width of the roads is about the 4-meter width of the equipment, and the roads occur about every 15 meters on the hillslope. Two pieces of equipment are needed for the cut-to-length method, a harvester and forwarder. The harvester fells, delimbs, and cuts the tree in the forest, and the forwarder picks up and transports the cut logs to the landing sites. The forwarder has an independent suspension that increases contact points with the ground, creating less impact while driving (Visser and Stampfer, 2015).

Cut-to-length tethered logging systems process the trees in the forest and operate on slash mats that cover the bare ground surface of the tether roads. Operating on slash mats reduces the amount of equipment tire contact with forest soils and can provide more protection to the ground

surface compared to operating on the bare ground surface (Ring et al., 2021). Additionally, slash application can reduce erosion after logging (Vinson et al., 2017). Processing the trees in the forest with the cut-to-length method leaves tree tops, branches, and litter in the forest, adding cover to the forest floor. The amount and type of slash that is applied on tether roads is dependent on stand conditions. Forests with lower stand densities have a lower supply of slash to cover the ground surface and forests with high tree mortality have slash comprised of dead timber with primarily pole-size material and a lack of green tops and branches. Applying dead timber slash is less ideal than applying healthy slash, but may still be effective for mitigating soil erosion on steep slopes.

The main objective of this study is to evaluate hydrologic and erosional responses to steep hillslope logging that utilizes cut-to-length tethered logging systems. Cut-to-length tethered logging is a recent technology in the US, and the soil disturbances and recovery from this approach is poorly understood. We seek to evaluate the erosion potential in a forested system that may have inadequate slash supply due to a lack of slash supply and a type of slash that is primarily woody material. We investigate how ground cover influences overland flow (hereafter runoff) and erosion rates by observing runoff and erosion rates under natural and simulated rainfall with low to extremely high rainfall intensities on a range of slopes.

2. Methods

2.1 Study Overview

In this study we assessed the potential erosion effects after a steep-slope salvage logging project in Central Colorado that utilized cut-to-length tethered logging equipment (Figure 1). The logging project occurred in 2019 and 2020, logging 140 hectares (346 acres) of beetle-infected and -killed forest on Monarch Pass within the Sawatch Mountain Range in the Pike and San Isabel National Forests, approximately 20 miles west of Salida, Colorado, United States (lat 38.515°, long -106.324°). We monitored natural rainfall, sediment yields, and erosional features for three field seasons post-logging from June through October 2021, 2022, and 2023. We measured precipitation and soil erosion using rain gauges, sediment fences, and forestry surveys. In 2023, we conducted rainfall simulations to evaluate erosional and hydrologic responses to simulated rainfall.

2.2 Site Description and Project Background

The site is a steep hillslope ranging from 3170 to 3602 meters in elevation. The hillslope transitions from subalpine to alpine as the treeline is located near the ridgeline. Additionally, the watershed is located at the headwaters of the Arkansas River. The slope of the hillslope ranges from 10 – 80% with an average slope of 44%. The aspect is west and northwest facing. The mean annual precipitation is 659 mm and mean annual temperature is -6.3 °C (1991 - 2020 Monthly Normals, NOAA). The soils at this site are predominantly sandy loams, the soil type ranges from Cryaquolls to Typic Dystrocryepts to Ustic Haplocryepts, and the soil family ranges from Leighcan, to Leighcan-Endlich, to Howardsville-Leighcan (NRCS, CO, 2023). The soils are somewhat excessively drained (NRCS, CO, 2023). The soil permeability class ranges from moderately slow to moderately rapid and the runoff class is predominantly classified as high (NRCS, CO, 2023).

The Monarch Pass area has experienced epidemic levels of spruce beetle (*Dendroctonus rufipennis*) and Western balsam bark beetle (*Dryocoetes confuses*) infestations in recent decades. The western balsam bark beetle has affected the Monarch Pass area since the early 2000s (U.S. Forest Service, 2018). Spruce beetle populations reached epidemic levels in southern Colorado during the early 2000s and USFS stand surveys first identified them in the Monarch Pass area in 2012 (U.S. Forest Service, 2018).

The forest stands in this logging project area are spruce-fir, dominated by Engelmann spruce (*Picea engelmanii*) and mixed with smaller amounts of subalpine fir (*Abies lasiocarpa*), lodgepole pine (*Pinus contorta*), bristlecone pine (*Pinus aristata*), and limber pine (*Pinus flexilis*). Some stands were near 75% mortality of mature overstory (U.S. Forest Service, 2018). The extent of tree mortality and beetle infestation prompted land managers to log the area with the goal to "*reduce the extent of spruce beetle infestation, western balsam bark beetle infestation, improve forest resiliency to insect and disease infestations, improve watershed health and aquatic habitat, reduce fuel loading, protect infrastructure and developed sites (e.g. ski area, campground, trail corridors), and provide for firefighter and public safety in the Monarch Pass area*" (U.S. Forest Service, 2018).

2.3 Logging Overview

The logging project included two adjacent logging sites: the first logging site harvested 75 hectares in 2021 and the second logging site harvested 64 hectares in 2022 (Figure 1). The USFS silviculture prescription mandated salvage logging of the dead and infested Engelmann spruce greater than 20 cm D.B.H. In addition to salvage logging, silviculturists prescribed the removal of trees that were near infrastructure and likely to blow down.

The logging project utilized ground-based Ponsse cut-to-length equipment with a tether system, which included a harvester and forwarder (Ponsse Bear Harvester, Ponsse Elephant King Forwarder, Vieremä, Finland). Both the harvester and forwarder were tethered. The project used the cut-to-length method meaning the harvester felled, delimbed, and bucked the tree within the harvest unit, and the forwarder loaded and transported the logs to landing sites. To operate on the steep terrain, the harvester and forwarder equipment was winch-assisted where a cable was attached to the equipment and to an upslope anchor, stabilizing the equipment on steep slopes.

The logging project design implemented 4-meter-wide roads perpendicular to the slope contour. The equipment operators created these roads by tethering the equipment to an upslope anchor and operating up and down the hillslope. They harvested trees in the tether road way and extended the feller buncher boom to cut between the tether roads. In coordination with the USFS management guidelines, operators scattered slash on the road surfaces to minimize bare soil exposure on the roads. Approximately 67% of the tether roads were covered in slash, and approximately 33% of the tether roads were exposed with patches of bare soil. Generally, slash refers to the green tops and branches from trees. However, the slash at this site is unique because it is slash from dead timber consisting of woody, non-commercial material that is pole-sized.

2.4 Rainfall Events

To evaluate rainfall intensities that generated hillslope soil erosion, we measured rainfall from June through October in 2021, 2022, and 2023 at two locations on the hillslope using tipping bucket rain gauges (RG3 Data Logging Rain Gauge, Onset HOBO, Bourne, MA) with a

resolution of 0.254 mm. We installed one rain gauge downslope at 3190 m elevation towards the northern end of the site and the second rain gauge upslope at 3365 m elevation towards the southern end of the site (Figure 1). We calculated the total rainfall (mm) and 15-min maximum rainfall intensities (I_{15}, mm/hr) for each precipitation event.

2.5 Soil Erosion from Rainfall Events

We conducted rill surveys at the end of the field season in 2021, 2022, and 2023 to measure the development and morphology of rill features across the hillslope. We surveyed approximately 30 of the same tether roads each year. We measured the width and depth of rills with a ruler, and the length and location of rills with a GPS device with 1 cm resolution (Emlid Reach RS2). We walked the tether roads from the base to top of the hillslope and collected measurements at the beginning, end, and approximately every 3 m of the rill. We used geospatial analysis to calculate the change in length, width, and depth of rills from year to year.

We used sediment fences to measure soil erosion generated from natural rainfall. We strategically installed the fences in tether roads and in between tether roads to assess the impact of different ground cover treatments on erosion rates. We installed sediment fences on the following three ground cover treatments: tether roads with predominantly bare soil, tether roads covered with slash, and the cut hillslope in between tether roads (Figures 2 & 3). We installed a total of 39 fences during this study. In 2021, we installed 27 fences within Logging Site 1, consisting of 10 on bare tether roads, 10 on slashed tether roads, and 7 on cut hillslope (Figure 1). In 2022, we installed 12 fences within Logging Site 2, consisting of 5 on bare tether roads, 5 on slashed tether roads, and 2 on cut hillslope (Figure 1). We utilized a block study design for the location of the sediment fences. We installed nearly all fences in groups corresponding to each ground cover treatment, with each group situated on a uniform slope contour. For accessibility, we installed nearly all fences within approximately 50 meters of a haul road on the hillslope.

We constructed the fences in a U-shape by attaching landscape fabric (Lumite ®) to 10-15 wooden stakes that we hammered into the ground (Figure 2). We attached landscape fabric to the ground surface inside of the fence to create a floor surface to collect the deposited sediment (Wilson et al., 2020). The fence dimensions were approximately 4 m wide, 1.5 m deep, and 0.5 m high. We dug a trench 30 m upslope of each sediment fence to create a ~0.01 ha area, with a width of 4 m and length of 30 m along the tether road, to control the contributing area of sediment transport. We slightly angled one side of the trench to divert upslope runoff from flowing into the contributing area of the sediment fence.

We collected soil that was deposited into fences after rainstorms that were significant enough to generate erosion. We visited the fences after significant precipitation events to verify if sediment accumulated in the fences. Once this was verified, we checked all fences, and weighed the total amount of soil accumulated in each fence. To correct the sediment weights for soil moisture content, we took a subsample from each fence to the Rocky Mountain Research Station (RMRS) in Fort Collins, CO and weighed the sample before and after drying in a oven at 105 degrees C for 24 hours. The dry weight equivalent was used to calculate the total sediment yield per ~0.01 ha contributing area.

2.6 Rainfall Simulation Experiments

We conducted rainfall simulations to evaluate erosional responses to high-intensity precipitation events across different slope and ground cover treatments. We performed a total of 18 rainfall simulations on 20%, 40%, and 60% slopes on bare tether roads, slashed tether roads, and cut hillslopes in between tether roads (Figure 1). We implemented two different rainfall intensities, approximately I_{15} 74 mm/hr, and I_{15} 134 mm/hr. The rainfall rate of I_{15} 74 mm/hr is the local precipitation frequency estimate for a precipitation event with a 10-year recurrence interval and the rainfall rate of I_{15} 134 mm/hr is the local precipitation frequency estimate for a precipitation event with a 100-year recurrence interval (NOAA, ATLAS). We held rainfall rates constant during all experiments and did not expose hillslopes to varying or dynamic precipitation inputs.

The rainfall simulator consisted of a portable-tripod, spray nozzle and plumbing system, collection tray, and water supply system (Figure 4). We designed the tripod with adjustable legs to adapt to the steep topography of the site. We placed a 3 m by 3 m pop-up tent with windscreens over the simulator to minimize wind interference. We used two nozzle head sizes and input water pressures to achieve the I_{15} 74 and 134 mm/hr rainfall intensities. The nozzle head size of 2.5 mm (*Quick FullJet,* Spraying Systems Company) with input water pressure of 7 psi generated rainfall of I_{15} 74 mm/hr, and the nozzle head size of 5.0 mm with input water pressure of 8 psi generated rainfall of I_{15} 134 mm/hr. We adjusted the nozzle head to the center of the plot frame at a height of 2.4 m.

For each rainfall simulation, we carefully inserted a 1.25 m by 1.00 m steel plot frame 3-6 cm into the ground. We sealed the plot on three sides to prevent water from moving laterally outside of the plot. The downslope side of the plot was connected to a triangle-shaped collection tray made of impermeable PVC fabric that allowed surface runoff and sediment to move downslope. We attached a funnel and tube to the collection tray and collected surface runoff in HDPE sample bottles.

We measured rainfall intensities before each simulation to ensure rainfall application accuracy. Approximately 10 minutes before the simulation, we placed a soil moisture sensor (Onset HOBO MX Soil Moisture Data Logger) in the center of the plot at a depth of ~10cm, and continuously recorded soil moisture in one-minute intervals until several minutes after rainfall application stopped. Prior to simulations, we performed ground cover surveys to determine the percent mineral soil, rock, litter, fine wood, coarse wood, herbaceous, woody basil, moss, and duff of each plot.

We conducted each rainfall simulation for 45 minutes, consisting of 45 one-minute sampling intervals. To determine the rate of runoff and soil erosion throughout the experiment, we collected surface runoff in a separate HDPE bottle for each one-minute sampling interval. We recorded the volume of water in each bottle to estimate the overland flow volume and rate during that time interval. We filtered the first 15, and then approximately every third runoff sample for the remainder of the simulation for total suspended sediment.

2.7 Statistical Analyses

We performed Kruskal-Wallis tests to investigate differences among ground cover and slope treatments in sediment production measured from sediment fences and rainfall simulations. If there was a significant or borderline significant Kruskal-Wallis result, we performed a

Dunne's post-hoc-test with a Bonferroni correction to conduct pairwise comparisons between the different ground cover treatments. We performed two-way Analysis of Variance (ANOVA) tests to investigate the difference among ground cover and study year in sediment production measured from sediment fences. If there was a significant ANOVA result, we performed a post-hoc test to conduct pairwise comparisons between each ground cover type for each year of the study. We performed one-way ANOVA tests to investigate the differences among ground cover in the runoff ratio and average sediment concentration from rainfall simulations. If there was a significant or borderline significant ANOVA result, we performed a Tukey's Honest Significant Difference (HSD) post-hoc test to conduct pairwise comparisons between the different ground cover treatments. We implemented separate simple linear regression models to investigate the relationship between bare soil coverage, sediment production, sediment concentration, and total runoff for each ground cover treatment.

3. Results

3.1 Rainfall Events

The 30-year-average total precipitation near Monarch Pass between June 15th and October 15th is 178 mm and the seasonal total precipitation at the study site was 169 mm in 2021, 273 mm in 2022, and 149 mm in 2023 (Table 1, Figure 5). The highest maximum 15-minute precipitation intensities were 37 mm/hr in 2021, 39 mm/hr in 2022, and 26 mm/hr in 2023 and were near the one-year recurrence interval for the local SNOTEL (Table 1, Figure 5).

3.2 Rill Surveys

Rills primarily developed on bare tether roads, and high concentrations of rills were located near ridgelines (Figure 6). The length of rills ranged from 1.7 to 58.0 m in 2021, 1.3 to 195.8 m in 2022, and 1.0 to 75.3 m in 2023 (Table 2). The mean length of rills was 18.3 m in 2021, 18.6 m in 2022, and 12.8 m in 2023 (Table 2). The median length of rills was 14.0 m in 2021, 9.6 m in 2022, and 6.5 m in 2023 (Table 2). The width of rills ranged from 3.0 to 20.0 cm in 2021, 2.0 to 8.0 cm in 2022, and 4.0 to 65.0 cm in 2023 (Table 2). The mean width of rills was 9.8 cm in 2021, 3.7 cm in 2022, and 20.5 cm in 2023 (Table 2). The median width of rills was 9.8 cm in 2021, 3.7 cm in 2022, and 20.5 cm in 2023 (Table 2). The depth of rills ranged from 2.0 to 14.0 cm in 2021, 1.0 to 12.0 cm in 2022, and 1.0 to 36.0 cm in 2023 (Table 2). The mean depth of rills was 5.2 cm in 2021, 3.1 cm in 2022, and 10.9 cm in 2023 (Table 2). The median depth of rills was 5.0 cm in 2021, 3.0 cm in 2022, and 10.0 cm in 2023 (Table 2).

3.2 Sediment Fences

There was strong evidence ($P<0.0001$) that sediment production was different on each ground cover treatment for each year of the study (Table 3). In 2021, there was strong evidence ($P<0.0001$) that sediment production was greater on bare tether roads than cut hillslope sites ($Z=4.33$) and suggestive but inconclusive evidence ($P = 0.0103$) that sediment production was greater on bare tether roads than slashed tether roads ($Z=2.70$) (Table 3). There was suggestive but inconclusive evidence ($P = 0.0910$) that sediment production was greater on cut hillslope sites than slashed tether roads ($Z=-1.88$) in 2021. In 2022, there was strong evidence that sediment production was greater on bare tether roads than cut hillslope sites ($P<0.0001$, $Z=0.21$) and slashed tether roads ($P=0.0004$, $Z=3.63$) (Table 3). There was no evidence ($P=0.4711$) that

there was a difference in sediment production on slashed tether road and cut hillslope sites in 2022 (Table 3). In 2023, there was strong evidence that sediment production was greater on bare tether roads than cut hillslope sites ($P<0.0001$, $Z=4.55$) and slashed tether roads ($P=0.0014$, $Z=3.32$) (Table 3). There was weak evidence ($P=0.1408$) that there was a difference in sediment production on slashed tether road and cut hillslope sites in 2023 (Table 3).

Throughout the three years of this study, we observed that the highest yielding erosion events occurred on bare tether roads (Figure 7). We considered 1 Mg/ha as a high yielding event, and in our study, we only observed that 3 % of erosion events exceeded 1 Mg/ha. Nearly all (11/12) of the events with sediment production greater than 1 Mg/ha occurred on bare tether roads (Table 4). Five of the six high-yielding events in 2021 were on bare tether roads, all 5 of the high-yielding events in 2022 were on bare tether roads, and the one high-yielding event in 2023 was also on a bare tether road (Table 4). The highest yielding erosion events were consistently measured on bare tether roads in all years of this study.

For each year of this study, the highest, middle, and lowest maximum sediment production events occurred on the same ground cover treatments. Each year, the highest sediment production event was on bare tether roads, second highest on slashed tether roads, and lowest on cut hillslopes in between tether roads (Figure 7). In 2021, the maximum sediment production was 8.09 Mg/ha on a bare road, 5.41 Mg/ha on a slashed road, and 0.17 Mg/ha on a cut hillslope (Table 4). In 2022, the maximum sediment production was 11.78 Mg/ha on a bare road, 0.34 Mg/ha on a slashed road, and 0.05 Mg/ha on a cut hillslope (Table 4). Similarly, in 2023, the maximum sediment production was 1.49 Mg/ha on a bare road, 0.16 Mg/ha on a slashed road, and 0.09 Mg/ha on a cut hillslope (Table 4).

The proportion of fences that had at least one erosion event per year varied among ground cover treatments and logging sites. In Logging Site 1 in 2021, all the fences on bare and slashed tether roads had at least one erosion event, while only four of the seven fences on cut hillslopes had erosion events (Table 4). In Logging Site 1 in 2022, seven of the ten fences on bare tether roads had at least one erosion event, while only one of the ten fences on slashed tether roads and one of the seven fences on cut hillslopes had at least one erosion event (Table 4). In Logging Site 1 in 2023, there was at least one erosion event that occurred in a fence in all three ground cover treatments (Table 4). In Logging Site 2, all fences had at least one erosion event each year, except for in 2022, when only one of the two fences on cut hillslopes had at least one erosion event (Table 4). Overall, the proportion of fences with erosion events varied each year, and the highest overall proportions occurred on bare tether roads.

We evaluated how sediment production varied each year of the study among each ground cover treatment. Bare tether roads generated higher sediment production in 2022 than in 2021 ($P<0.0001$, $T\text{-ratio}=5.85$) and 2023 ($P<0.0001$, $T\text{-ratio}=-5.60$) (Table 5). There was no significant difference in sediment production on bare tether roads when comparing 2021 and 2023 ($P=0.8560$, $T\text{-ratio}=1.98$) (Table 5). Slashed tether roads generated higher sediment production in 2022 than in 2021 ($P<0.0001$, $T\text{-ratio}=5.52$) and 2023 ($P<0.0001$, $T\text{-ratio}=-6.29$) (Table 5). There was no significant difference in sediment production on slashed tether roads when comparing 2021 and 2023 ($P=0.9992$, $T\text{-ratio}=0.66$) (Table 5). On cut hillslopes, there was no significant difference in sediment production between 2021 and 2022 ($P=.1207$, $T\text{-ratio}=2.80$), but there was significantly lower sediment production in 2023 than in 2022 ($P=0.0003$, $T\text{-ratio}=-4.54$) (Table

5). There was no significant difference in sediment production on cut hillslopes when comparing 2021 and 2023 (P=0.995, T-ratio=0.844) (Table 5).

We observed that the maximum erosion rates were generally lower the third year of the study compared to the first and second year of the study (Figure 7). In Logging Site 1 on bare tether roads, the maximum erosion rate was 8.09 Mg/ha one year since harvest, increased to 11.78 Mg/ha two years since harvest, and then decreased to 1.3 Mg/ha three years since harvest (Table 4). In Logging Site 1 on slashed tether roads, the maximum erosion rate was 5.41 Mg/ha one year since harvest, decreased to 0.08 Mg/ha two years since harvest and increased to 0.15 Mg/ha three years since harvest (Table 4). In Logging Site 1 on cut hillslopes, the maximum erosion rate was 0.17 Mg/ha in 2021, decreased to 0.03 in 2022, and increased to 0.07 in 2023 (Table 4).

3.3 Rainfall Simulations

Throughout the 18 rainfall simulations, all experimental plots generated runoff (Table 6). The onset of runoff varied for all simulations but was generally shorter at sites on bare tether roads, and longer at sites on slashed tether roads or cut hillslopes in between tether roads (Table 6). The average onset of runoff was two minutes on bare tether roads, four minutes on slashed tether roads, and three minutes on cut hillslopes (Table 6). The runoff hydrographs were generally consistent in their shape and rate of runoff throughout the simulations. Most of the runoff hydrographs on bare tether roads show that runoff rates remained consistent and increased at a slight steady rate throughout the experiment (Figure 8). Additionally, the runoff hydrographs on slashed tether roads remained generally consistent and steady throughout the experiments (Figure 8). The two 74 mm/hr simulations on cut hillslopes also show consistent runoff rates, however, the runoff generally decreased throughout the experiment on a 40% cut hillslope and 134 mm/hr rainfall and the runoff generally increased throughout the experiment on a 60% cut hillslope and 134 mm/hr rainfall (Figure 8).

The proportion of rainfall that became runoff (i.e., the runoff ratio) varied from 1 to 54% (Table 6). There was suggestive but inconclusive evidence (P=.0662) that runoff ratios were different among ground cover treatments (Table 7). There was borderline significant evidence (P=0.0726) that runoff ratios were higher on bare tether roads than slashed tether roads (Table 7). There was no significant difference in runoff ratios between bare tether roads and cut hillslope sites (p = 0.1873), though the difference value of -17.82 indicate lower runoff ratios on cut hillslope sites compared to bare tether roads (Table 7). Additionally, there was no significant difference in runoff ratios between cut hillslope sites and slashed tether roads (P=0.9796, diff = -1.86) (Table 7). The mean runoff ratio on bare tether roads was 33% from 74 mm/hr rainfall and 34% from 134 mm/hr rainfall (Table 6). The mean runoff ratio on cut hillslope plots was 11% from 74 mm/hr rainfall and 26% from 134 mm/hr rainfall (Table 6). The slashed tether roads had runoff ratios of 18% from the 74 mm/hr rainfall experiments and 26% from 134 mm/hr rainfall experiments (Table 6). Across all ground cover treatments, the mean runoff ratios were greater during 134 mm/hr relative to 74 mm/hr experiments.

We did not observe clear trends between runoff ratios and the slope of the experimental plots. The runoff ratios on bare tether roads ranged from 31% on a 20% slope, 32 to 54% on 40% slopes, and 10 to 39% on 60% slopes (Figure 9). The runoff ratios on cut hillslope plots ranged from 15 to 18% on 40% slopes and 7 to 33% on 60% slopes (Figure 9). The runoff ratios on

slashed tether roads ranged from 4% on a 20% slope, 32 to 54% on 40% slopes, and 10 to 39% on 60% slopes (Figure 9). Additionally, there was no evidence of a difference in total runoff across slope treatments (Table 7). Overall, we observed a large spread between rainfall runoff ratios among each slope treatment when grouped by ground cover treatment, indicating a lack of relationship between slope and ground cover treatments.

We evaluated sediment yields throughout the duration of the 45-minute rainfall simulations and observed that peak sediment yields generally occurred during the first 15 minutes and slowly decreased the rest of the simulation (Figure 10). Fifteen of the 18 simulations showed this trend of peak sediment concentrations within the first 15 minutes after runoff started, and a steady decrease in concentration during the remainder of the simulation (Supplemental Figure 2). The sedigraphs with the largest peaks generally occurred on bare tether roads, except for one high-intensity simulation on 60% slope on a cut hillslope site (Supplemental Figure 2). While the shape of the sedigraph peaks is generally consistent, there are four sedigraphs with noticeably larger peaks. These include three simulations on bare tether roads with two on 60% slopes from both 74 and 134 mm/hr rainfall, and one on 40% slope from 134 mm/hr, and one simulation on a 60% cut hillslope and 134 mm/hr rainfall (Supplemental Figure 2).

There was no evidence of a difference in average sediment concentration on bare tether roads compared to cut hillslope sites (P=0.884) or slashed tether roads (P=0.1395) (Table 7). Although these differences were not significant, the difference values (cut: diff = -7462.98, slash: diff = -27278.50) suggest lower trends in average sediment concentrations on cut hillslope sites and slashed tether roads compared to bare tether roads (Table 7). Additionally, the average sediment concentrations on slashed tether roads were lower than on cut hillslope sites (diff = -19715.47, P=0.4409), though this difference was not significant (Table 7). Visualizing the data averaged by ground cover for each rainfall intensity applied, we observed the highest sediment concentrations occurred during simulations on bare tether roads, the second highest concentrations occurred during simulations on cut hillslopes, and the lowest sediment concentrations occurred during simulations on slashed tether roads (Figure 10).

There was suggestive but inconclusive evidence (P=.08) that sediment production was different among ground cover treatments. There was strong evidence that sediment production was significantly higher on bare tether roads compared to slashed tether roads (P=0.01, Z=2.20), while there were no significant differences between cut hillslope and bare tether roads or between slashed tether road and cut hillslope (Table 7). Bare tether roads generated three of the four highest erosion rates, ranging from 38 to 68 g/m^2, while slashed tether roads generated three of the four lowest sums of eroded sediment, ranging from zero to two g/m^2 (Figure 11). A simulation on 60% cut hillslope plot and 134 mm/hr rainfall generated the highest sum of eroded sediment, which produced 68 g/m^2 (Figure 11). Of the four total simulations conducted on cut hillslope plots, one yielded the highest sediment production (i.e. 68 g/m^2), while the other three simulations on this ground cover only produced four to seven g/m^2 (Figure 11). Additionally, there was no evidence of a difference in sediment production across slope treatments (P=0.415, X^2=1.76) (Table 7).

There was weak evidence of a significant difference in sediment production from 74 mm/hr rainfall compared to 134 mm/hr rainfall (P=0.1113). Though not significant, the sediment production was generally lower from 74 mm/hr rainfall (median = 0.08 Mg/ha) compared to 134 mm/hr rainfall (median = 0.39 Mg/ha). On bare tether roads, sediment yields were approximately

two to four times higher from 134 mm/hr rainfall than 74 mm/hr rainfall, and on cut hillslope plots, sediment yields were approximately two to 21 times higher from 134 mm/hr rainfall compared to 74 mm/hr rainfall (Figure 11). However, on slashed tether roads, the sediment yields remained similar to what they were from 75 mm/hr rainfall as well as when the higher rainfall intensity (i.e. 134 mm/hr) was applied (Figure 11).

We compared the erosion rates from each of the rainfall simulations to the percentage of bare soil coverage at each plot. Simple linear regression analyses show that bare soil percentage moderately explained the amount of sediment production across all simulation plots (P=0.0211, adj. $R^2 = 0.25$). When 74 mm/hr rainfall was applied, bare soil percentage explained 17% of the amount of sediment production (Table 7). When 134 mm/hr rainfall was applied, bare soil percentage explained 90% of the amount of sediment production (P=0.0023) (Table 7). The four highest sediment producing experiments generated between 0.4 and 0.75 Mg/ha of sediment and occurred on plots with 58 to 90% bare soil coverage (Figure 12). The four lowest sediment producing experiments generated between 0.01 and 0.09 Mg/ha of sediment and occurred on plots with 4 to 19% bare soil coverage (Figure 12). The eight simulation experiments with erosion rates in between the lowest and highest rates had a larger spread of percentage of bare soil coverage. These simulations generated erosion rates between 0.04 and 0.15 Mg/ha and occurred on plots with 5 to 83% bare soil coverage (Figure 12).

We utilized simple linear regression models to understand the relationship between sediment concentration, sediment production, and runoff on each ground cover treatment (Figure 13). Total runoff moderately to strongly explained the amount of sediment production on bare tether roads with significant evidence ($P = 0.0219$, adj. $R^2 = 0.62$) (Table 7). Total runoff moderately explained the amount of sediment production on slashed tether roads with significant evidence ($P = 0.0438$, adj. $R^2 = 0.51$) and very strongly explained the amount of sediment production on cut hillslopes with borderline significant evidence ($P = 0.0859$, adj. $R^2 = 0.75$) (Table 7). Sediment concentration moderately to strongly explained the amount of sediment production on bare tether roads with significant evidence ($P = 0.049$, adj. $R^2 = 0.49$)(Table 7). Sediment concentration moderately explained the amount of sediment production on slashed tether roads with weak evidence ($P = 0.1523$, adj. $R^2 = 0.23$), and very strongly explained the amount of sediment production on cut hillslopes with borderline significant evidence ($P = 0.0718$, adj. $R^2 = 0.80$) (Table 7). The total runoff did not significantly explain the average sediment concentration across ground cover treatments (Table 7).

4. Discussion

4.1 Evaluating runoff and erosion from natural and simulated rainfall on steep, logged hillslopes

Our results suggest that greater slash and plant ground cover reduces surface runoff (hereafter runoff). Our rainfall simulation results showed that bare tether roads generated higher runoff ratios than slashed tether roads, though the difference was borderline significant (P=0.0726). In our study, the simulations on cut hillslope sites generated both low and high runoff rates and rainfall-runoff ratios relative to the other ground cover treatments. The variation in average runoff rates (6 - 47%) and ratios (7 - 33%) that we observed on cut hillslope sites can moderately be explained by the variation in plot bare soil coverage (10 - 59%). Of the four simulations on cut hillslope sites, one simulation generated nearly two to eight times greater

average runoff rates and was composed of nearly two to six times as much bare soil than the other cut hillslope simulations. The high runoff rates at this site could be explained by the lack of vegetation cover. Noelle et al. (2017) simulated rainfall on 30% slopes and observed that greater plant cover reduced runoff. Runoff increases with the extent of bare soil and is limited by either increasing slash or plant cover.

From our rainfall simulation portion of the study, the orientation and size distribution of slash in the plots could have influenced rainfall runoff ratios. The three simulations with the highest runoff ratios on slashed tether roads (simulations #8, #14, #16) had plots with most of the coarse slash oriented downslope (Supplemental Figure 3). While the highest proportions of rainfall that became runoff generally occurred on bare tether roads, the third highest runoff ratio was from a simulation on a 60% slope slashed tether road and 74 mm/hr rainfall. The runoff ratio from this simulation was much higher than the 1-22% runoff ratio range of the other simulations on slash tether roads. This could be influenced by the lower proportion of coarse logs in the plot compared to other slash plots, as well as the downslope orientation of the coarse logs. Slash is a hard, almost non-permeable surface. Additionally, the slash at this site was from dead timber, primarily consisting of pole-sized, woody material. When coarse slash is oriented downslope, it can guide runoff downslope and increase runoff velocities due to minimal infiltration.

Onset of runoff during rainfall application varied between ground cover treatments, suggesting that some ground cover treatments are more susceptible to high runoff rates in response to rain events. We attribute the shorter overland flow start times on bare tether roads to the bare soil coverage that decreased infiltration capacity, making it quicker for runoff to begin. In contrast, we attribute the longer overland flow start times on slashed tether roads to the higher coverage of plant litter and woody debris that increased soil infiltration.

Our results confirm that slash application after salvage logging on steep slopes reduces erosion. Prats et al. (2021) found that slash application on compacted skid trails, compared to bare compacted skid trails, reduced sediment yields by approximately 70%. In our study, sediment yield was 91% less on slashed tether roads relative to bare tether roads after natural rainfall and 81% less on slashed tether roads relative to bare tether roads when we simulated high-intensity rainfall.

The dominant erosional process we observed during rainfall simulations was interrill erosion, while the erosional processes observed from natural rainfall and measured with sediment fences were dominated by both rill and interrill erosion. The small plot scale of 1.25 m^2 and completion of one, 45-minute rainfall event at each plot limited the space and time needed for rill features to form. Interrill erosion transports sediment between rills and the erosional processes that dominate this sediment transfer between rills is rain-drop impacted sheet flow in which soil is detached by rainfall impact and carried in the runoff (Young and Wiersma, 1973). We observed the highest erosion rates on plots with the highest amounts of bare soil coverage, which is potentially related to rain drop impact effect on bare soil. Slash cover reduces the rain-drop impact on soil, which is likely why we observed lower runoff and erosion on slashed plots. Lower runoff and erosion rates on slashed plots are also likely due to the slash coverage slowing down the water as it reaches the soil surface, allowing water to infiltrate soil more easily. A reason why some higher erosion rates were observed on slashed ground cover, where there was little raindrop contact with bare ground, could be due to the raindrop impact on the slash that was covered with a thin layer of dust and sediment. The raindrop impact and contact with sediment

particles covering the slash, transported high concentrations of sediment during the beginning of simulations while there was a supply of sediment particles covering the slash. Across the hillslope study site, rill features primarily developed on bare tether roads, few naturally formed on cut hillslopes in between tether roads, and almost none formed on slash tether roads. We observed that it was easier for rills to form on areas of the hillslope where bare mineral soil was exposed. The extent of rills on bare soil facilitated the hydraulic power and erosivity of runoff, and therefore increased erosion rates on bare tether roads.

The total rainfall and maximum i15 rainfall intensities we observed over three summers are representative of the natural rainfall regime of the local area. The erosion we measured with sediment fences was generated from total rainfall each year that was near or above the local average and i15 maximum rainfall intensities that were near the local i15 maximum rainfall intensities with a one-year-recurrence-interval. Additionally, we observed a range (i15 5 – 35 mm/hr) of maximum rainfall intensities that generated both small and large (0.01 – 11.78 Mg/ha) erosion events.

We observed the highest erosion rates on bare and slashed tether roads during the first and second year of the study. Croke et al. (2001) measured surface erosion from simulated rainfall 0.5, 1.5, and 5 years after logging skid trails were constructed and found that erosion rates exponentially decreased with recovery time and that the most amount of soil loss occurred the first 1-2 years after logging. Decreases in erosion over time could be attributed to factors such as vegetation regrowth (Cerda and Doerr, 2005) and soil cohesion influencing slope stability (Fattet et al., 2011).

The Universal Soil Loss Equation (USLE) demonstrates that runoff and erosion increase with increasing slope. The reason our results do not show as clear of a relationship between slope and erosion is that we were unable to adequately test the effect of slope during rainfall simulations, as the slope varied little among the plots. In the rainfall simulation portion of our study, we examined the specific slope range of 20 - 60%, but we completed the majority (16/18) of the simulations on 40% or 60% slopes. There could have been a clearer relationship if we completed more replicates in this study on only 20 and 60% slopes, for example. The variations in soil aggregate stability and composition of ground cover on bare tether road sites could also explain this.

Similar to other studies, we observed that soil erosion was greatest during the onset of intense rainfall and steadily decreased the rest of the simulation. Fox and Bryan (2000) simulated rainfall on different slopes and observed that soil erosion peaked during the beginning of the simulation and decreased at a constant rate during the rest of the simulation. Highest erosion potential occurring near the onset of rainfall can be explained by soil particle detachment from the surface that are then flushed away early on in the rain event. After removal of this initial portion of sediment the system becomes supply limited and erosion decreases.

4.2 Evaluating cut-to-length tethered logging systems on steep hillslopes

A goal of our rainfall simulation study was to estimate the erosion potential of logged hillslopes when they undergo high and extremely high-intensity rainstorms. Our study demonstrates that erosion potential from our simulated 10 and 100-year-recurrence-interval storms were similar to, and less than, the maximum erosion rates that we measured with sediment fences after 1-year-recurrence-interval natural rainstorms. High and extremely high-

intensity rainstorms are capable of triggering catastrophic events such as shallow landslides and debris flows. Steep slopes are especially susceptible to landslides, and the stability of the slope controls slope failure, making forested mountainous areas of particular concern (Rickli and Graf, 2009). The condition of the forest also influences landslide likelihood. Rickli and Graf (2009) found that the highest frequency of forest landslides occurred in stands that had windthrow and beetle-kill damage compared to healthier stands with diverse stand structures. By measuring erosion from natural and simulated rainfall, our study tested the limits of a system with severe beetle kill that was salvage logged. Simulating 10 and 100-year recurrence interval rainfall intensities did not generate erosion rates greater than the erosion rates measured in sediment fences after natural rainfall intensities that ranged from 1 to 37 i15 mm/hr suggesting that the likelihood of erosion rates high enough to trigger landslides on this hillslope could be low.

The erosion rates that we observed during the three years of this study, both from natural and simulated rainfall, are relatively moderate compared to erosion rates from other disturbances. Model estimates of global erosion rates on forest land cover range from 0 t/ha/yr to 7.8 t/ha/yr, with a median of about 0.1 t/ha/yr (Borrelli et al., 2021) (Table 8). Model estimates of global erosion rates on bare land range from 0 t/ha/yr to more than 9.1 t/ha/yr, with a median of about 0.5 t/ha/yr (Borrelli et al., 2021) (Table 8). In a study that evaluated different erosion treatments on bladed skid trails on 15-20% slopes with sandy clay loam soils, they measured annual erosion rates of 6 t/ha/yr when water bars were installed above and below the 76 m treatment and pine slash was piled on the ground, compared to annual erosion rates of 138 t/ha/yr when only water bars were installed (Wade et al., 2012) (Table 8). The high erosion rates (138 t/ha/yr) from skid trails without slash and only water bars occurred during a period with high amounts of rainfall and only 9.5% ground cover (Wade et al., 2012). Modeled erosion rates of cut-to-length tethered logging on a eucalyptus plantation in Brazil with sandy clay-sandy clay loam soils on 50 – 78 % slopes and 1244 mm annual rainfall estimated erosion rates of 0.4 – 30 t/ha/yr (Garren et al., 2019) (Table 8). In contrast, we measured erosion rates of 0 – 2 t/ha/yr after summer rainstorms on a site that was cut-to-length tethered logged and located on a high-elevation mountain pass in Central Colorado with 659 mm annual rainfall.

Our results suggest that there is some erosion disturbance from logging equipment in between tether roads. The cut hillslope sites in between tether roads are susceptible to erosion due to the lack of forest canopy interception and the amount of bare soil coverage. It is estimated that 10-50% of precipitation is lost to canopy interception and does not reach the ground surface (Roth et al., 2007). On steep forested hillslopes, erosion is not as problematic because of the tree and understory cover. When there is extensive logging, the trees and understory are removed, and steep hillslopes become more vulnerable to erosion. The litter and organic matter removed during the logging operations removes interception of raindrop impact and decreases infiltration potential. Additionally, the cut hillslope areas in between tether roads that had high bare soil coverage before logging, are more susceptible to erosion and easily disturbed by logging operations. Consequently, as the cut-to-length logging methods process the trees in the forest, the felling and loading of the trees in between tether roads and onto the harvester are of particular concern where there is already low vegetation cover.

At our study site, the cut hillslope areas in between tether roads were prescribed to remove all beetle-infested trees and those with potential for windthrow or risk to infrastructure. As logging was extensive at the site due to the nearly 75% beetle-killed tree mortality in some

areas, the forest density post-logging was very low. In the context of our study, low-density stands still exist on the cut hillslopes in between tether roads, but no stands exist on the tether roads as all trees were removed. This implies that the cut hillslope areas have more rainfall interception from canopy coverage than tether roads where the most disturbance from logging equipment occurred, possibly underestimating erosion rates from natural rainfall compared to the other ground cover treatments.

Upper hillslope areas near ridgelines can be more susceptible to erosion as they tend to have lower stand densities as they transition from subalpine to alpine environments. The forest floors in these areas tend to have lower plant coverage, less tree litter to contribute to soil organic matter, and fewer deep roots, making the soil in these areas less stable and more susceptible to disturbance. Tethered logging operations in high-elevation, steep forests with lower stand densities can have a shortage of slash supply to cover the tether road networks created during harvesting. While our study did not install sediment fences or complete rainfall simulations near ridgelines, our rill surveys evaluated the extent and morphology of rill features on the upper hillslopes near ridgelines. The highest concentrations of rill erosional features in this study were found on the upper parts of the hillslopes. In subalpine and alpine mountainous forests, the upper parts of the hillslopes and ridgelines are susceptible to erosion.

The practical design and intensive application of slash residue on tether roads is an influential strategy for mitigating erosion, but it poses the opportunity cost of compromising other ecological processes. In our study site, mitigating erosion after salvage logging was foremost due to the steep slopes and likelihood of sedimentation into headwater streams. The steep morphology of the logged hillslopes also influenced slope stability concerns regarding the possibility of triggering shallow landslides. However, heavy slash application poses concerns to other ecological processes such as wildfire fuel supply (Stephens, 1998) and limitation of tree regeneration (Waters et al., 2004). Consequently, another motivation for logging at this site was to increase wildfire safety and resilience in the event of a wildfire. Due to the severe tree mortality from beetle kill, the dead trees were weak and would have posed severe falling hazards if firefighter support was needed on the hillslope. Overall, motivations for land management vary, and it is important to evaluate the risks associated with the site of interest when prescribing slash applications.

5. Limitations

In this study we estimated erosion rates on a range of scales consisting of 1.25 m^2 rainfall simulation plots, ~0.01 ha (~4 m width of tether road x 30 m length of tethered road) contributing areas of erosion measured with sediment fences, and the scale of the extent of the hillslope as we measured rill development. Simulating erosion in a 1.25 m^2 area limited the space for dominant erosional processes such as rill erosion to develop. Additionally, confining the sediment fence contributing area to a length of 30 m above each sediment fence could have contributed to underestimating potential erosion rates in this study. We observed some rill features that were longer than 30 m, and confining the contributing area that erosion collected in fences could have limited rill soil erosion potential, possibly underestimating erosion rates. Another limitation of this study is that our rainfall simulations were longer than the natural regime of monsoonal high-intensity rain events in high-elevation mountain systems. Our rainfall simulation experiments simulated high intensity rainfall for 45 minutes, whereas natural regimes

consist of frequent, short, high-intensity rain events in the summer. The longer duration of our simulated rainfall, as opposed to simulating pulses of ~10 minute high-intensity storms, for example, could have generated different hydrologic and erosional processes than what we would have observed in the natural regime.

6. Conclusions

We investigated the hydrologic and soil erosion responses to natural and simulated rainfall on a cut-to-length tether logged hillslope to evaluate soil erosion potential and slash mitigation strategies after logging. The use of cut-to-length tethered logging in the US is relatively new, and we aimed to evaluate the erosion responses to this logging approach. Additionally, current slope policies restrict logging on slopes greater than 40% and cut-to-length tethered logging provides an option for treating forests with slopes greater than the current limit.

During summers 2021 - 2023, we measured sediment accumulation after natural rainfall in 39 sediment fences installed across the 140-hectacre site. During the most recent field season (2023), we additionally measured runoff and erosion during 18 rainfall simulations in the field consisting of 45 minutes of rainfall and 10 and 100-year-recurrence interval rainfall intensities (i.e. 74 and 134 mm/hr) on 20, 40, and 60% slopes. In both the natural and simulated rainfall components of this study, we evaluated erosion on hillslopes with three different ground cover types: tether roads exposed with bare soil, tether roads covered with slash, and cut hillslope areas in between tether roads.

From simulating high and extremely high rainfall intensities, we observed marginally significant evidence ($P=0.0726$) that slash application reduces runoff rates on tether logging roads. The runoff coefficients (runoff/rainfall) from simulated rainfall averaged by ground cover type were 36% on bare tether roads and 17% on slash tether roads, demonstrating that slash application can increase soil infiltration and decrease runoff after disturbance. The average runoff coefficient on cut hillslope areas in between tether roads was 18%, suggesting that runoff rates on areas in between tether roads are moderately low due to vegetation cover and less equipment disturbance than tethered roads.

Our results suggest that bare soil exposure on logging tether roads and in between tether roads increases the likelihood of erosion. We estimated annual erosion rates of 0 – 2 t/ha/yr from rain events occurring from mid-June through mid-October, which are substantially lower than erosion rates after traditional steep slope logging methods. For both natural and simulated rainfall, we observed strong evidence that erosion rates were lower on tether roads where slash was applied. Sediment yield was 91% less on slashed tether roads relative to bare tether roads after natural rainfall and 81% less on slashed tether roads relative to bare tether roads when we simulated high-intensity rainfall. We also observed both low and high erosion rates on cut hillslope areas in between tether roads, suggesting that areas in between tether roads with high bare soil coverage are susceptible to disturbance and high erosion rates. Additionally, we observed that the magnitude of erosion events after natural rainfall were highest during the first and second year of the study, suggesting that the first and second year after logging can be more susceptible to erosion. A goal of our study was to evaluate erosion rates in a bark beetle-impacted forested system that could have had inadequate slash supply for logging on steep slopes. Our study observed low to moderate erosion rates from cut-to-length tethered logging in a system with slash supply comprised of pole-sized dead timber lacking green tree tops and

branches. The low to moderate erosion rates we observed in this system indicate this logging method may have a reasonable erosion risk for logging on slopes greater than 40%. To further explore the soil erosion and recovery of this logging method, further research should be conducted in areas with different rainfall and soil regimes to evaluate the cover, slope, and rainfall intensity thresholds that generate high erosion rates.

Acknowledgements

This study would not be possible without the contributions of many people. Project support was provided by the Pike San Isabel National Forest. This research was also partially supported by the intramural research program of the U.S. Department of Agriculture, National Institute of Food and Agriculture, Hatch program accession number 7007074. Dr. Tim Covino was partially supported by NSF-EAR 1945504. We sincerely appreciate Alex Rudney and Jamie Krezelock (Pike San Isabel National Forest) for creating the project layout and requesting our involvement in studying it. We also appreciate the Arkansas River Watershed Collaborative for coordinating the contract and logging project and Andy Lerch (now with the Colorado State Forest Service) for administering the contract. We thank Preston Green and Matt Matioda from Miller Timber Services, Cut to Length Division for providing logging services and coordinating with our study. We are very grateful to Tim Fegel, Maggie Windingstad, Jerrell Mock, Garret Dickson, Russell Benson, Keen McFarland, Chris Moss, Olivia Laconis, Shannon Iral, and Ashlynn Piwowarczyk from RMRS for their extensive field work and lab support. We also thank Dr. Peter Nelson from Colorado State University for supporting this study by acquiring and processing drone imagery of the site.

Figures

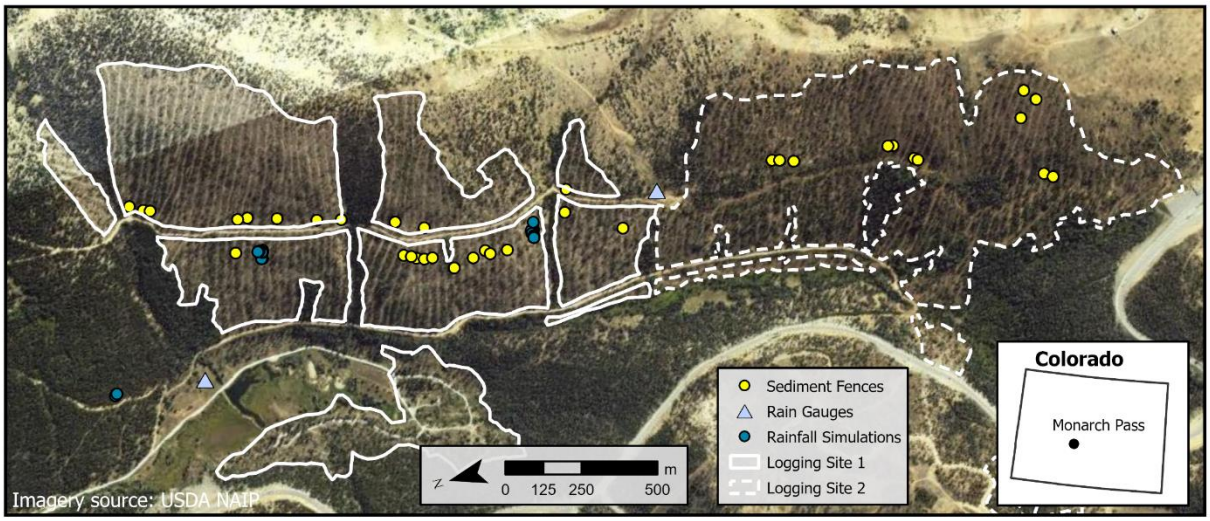


Figure 1. Site map of sediment fence, rainfall simulation, and logging site locations. Tether logging roads are within the logging site boundaries. Haul roads are horizontal on the hillslope and are located at the base, mid-slope, and top of the hillslope. The treeline begins above the logging site boundaries (eastern direction). Wetlands are located below the logging site boundaries (western direction) and stream networks are located below the southern portion of logging site 2. The highway below the harvest units is the state highway that goes through Monarch Pass, Colorado.

Figure 2. Photo of a sediment fence on a bare tether road. The tether road transitions to slash cover downslope of the fence. The fence dimensions are approximately 4 m wide (i.e. the 4 m width of the tether road), 1.5 m deep, and 0.5 m high.

Figure 3. Drone imagery showing an example of a sediment fence installed in each ground cover treatment: (left) a bare tether road, (middle) a slashed tether road, (right) a cut hillslope in between tether roads. Drone imagery was acquired and processed by Dr. Peter Nelson, Colorado State University.

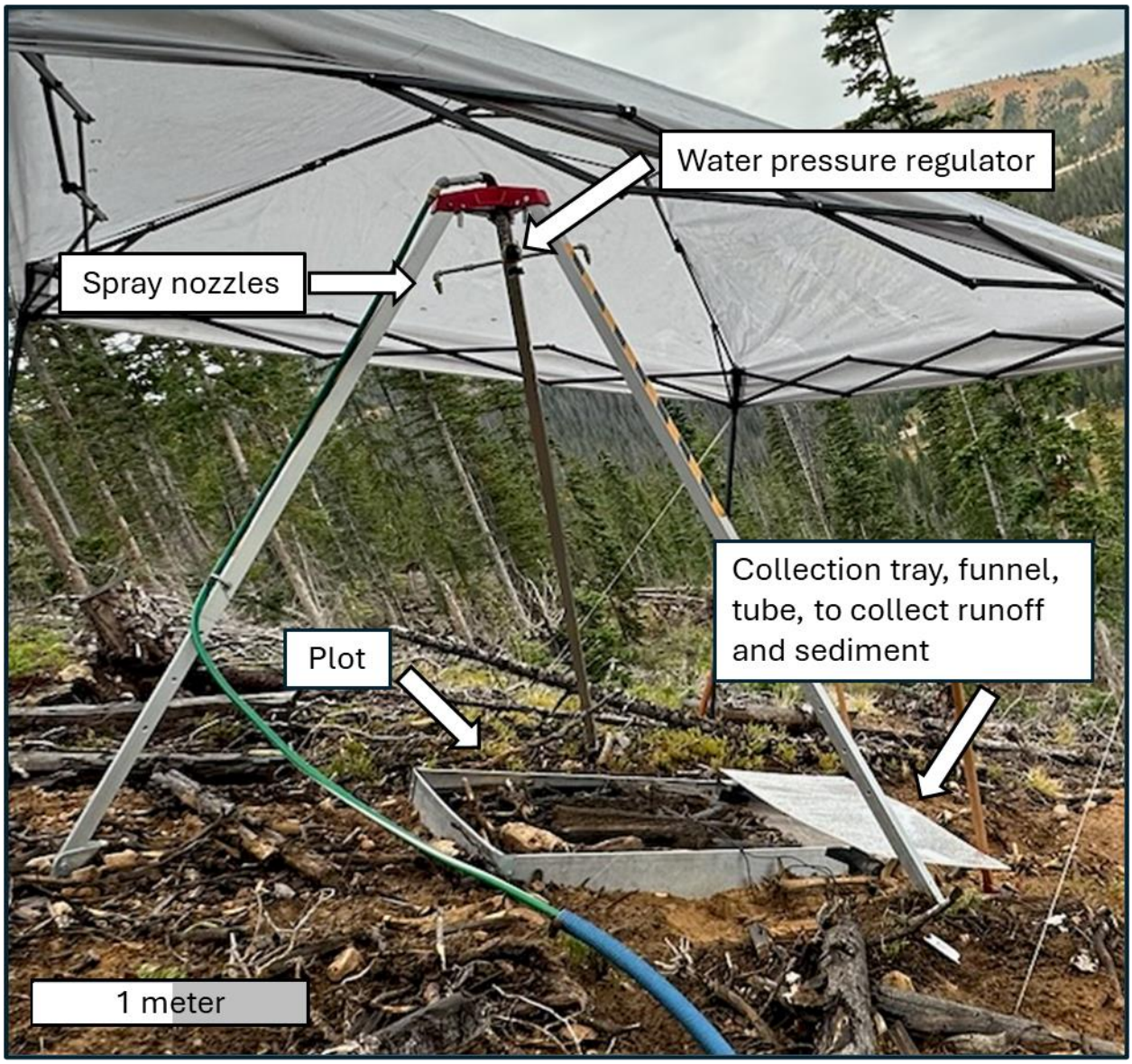


Figure 4. Photo and overview of the rainfall simulator. This photo is rotated to make it easier to see the rainfall simulator. The rainfall simulator set up on a slashed tether road on 60% slope. The plot is 1.25 m long and 1.00 m wide and the height of the spray nozzles is 2.4 m. The collection tray, funnel, and tube are out of view and underneath the plastic cover shown in the photo.

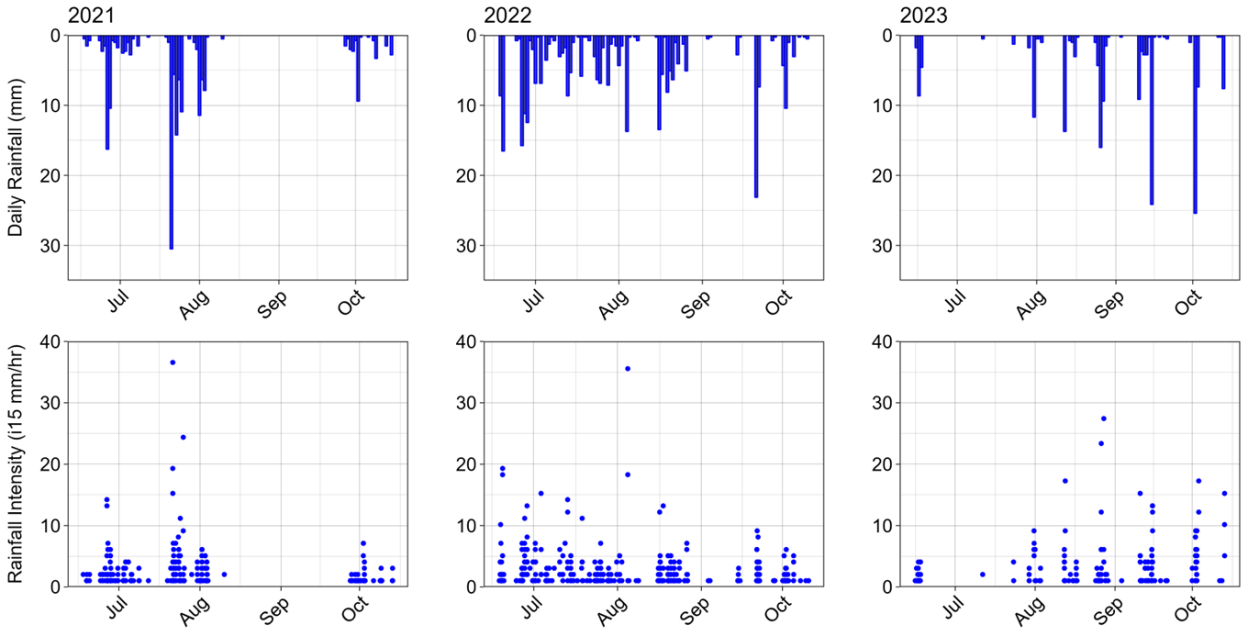


Figure 5. Daily precipitation and maximum 15-minute rainfall intensities (I_{15} mm/hr) of storms between June 15th and October 15th in 2021, 2022, and 2023. Precipitation data is from site tipping bucket rain gauges.

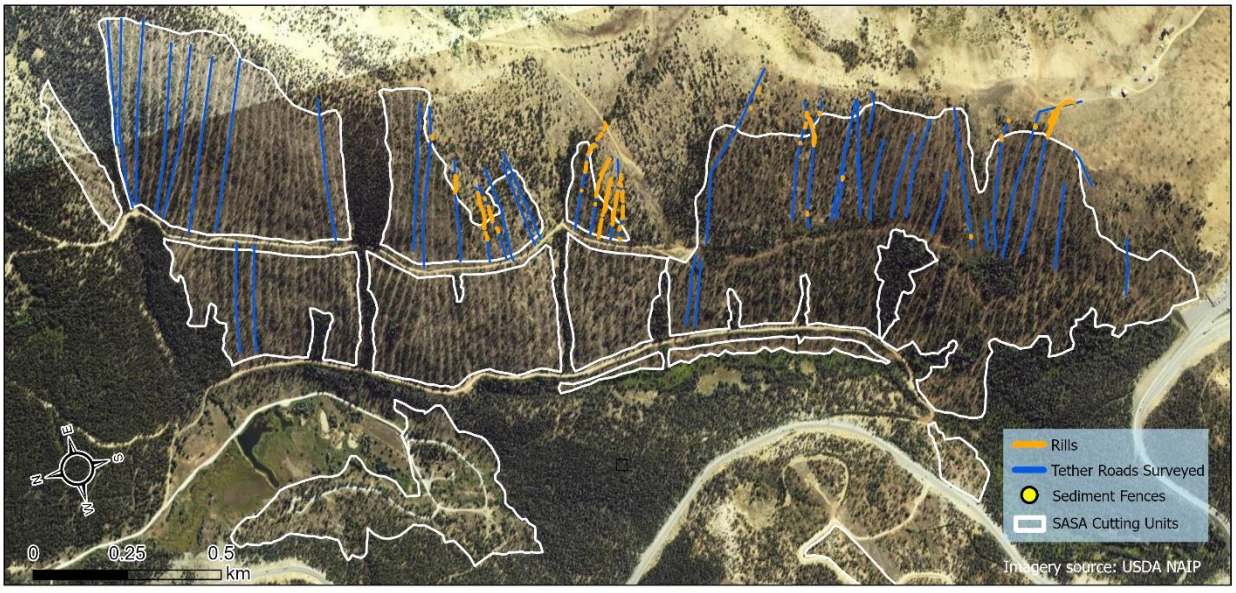


Figure 6. Map of rill surveys conducted in 2023. The orange lines show the rills identified on the tether roads while surveying and the blue lines show all the tether roads that were hiked. The ridgeline is located above the cutting units where the treeline is.

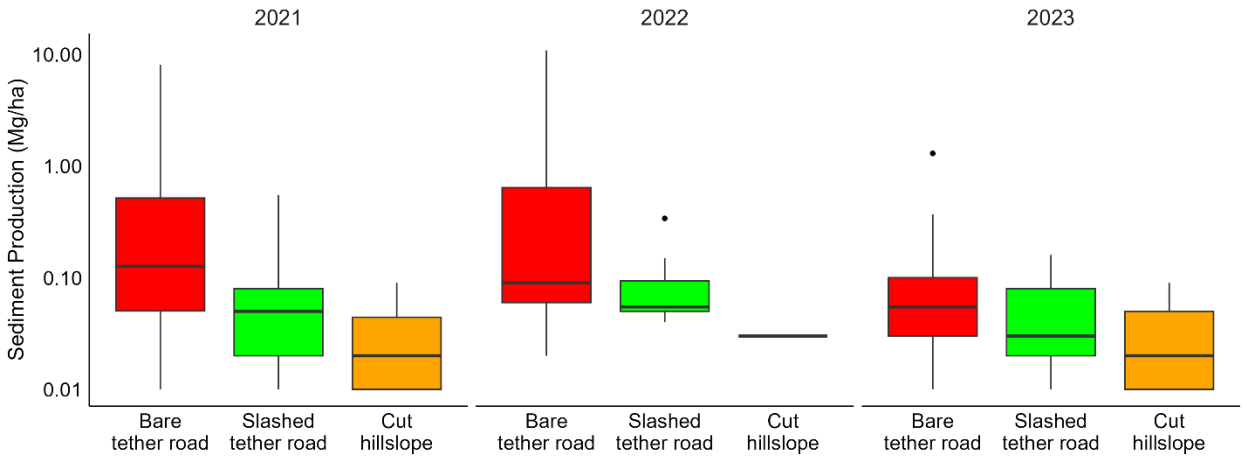


Figure 7. Boxplots of erosion event data measured in sediment fences on bare tether roads, slashed tether roads, and cut hillslopes in between tether roads. The soil that deposited in sediment fences was measured after rainstorms that generated erosion and deposited sediment in at least one of the 39 fences installed across the hillslope. Rainstorm events only generated erosion at some of the fence sites. This analysis presents 0 Mg/ha for when no sediment was deposited in a fence, and the corresponding sediment production rate when there was sediment deposited in a fence.

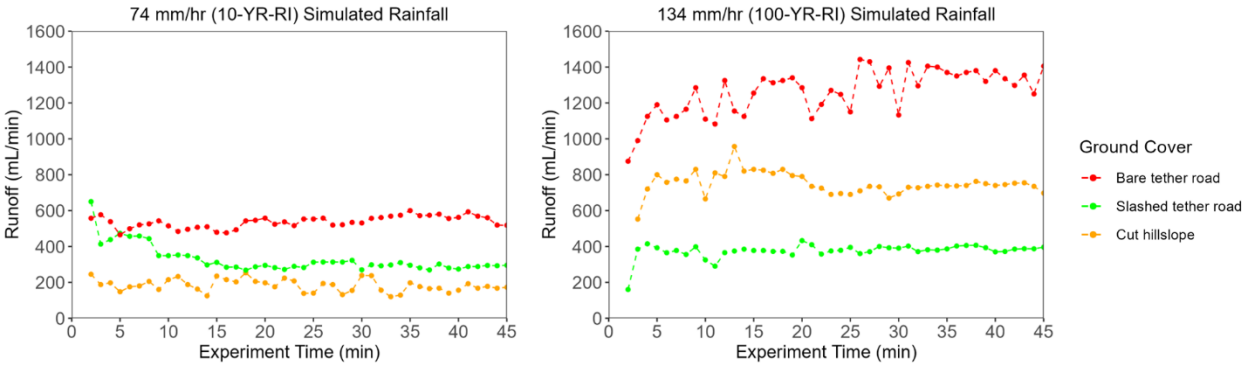


Figure 8. Surface runoff averaged by ground cover treatment. Plot (a) averages five simulations on bare roads, five simulations on slashed roads, and two simulations on cut hillslopes, and plot (b) averages two simulations on bare roads, two simulations on slashed roads, and two simulations on cut hillslopes. The runoff is equal to the volume of runoff for each minute of the simulation.

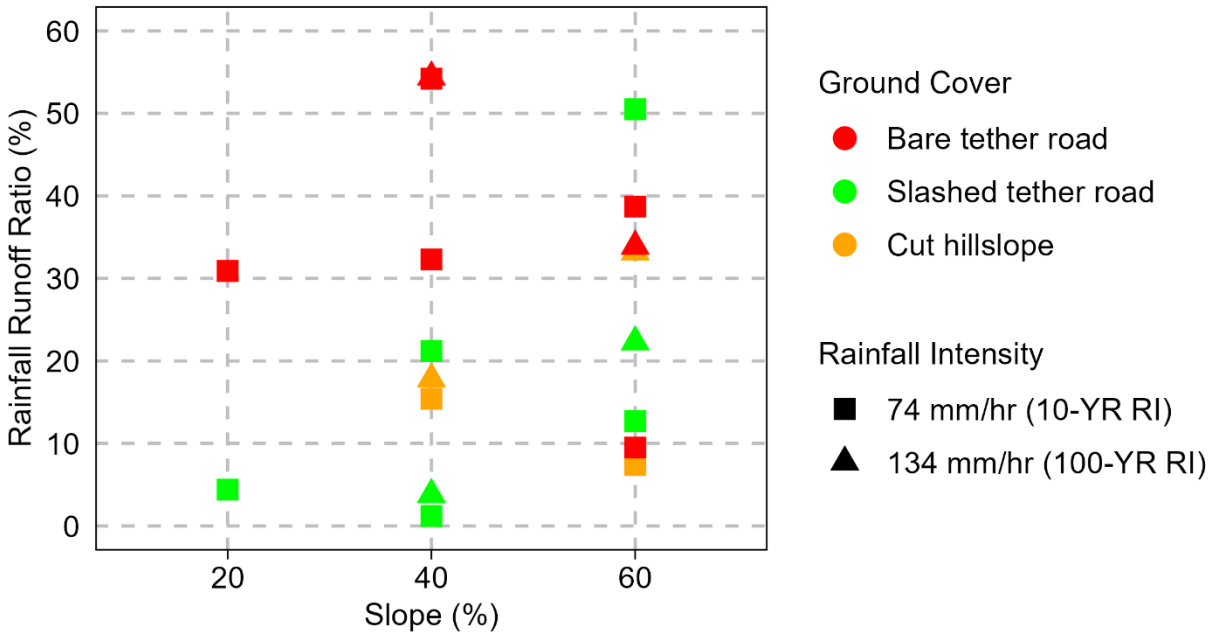


Figure 9. The relationship between rainfall runoff ratio and slope for each rainfall simulation. Each point represents one simulation. Points are symbolized by the ground cover of the site and the rainfall intensity applied during the simulation.

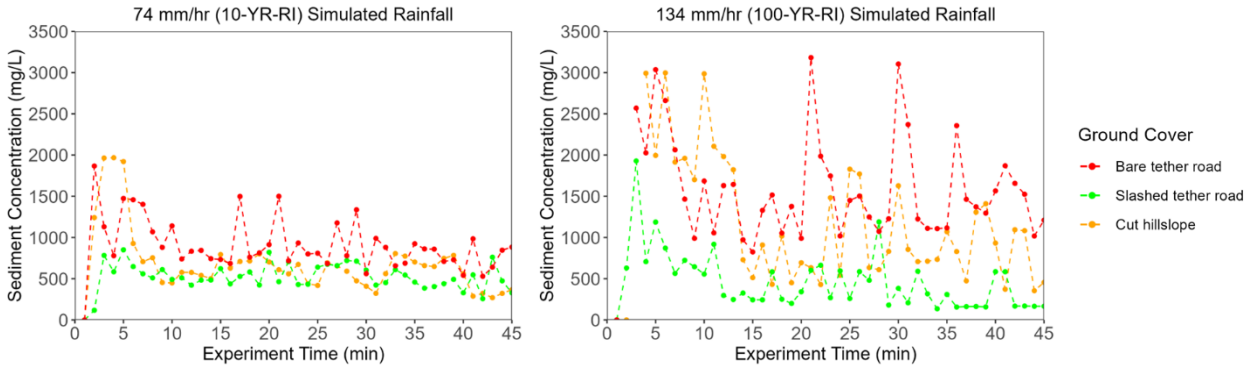


Figure 10. Sediment concentrations in overland flow averaged by ground cover treatment. Plot (a) averages five simulations on bare roads, five simulations on slashed roads, and two simulations on cut hillslopes, and plot (b) averages two simulations on bare roads, two simulations on slashed roads, and two simulations on cut hillslopes. The sediment concentration is equal to the sediment yield (mg) filtered from the overland flow divided by the volume (L) of the overland flow for each minute of the simulation.

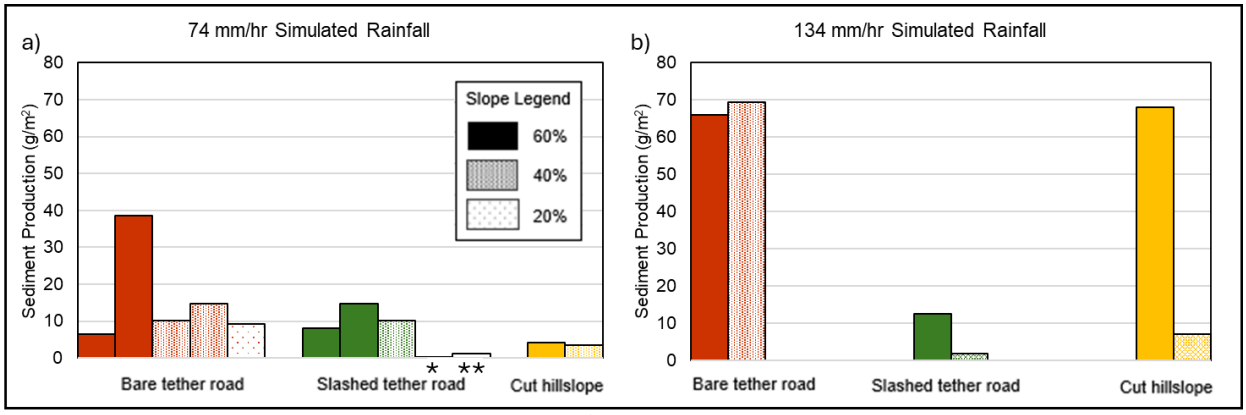


Figure 11. The total sediment production (g/m^2) from each of the 18 rainfall simulations. Each bar represents one simulation. Panel (a) shows 10-Year-RI (74 mm/hr) rainfall and panel (b) shows 100-Year-RI (134 mm/hr) rainfall. Bars are symbolized according to the percent slope of the simulation site. * Indicates a slash tether road on 40% slope and ** indicates a slash tether road on 20% slope.

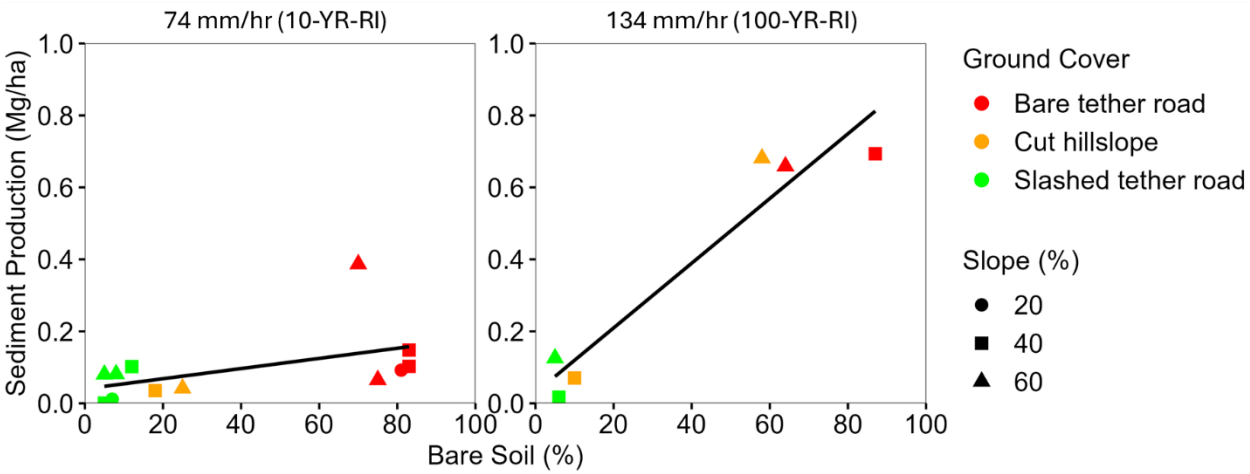


Figure 12. The relationship between sediment production and the percent of bare soil at each site. Each point represents one simulation. The points are symbolized by ground cover treatment and slope.

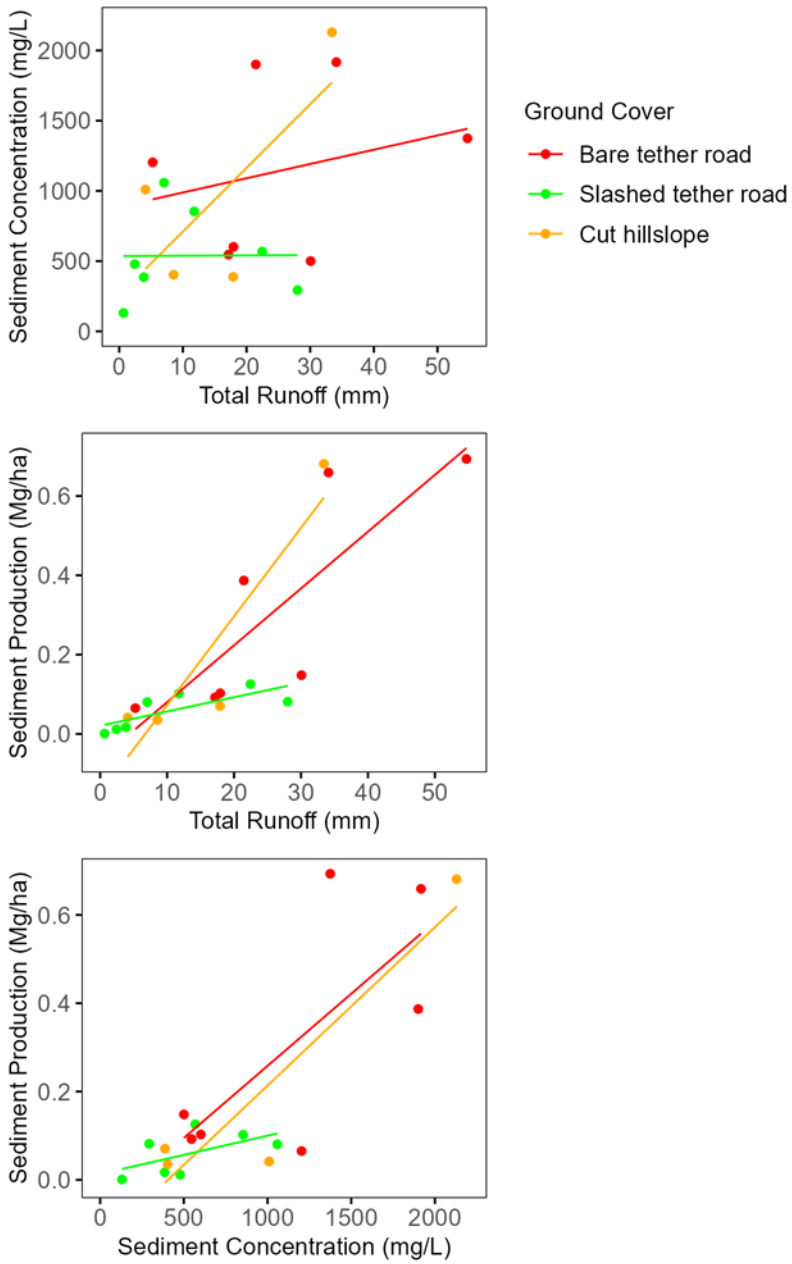
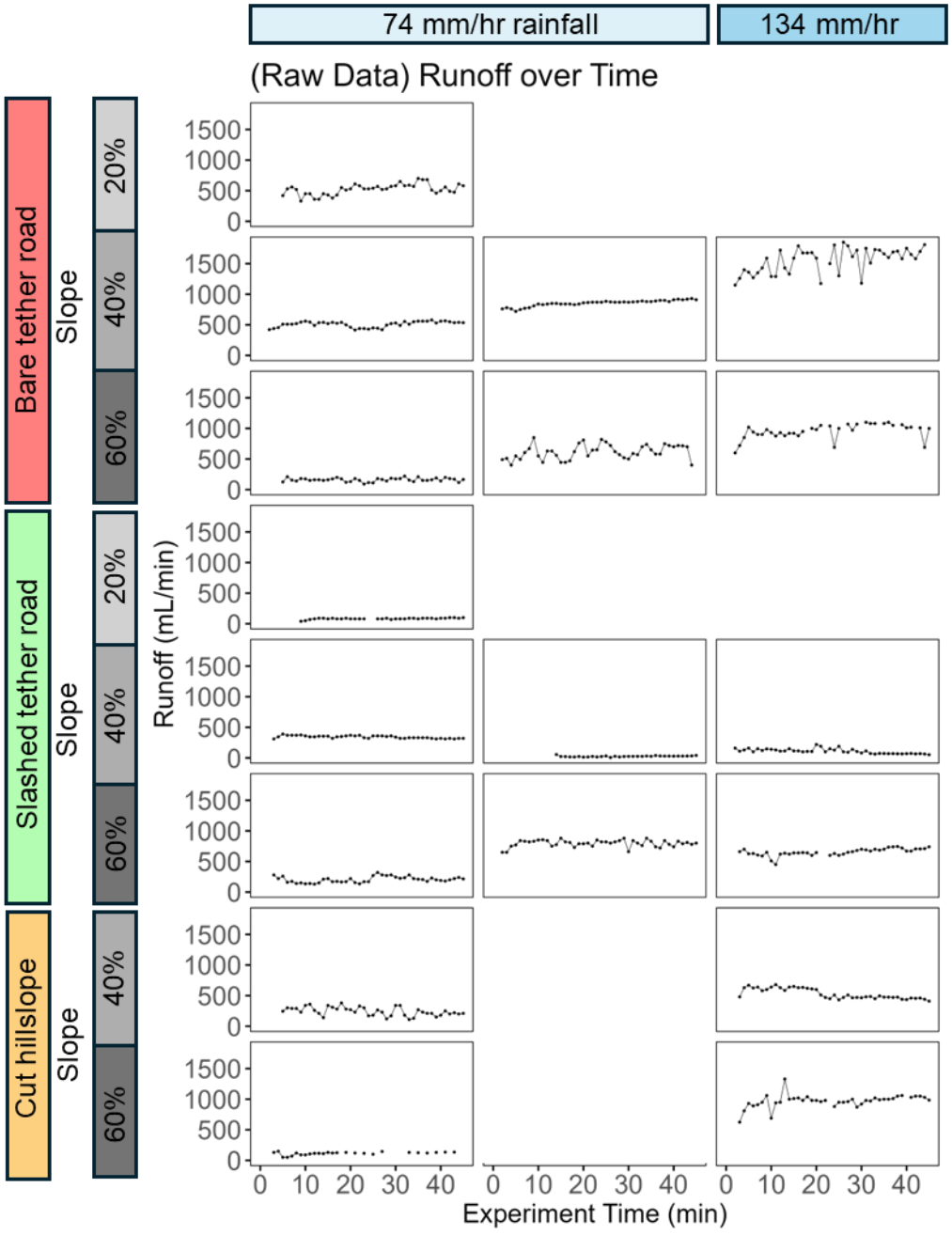
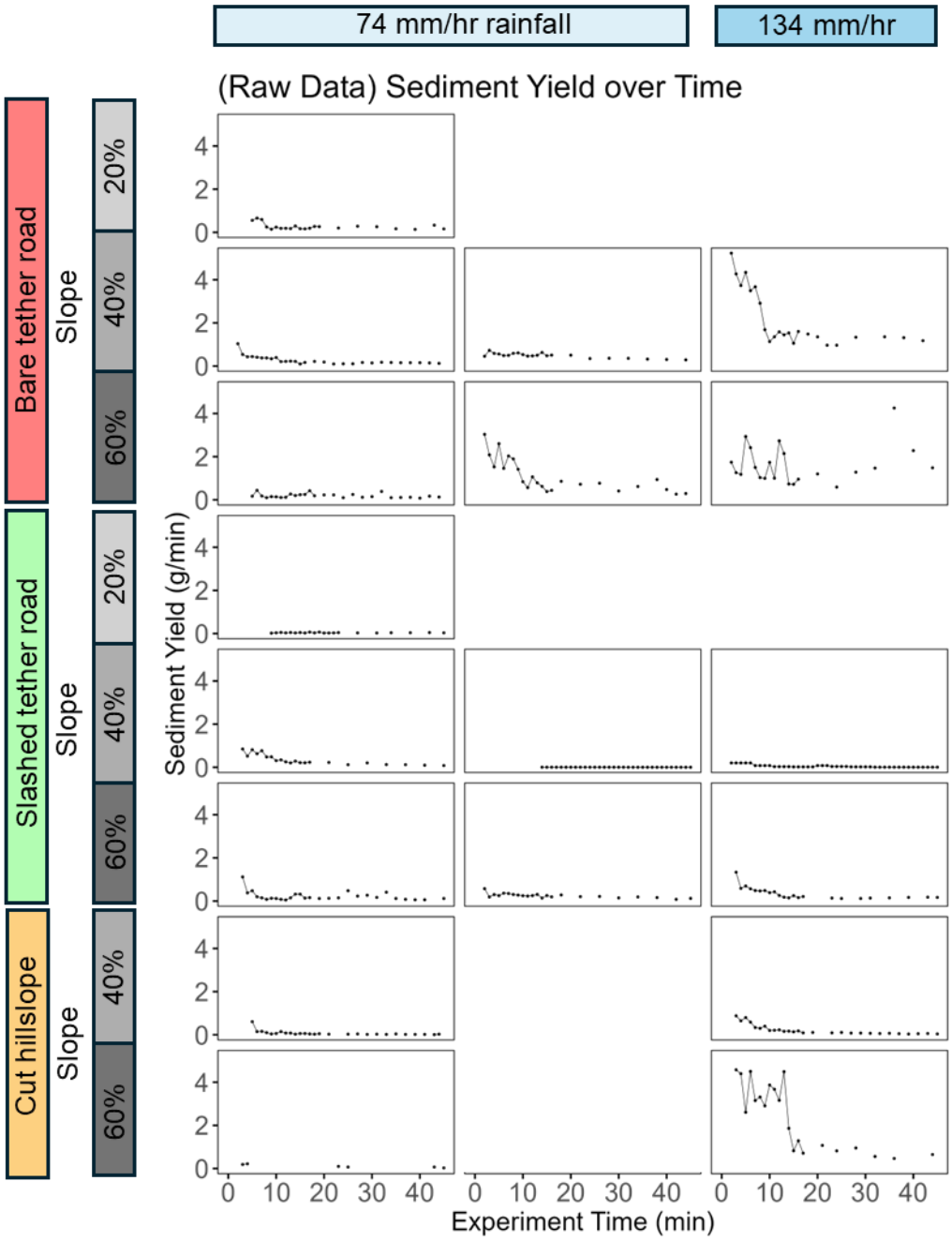


Figure 13. The relationship between runoff (mm), average sediment concentration (mg/L), and sediment production (Mg/ha) for each rainfall simulation. A simple linear regression line was added for each ground cover type.



Supplemental Figure 1. Runoff hydrographs with raw data showing the runoff (mL) per one minute interval for each rainfall simulation.



Supplemental Figure 2. Sedigraphs showing the total sediment (g) in overland flow per one minute interval for each rainfall simulation.

Sim. #18, slashed tether road,
20% slope, 74 mm/hr rainfall
Runoff ratio: 4%

Sim. # 1, slashed tether road,
40% slope, 74 mm/hr rainfall
Runoff ratio: 1%

Sim. #16, slashed tether road
40% slope, 74 mm/hr rainfall
Runoff ratio: 21%

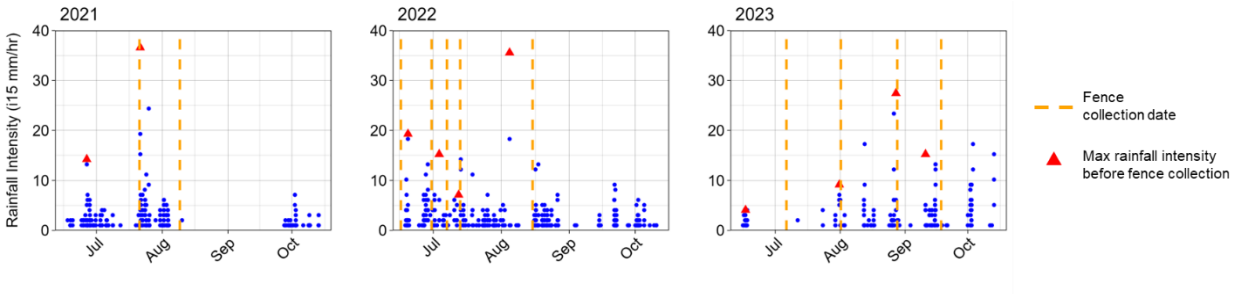
Sim. #2, slashed tether road
40% slope, 134 mm/hr rainfall
Runoff ratio: 4%

Sim. #7, slashed tether road
60% slope, 74 mm/hr rainfall
Runoff ratio: 13%

Sim. #14, slashed tether road
60% slope, 74 mm/hr rainfall
Runoff ratio: 51%

Sim. #8, slashed tether road
60% slope, 134 mm/hr rainfall
Runoff ratio: 22%

Supplemental Figure 3. Photos of each rainfall simulation plot on slashed tether roads. The slope of the ground, rainfall intensity applied, and rainfall runoff ratio is shown for each simulation.



Supplemental Figure 4. The i15 rainfall intensities (mm/hr) for each rainfall event in 2021, 2022, and 2023. The plots show the sediment fence collection dates in orange and the maximum rainfall intensity before each collection date in red.

Tables

Table 1. Comparison of precipitation measured from tipping bucket rain gauges in 2021, 2022, and 2023 to local historical precipitation data. * Indicates the 30-year-historical-average precipitation from June 15 – October 15 during the years 1990 – 2020 recorded from the nearby SNOTEL site Porphyry Creek (elevation 3288 m). ** Indicates the local I15 rainfall intensity with a one-year recurrence interval sourced from NOAA's Precipitation Frequency Data Server.

Site	**Local**	**Monarch**		
June 15 - Oct 15	historical precip.	2021	2022	2023
Total precip. (mm)	178*	169	273	149
Mx i15 (mm/hr)	32 (1-YR-RI)**	37	39	26

Table 2. Table of rill measurements showing the minimum, maximum, median, mean, and count of the length, depth, and width of rills each year of the study.

	Length (m)			**Width (cm)**			**Depth (cm)**		
	2021	**2022**	**2023**	**2021**	**2022**	**2023**	**2021**	**2022**	**2023**
max	58.0	195.8	75.3	20.0	8.0	65.0	14.0	12.0	37.0
min	1.7	1.3	1.0	3.0	2.0	4.0	2.0	1.0	1.0
median	14.0	9.6	6.5	10.0	4.0	17.0	5.0	3.0	10.0
mean	18.3	18.6	12.8	9.8	3.7	20.5	5.2	3.1	10.9
count	19	75	82	19	75	82	19	75	82

Table 3. Statistics for tests of the effects of ground cover on the response of sediment production measured with sediment fences.

Sediment Fences

		test	df	test statistic	*P*-value
Sediment production (2021)					
Cover		Kruskal-Wallis	2	$X^2 = 19.43$	0.0000
	Cut hillslope vs. Bare	Dunne	-	Z = 4.33	0.0000
	Slash vs. Bare	Dunne	-	Z = 2.70	0.0103
	Slash vs. Cut hillslope	Dunne	-	Z = -1.88	0.0910
Sediment production (2022)					
Cover		Kruskal-Wallis	2	$X^2 = 21.59$	0.0000
	Cut hillslope vs. Bare	Dunne	-	Z = 4.21	0.0000
	Slash vs. Bare	Dunne	-	Z = 3.63	0.0004
	Slash vs. Cut hillslope	Dunne	-	Z = -1.01	0.4711
Sediment production (2023)					
Cover		Kruskal-Wallis	2	$X^2 = 22.91$	0.0000
	Cut hillslope vs. Bare	Dunne	-	Z = 4.55	0.0000
	Slash vs. Bare	Dunne	-	Z = 3.32	0.0014
	Slash vs. Cut hillslope	Dunne	-	Z = -1.68	0.1408

Table 4. Table of the minimum and maximum sediment production events, the number of high-yielding events > 1 Mg/ha, and the number of fences with sediment production presented for each logging site and year since logging.

Logging Phase 1

	2021 (1-YR)			2022 (2-YRS)			2023 (3-YRS)		
	Bare Road	Slashed Road	Cut Hillslope	Bare Road	Slashed Road	Cut Hillslope	Bare Road	Slashed Road	Cut Hillslope
Min and Max (Mg/ha)	[0.01, 8.09]	[0.01, 5.41]	[0.01, 0.17]	[0.03, 11.78]	[0.04, 0.08]	[0.03]	[0.01, 1.3]	[0.01, 0.15]	[0.01, 0.07]
Events > 1.00 Mg/ha	5	1	0	4	0	0	1	0	0
Fences with Erosion	10/10	10/10	4/7	7/10	1/10	1/7	10/10	10/10	7/7

Logging Phase 2

	2022 (1-YR)			2023 (2-YRS)		
	Bare Road	Slashed Road	Cut Hillslope	Bare Road	Slashed Road	Cut Hillslope
Min and Max (Mg/ha)	[0.02, 6.62]	[0.05, 0.34]	[0.05]	[0.01, 0.34]	[0.01, 0.16]	[0.01, 0.09]
Events > 1.00 Mg/ha	1	0	0	0	0	0
Fences with Erosion	4/6	5/6	1/3	5/5	5/5	2/2

Table 5. Statistics for tests of the effects of ground cover and year on the response of sediment production.

Sediment Fences

Test = ANOVA using Aligned Rank Transform (ART) and post-hoc pairwise comparison

Sediment Production Comparison	Estimate	SE	df	t-ratio	P-value
Bare, 2021 vs. Bare, 2022	105.46	18	307	5.849	<.0001
Bare, 2022 vs. Bare, 2023	-77.66	13.9	307	-5.595	<.0001
Bare, 2021 vs. Bare, 2023	27.8	18.6	307	1.498	0.856
Cut hillslope, 2021 vs. Cut hillslope, 2022	61.06	21.8	307	2.796	0.1207
Cut hillslope, 2022 vs. Cut hillslope, 2023	-80.26	17.7	307	-4.538	0.0003
Cut hillslope, 2021 vs. Cut hillslope, 2023	-19.2	22.7	307	-0.844	0.9954
Slash, 2021 vs. Slash, 2022	99.58	18	307	5.523	<.0001
Slash, 2022 vs. Slash, 2023	-87.28	13.9	307	-6.288	<.0001
Slash, 2021 vs. Slash, 2023	12.29	18.6	307	0.663	0.9992

Table 6. Runoff and erosion data for each rainfall simulation.

Ground Cover	Simulation number	Slope percent (%)	Antecedent soil moisture vwc (m^3/m^3)	Application rate (mm/hr)	Time to initial runoff (min)	Average runoff (mm/hr)	Runoff/rainfall ratio (%)	Average sediment concentration in runoff (g/l)	Total sediment yield (g)
Bare	17	20	0.3	74	4	25	31	0.55	12
Bare	4	40	0.27	74	1	24	32	0.60	13
Bare	15	40	0.14	74	1	41	54	0.50	19
Bare	3	40	-	134	1	74	54	1.39	87
Bare	11	60	0.13	74	4	8	10	1.20	8
Bare	13	60	0.07	74	1	29	39	1.90	48
Bare	12	60	0.26	134	1	47	34	1.92	82
Slashed	18	20	0.19	74	8	4	4	0.48	1
Slashed	1	40	0.12	74	12	1	1	0.13	0
Slashed	16	40	0.09	74	2	16	21	0.86	13
Slashed	2	40	0.03	134	1	5	4	0.39	2
Slashed	7	60	0.04	74	2	10	13	1.06	10
Slashed	14	60	0.07	74	1	38	51	0.30	10
Slashed	8	60	0.08	134	2	31	22	0.58	16
Cut Hillslope	5	40	0.06	74	4	12	15	0.41	4
Cut Hillslope	6	40	0.17	134	2	25	18	0.39	9
Cut Hillslope	10	60	0.01	74	2	6	7	1.01	5
Cut Hillslope	9	60	0.05	134	2	47	33	2.16	85

Table 7. Statistics for the tests of the effects of ground cover, slope, bare soil coverage, and rainfall intensity on the response of runoff ratio, average sediment concentration, and sediment production measured with rainfall simulations. Statistics for the relationships between total runoff, average sediment concentration, and sediment production measured with rainfall simulations.

Rainfall Simulations

	test	df	test statistic	*P*-value
Runoff Ratio				
Cover	ANOVA	2	F = 3.29	0.0652
Cut hillslope vs. Bare	Tukey	-	diff = -17.82	0.1873
Slash vs. Bare	Tukey	-	diff = -19.69	0.0726
Slash vs. Cut hillslope	Tukey	-	diff = -1.86	0.9796
Slope	Kruskal-Wallis	2	X^2 = 1.69	0.4289
Bare Soil Coverage (%)	SLR	16	Adj. R^2 = 0.33	0.0071
74 mm/hr rainfall	SLR	10	Adj. R^2 = 0.16	0.1081
134 mm/hr rainfall	SLR	4	Adj. R^2 = 0.79	0.0114
Avg. Sediment Concentration				
Cover	ANOVA	2	F = 2.51	0.1510
Cut hillslope vs. Bare	Tukey	-	diff = -7462.98	0.8840
Slash vs. Bare	Tukey	-	diff = -27178.50	0.1395
Slash vs. Cut hillslope	Tukey	-	diff = -19715.47	0.4409
Total Runoff	-	-	-	-
Bare	SLR	5	Adj. R^2 = -0.10	0.5255
Slash	SLR	5	Adj. R^2 = -0.20	0.9086
Cut hillslope	SLR	2	Adj. R^2 = 0.27	0.2817
Sediment production				
Cover	Kruskal-Wallis	2	X^2 = 5.13	0.0800
Cut hillslope vs. Bare	Dunne	-	Z = 1.42	0.2336
Slash vs. Bare	Dunne	-	Z = 2.20	0.0414
Slash vs. Cut hillslope	Dunne	-	Z = 0.46	0.9694
Slope	Kruskal-Wallis	2	X^2 = 1.76	0.4150
Bare Soil Coverage (%)	SLR	16	Adj. R^2 = 0.25	0.0211
74 mm/hr rainfall	SLR	10	Adj. R^2 = 0.17	0.1030
134 mm/hr rainfall	SLR	4	Adj. R^2 = 0.90	0.0023
Rainfall Intensity	Kruskal-Wallis	1	X^2 = 2.5	0.1113
Avg. Sediment Concentration	-	-	-	
Bare	SLR	5	Adj. R^2 = 0.49	0.0490
Slash	SLR	5	Adj. R^2 = 0.23	0.1523
Cut hillslope	SLR	2	Adj. R^2 = 0.80	0.0718
Total Runoff	-	-	-	-
Bare	SLR	5	Adj. R^2 = 0.62	0.0219
Slash	SLR	2	Adj. R^2 = 0.51	0.0438
Cut hillslope	SLR	2	Adj. R^2 = 0.75	0.0859

Table 8. Overview of annual erosion rate estimates on forested land cover, bare land cover, untethered logging disturbance, and tethered logging disturbance.

Land Cover/Disturbance	Annual erosion rate (t/ha/yr)	Reference
Forest land	0 - 7.8	Borrelli et al. 2021
Bare land	0 - 9.1	Borrelli et al. 2021
Skid trails	6 - 138	Wade et al. 2012
Tethered logging (modeled)	0.4 - 30	Garren et al. 2019
Tethered logging	~ 0 - 2	Our study

CHAPTER THREE

CONCLUSION

In the West, forest disturbances have increased in extent and severity in recent decades and are projected to continue to increase (McGinley et al., 2023). Bark beetle infestations are a primary forest disturbance in the Western United States and have affected 59.2 million acres of coniferous forest since 2000 (Paschke, 2021). Bark beetle impacted forests can require land management because of post-disturbance damage to the landscape, such as overstory canopy fuels and windthrow, that can create safety hazards for public use of the forest and impact firefighter safety in the case of wildfire. Much of the forested land cover impacted by bark beetles that land managers aim to treat (i.e., log) are steep, high-elevation forested hillslopes. However, much of these areas are unable to be treated because current slope policies restrict logging on slopes greater than 40%. Cut-to-length tethered logging provides an option for treating steep-sloped forests because it is cable-assisted, exerting less force on the ground surface compared to other methods.

In this study, we investigated the hydrologic and erosional effects of a cut-to-length tethered logging project on Monarch Pass, Colorado that had severe bark beetle disturbance and forest mortality. Due to the severe tree mortality, this site could have had slash supply that was inadequate for erosion mitigation because it was from dead timber, primarily consisting of pole-size woody material, lacking green tops and branches. For three summer field seasons, we measured sediment accumulation after natural rainfall in 39 sediment fences installed across the 140-hectacre site. During the most recent field season (2023), we additionally measured runoff and erosion during 18 rainfall simulations in the field consisting of 45 minutes of rainfall and 10

and 100-year-recurrence interval rainfall intensities (i.e. 74 and 134 mm/hr) on 20, 40, and 60% slopes. Both the natural and simulated rainfall components of this study evaluated erosion on three different ground cover types: tether roads exposed with bare soil, tether roads covered with slash, and cut hillslope areas in between tether roads.

We observed marginally significant evidence that slash application reduces runoff rates on tether logging roads. The runoff per unit rainfall from simulated rainfall averaged by ground cover type were 36% on bare tether roads and 17% on slash tether roads, demonstrating that slash application can increase soil infiltration and decreases runoff after disturbance. The average runoff coefficient on cut hillslope areas in between tether roads was 18%, suggesting that runoff rates on areas in between tether roads are moderately low due to vegetation cover and less equipment disturbance than tethered roads. For both natural and simulated high-intensity rainfall, we observed strong evidence that erosion rates were lower on tether roads where slash was applied. Sediment yield was 91% less on slashed tether roads relative to bare tether roads after natural rainfall and 81% less on slashed tether roads relative to bare tether roads when we simulated high-intensity rainfall. We also observed both low and high erosion rates on cut hillslope areas in between tether roads, suggesting that areas in between tether roads with high bare soil coverage are susceptible to disturbance and high erosion rates. Additionally, we observed that the magnitude of erosion events after natural rainfall were highest during the first and second year of the study, suggesting that the first and second year after logging can be more susceptible to erosion. A goal of our study was to evaluate erosion rates in a bark beetle-impacted forested system that could have had inadequate slash supply for logging on steep slopes. Our study observed low to moderate erosion rates from cut-to-length tethered logging in a system

with slash supply comprised of pole-sized dead timber lacking green tree tops and branches. The low to moderate erosion rates we observed in this system indicate this logging method may have a reasonable erosion risk for logging on slopes greater than 40%. To further explore the soil erosion and recovery of this logging method, further research should be conducted in areas with different rainfall and soil regimes to evaluate the cover, slope, and rainfall intensity thresholds that generate high erosion rates.

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