THESIS

LABORATORY EVALUATION OF A POST-FIRE GROUND TREATMENT TO MITIGATE SOIL EROSION AND RUNOFF

Submitted by

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ABSTRACT

LABORATORY EVALUATION OF A POST-FIRE GROUND TREATMENT TO MITIGATE SOIL EROSION AND RUNOFF

The objective of this study was to assess the efficacy of using agricultural straw mulch as a post-fire ground treatment to mitigate soil erosion and runoff. A laboratory research program was carried out to measure soil erosion and runoff in a physical slope-model experiment (surface dimensions = 76 cm long x 30 cm wide). Intact block samples were collected that represented conditions in Colorado wildfire prone areas. The vegetation on select block samples was burned to simulate a high-intensity wildfire. Unburned block samples with varying amounts of vegetation and burned block samples with varying amounts of straw mulch (0, 0.06, 0.11, and 0.22 kg/m^2) were tested in the slope-model experiment at a slope of 28^o under a simulated rainfall of 48 mm/h for 40 min. Burned block samples were exposed to two rainfall simulations conducted three days apart to explore changes in soil hydraulic properties due to potential soil crust formation. Runoff, and eroded sediment were collected during simulated rainfall, and intact subsamples were collected from unburned and burned block samples after the rainfall simulations to evaluate the effects of high severity burning on physical characteristics and hydraulic and mechanical properties (i.e., dry density, total organic carbon, hydraulic conductivity, water repellency, and shear strength). Burning exponentially increased erosion compared to unburned conditions and all rates of straw mulch reduced soil erosion to levels consistent with unburned samples. Runoff and erosion increased with a decrease in natural surface vegetation on unburned samples and increased with a decrease in straw mulch applied to burned samples. Notable changes in geotechnical properties with high severity burning were not found in this study, which suggested that the observed increase in erosion on bare burned samples during rainfall simulations was attributed to destruction of surface cover with burning.

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CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Wildfires are a natural phenomenon in Colorado and the Western U.S., and the frequency of large, destructive wildfires has increased over the past decade and is forecasted to increase due to climate variability (e.g. Jolly et al. 2015) and fuel accumulation from fire suppression (e.g. Gayton 1998; Smalley et al. 2000). Over 30 million acres of land have been burned by wildfires in the U.S. in the last five years alone. Potential damage to the human and built environments is not only associated with burned lands, homes, and infrastructure during a wildfire, but can extend for years after a wildfire in the form of increased runoff from precipitation, soil erosion, and debris flows. The frequency and magnitude of runoff, soil erosion, and debris flows increases following a wildfire due to burned surface vegetation that reduces soil stabilization, increases raindrop impact on soil from loss of cover, and promotes soil hydrophobicity that inhibits infiltration and retention of water (DeBano 2000; Ice et al. 2004; Santi and Morandi 2013).

Post-fire ground treatments that mitigate erosion and runoff to decrease damage to transportation infrastructure focus on soil stabilization, and generally are implemented as soon as possible following a wildfire (USFS 2013). The state-of-practice in post-fire ground treatment includes erosion barriers, mulching, chemical soil treatments, or a combination of these options (Napper 2006; Robichaud et al. 2010). Mulching refers to ground-cover treatments (e.g., agricultural straw or wood-based mulch) that are surface applied to reduce raindrop impact and minimize erosion and overland flow (Bautista et al. 2009). This treatment can also increase infiltration and soil moisture content to enhance root uptake and vegetative regeneration. Mulching is a preferred ground treatment alterative for emergency response required over large land areas and/or in short timeframes (Robichaud et al. 2010).

In general, post-fire ground treatment actions remain ad hoc with a need for knowledge of short-term and long-term benefits accompanying different treatment alternatives. Several experiments have been conducted in the field to analyze how treatments may reduce runoff and erosion (described subsequently). However, few studies have been conducted in a laboratory setting where variables influencing post-fire erosion and runoff can be controlled (e.g. Foltz and Copeland 2009; Foltz and Wagenbrenner 2010). Even fewer studies have been conducted on undisturbed soil samples in the laboratory, which is imperative since soil structure plays a vital role in erosion and runoff (Morgan 2005). Limited post-fire studies have paired erosion and runoff tests with soil property testing to better understand the mechanisms behind post-fire increases in runoff and erosion. Understanding why runoff and erosion increases after burning a soil is important to understanding how post-fire ground treatments are effective in mitigating runoff and erosion.

1.2 Research Objectives and Tasks

The objective of this study was to assess the efficacy of a post-fire ground treatment in mitigating soil erosion and runoff. A laboratory-scale slope-model experiment was constructed with a rainfall simulator and the ability to measure runoff and erosion. Straw mulch was used as the post-fire ground treatment and slope-model experiments were conducted on unburned and burned block samples collected from U.S. Forest Service land in Colorado. Experiments were conducted with no straw mulch and application rates of straw mulch = 0.06, 0.11, and 0.22 kg/m^2. This study represents a step towards understanding the mechanisms of post-fire increases in runoff and erosion at the macro and micro scale. Results from this study will be beneficial for researchers and land managers. Although the rates and magnitudes of runoff and erosion will vary based on location and size of area considered, the mechanisms observed in this laboratory-scale study will be applicable at field-scale.

The following research tasks were completed as a part of this study:

1. Reviewed literature related to post-fire soil susceptibility to enhanced runoff and erosion;
2. Collected intact block samples that were representative of ground conditions in wildfire prone areas;
3. Conducted laboratory-scale slope-model experiments to evaluate the efficacy of post-fire ground treatments on mitigating erosion and runoff; and
4. Evaluated effects of high severity burning on geotechnical properties of a Colorado soil.

CHAPTER 2: BACKGROUND

2.1 Wildfires in Mountain West States

Wildfires are increasing in frequency and severity in Mountain West States due in large part to climate variability (e.g. Jolly et al. 2015) and fuel accumulation from fire suppression (e.g. Gayton 1998; Smalley et al. 2000). Damage caused by wildfires can extend beyond burned lands, homes, and infrastructure in the form of increased runoff from precipitation, soil erosion, and debris flows.

The wildland urban interface can be defined as the intersection of developed areas and non-developed areas, especially those where a high potential for wildfire exists and threatens anthropogenic activities. With more than 6.6 million acres of wildland urban interface area in Colorado, the protection of lives, infrastructure, and municipal water sources from negative effects of wildfire is critical (Colorado State Forest Service 2013). There are many social and economic costs imparted by wildfires, including fire mitigation and suppression, property loss or reduction in home values, loss of tax revenue, and injuries or loss of life (Fried et al. 2004; Graham et al. 2011). Millions of taxpayer dollars are spent to suppress and control large fires. Millions more are spent in attempts to stabilize post-fire soil conditions that can lead to mass erosion and debris flows that can damage roads and property, and degrade soil and water resources (Robichaud et al. 2014).

The suppression cost for the High Park Fire that occurred during the summer of 2012 in Larimer County, Colorado was approximately $39.2 million. An estimated additional $24 million will be needed to address emergency stabilization treatments and treatments for public roads and private lands (BAER 2012). Within the High Park fire area there were 332 km of county roads, Colorado Department of Transportation (CDOT) highways, forest service roads, and private roads and nearly 32,380 ha were considered moderate to high soil erosion potential (BAER 2012). The 1996 Buffalo Creek fire in Colorado caused over $20 million in damage to Denver’s water supply system (Lynch 2004). With an increase in wildfire frequency and burn area in Colorado, understanding post-fire soil conditions is becoming increasingly important to cost-effectively protect critical infrastructure and resources.

2.2 Wildfire Effects on Soil Properties

Runoff and soil erosion are both inversely related to the infiltration capacity of a soil. Infiltration capacity depends on, in part, the amount of ground cover, amount of soil organic matter, and presence of soil water repellency. Greater levels of organic matter increase porosity, which increases water storage capacity in soil. Higher amounts of surface roughness create longer flow pathways, which increase the amount of time water has to infiltrate the soil. Thus, ground cover can increase infiltration by increasing surface roughness and organic matter that can prevent soil sealing and mitigate soil detachment, which combine to reduce erosion and runoff. The erodibility of a soil is dependent on infiltration capacity and the ability of soil particles to resist detachment (Wischmeier and Mannering 1969). The ability of soil particles to resist detachment is largely dependent on particle size and the presence of detaching forces such as raindrops and surface flow (Morgan 2005).

Infiltration capacity and ability to resist particle detachment can be altered by moderate- to high-severity wildfires. Wildfires often decrease infiltration capacity by increasing soil dry density through aggregate breakdown (Moody and Martin 2001; Moody and Martin 2009; Ebel et al. 2012), increasing soil sealing by sediment and ash particles following loss of surface cover (Neary et al. 1999; Larsen et al. 2009), and forming a water repellent layer near the soil surface (DeBano 2000; Doerr et al. 2000). Soil particle detachment increases following a wildfire due to loss of soil cover and increased propensity for raindrops to impact and subsequently mobilize soil particles (Morgan 2005). These aforementioned factors, along with other changes in soil physical characteristics and hydraulic and mechanical properties, result in increased runoff and sediment yield following moderate- to high-severity wildfires.

2.3 Post-Fire Ground Treatments

The United States Department of Agriculture (USDA) Forest Service Burn Area Emergency Rehabilitation (BAER) is the formal authority for post-fire response and rehabilitation measures. The goals of BAER are to (1) minimize the threat to life and property onsite or offsite; (2) reduce the loss of soil and onsite productivity; (3) reduce flooding potential; and (4) reduce deterioration of water quality (Neary et al. 2009). To accomplish these goals, BAER teams prescribe hillslope, channel, and/or road treatments. In the past decade, spending on post-fire treatment has increased due to the threat of debris flows and erosion near the growing wildland-urban interface (Robichaud et al. 2000). However, analysis of Burned Area Report forms from over 470 fires estimated that for every dollar spent on post-fire treatments, up to $200 is saved from losses (Robichaud et al. 2000).

Hillslopes are the critical source area for damaging surface runoff and debris flows (MacDonald and Robichaud 2008). Hillslope treatments are implemented to immediately reduce surface runoff and erosion on hillslopes by stabilizing the soil, reducing raindrop impact, promoting infiltration, and/or trapping sediment (Robichaud et al. 2000). Broadcast seeding, seeding plus fertilizer, mulching, contour-felled logs, contour trenching, scarification and ripping, temporary fencing, erosion mats, straw wattles, slash scattering, silt fences, geotextiles, and sand bags are all BAER hillslope treatments. Although certain treatments are known to be more effective than others, the effectiveness of each treatment is dependent on characteristics of the fire and factors unrelated to the fire event. The post-fire response and treatment effectiveness rely on fire characteristics such as burn severity, soil burn severity, amount of bare soil, soil water repellency, soil erodibility, and time since the fire. Factors independent of the fire event that greatly impact the effectiveness of a given ground treatment are rainfall intensity, topography, and land use (Neary et al. 2005; MacDonald and Robichaud 2008; Robichaud et al. 2010). Considering that all aforementioned factors influence treatment effectiveness, the factors will also influence post-fire erosion (i.e., sediment yield).

Until the 21st century, broadcast seeding was the most common post-fire rehabilitation treatment. This treatment is typically applied aerially and is used to promote rapid vegetation establishment and infiltration to stabilize the soil through plant roots. Seed mixes commonly include legumes to fix nitrogen and native and non-native annual and perennial grasses. Some native species commonly used for post-fire stabilization treatment in Colorado are Canby bluegrass (*Poa canbyi*), slender and streambank wheatgrass (*Elymus genus*), and green needlegrass (*Nassella viridula*). Common non-native or invasive species used are white oat (*Avena sativa*), mountain brome (*Bromus marginatus*), and Idaho fescue (*Festuca idahoensis*) (Bruggink 2007). Although broadcast seeding is cost-effective, non-native species can delay the recovery of natural flora and alter the ecosystem (Baron 1962; Anderson and Brooks 1975; Elliot and White 1987; Conrad et al. 1991).

Bruggink (2007) reported that burned, unseeded plots following the Buffalo Creek Fire in Colorado had higher total species richness than burned plots treated with aerial seeding. Furthermore, studies have shown that grass seed application does not produce a significant increase in ground cover during the first year after a fire event, which is considered the critical year (Roby 1989; Robichaud et al. 2000; Beyers 2004; Robichaud et al. 2013). Seeding becomes effective in erosion control through re-establishing vegetation, which typically requires at least two years after the fire event. Some seeding treatments also include the application of fertilizers to promote germination and rapid vegetation growth.

Mulching is increasingly becoming a preferred post-fire rehabilitation treatment for land managers. Mulching is a popular treatment option because, like broadcast seeding, mulch can be applied aerially instead of only through ground-based dispersal. Aerial treatment application is viable for otherwise inaccessible areas. Studies on multiple fires indicate that mulching is highly effective post-fire rehabilitation treatment because ground cover is immediately established (MacDonald and Larsen 2009). Agricultural straw mulch and wood-based mulches are commonly used to protect the soil surface from raindrop impact and promote infiltration. Many studies have reported that agricultural straw mulch and wood-based mulches considerably reduced post-fire sediment yield at low cost (Bautista et al. 2009; Robichaud 2000, Yanosek et al. 2006; Foltz and Copeland 2009; Foltz and Wagenbrenner 2010).

In recent years sustainability and environmental impacts associated with human actions have gained attention. Common erosion control practices, such as aerial application of agricultural straw mulch, may be recognized as potentially harmful to the ecosystem. Agricultural straw is non-native and can introduce non-native species, which inhibit re-growth of native vegetation (Foltz and Wagenbrenner 2010). There have been instances where even certified “weed free” straw contains noxious weed seeds. This occurred with straw used in the post-fire treatment of the Hayman Fire in Colorado (Robichaud et al. 2003). Although using agricultural straw as a post-fire stabilization treatment is less expensive than other mulches, straw mulch requires weed monitoring years after the treatment application, which can be expensive (Robichaud et al. 2013). Thus, mulches that are locally-sourced and cost-effective are considered viable alternatives to straw mulch.

2.4 Laboratory-Scale Slope-Model Experiment

Over the past few decades, numerous studies have been conducted to evaluate (i) the effectiveness of post-fire ground treatments in mitigating runoff and erosion and (ii) mechanisms of post-fire increases in runoff and erosion (e.g., Burroughs and King 1989; Yanosek et al. 2006; Larson et al. 2009; Foltz and Wagenbrenner 2010; Schmeer 2014). Although past studies have considered simulated rainfall, disturbed soil samples, and in situ burned soil samples, among other factors, limited laboratory experiments have been conducted on undisturbed soil samples with simulated rainfall to represent natural precipitation events. Few runoff and erosion studies analyzing post-fire ground treatments on burned soil have included unburned soil samples, as well (e.g. Foltz and Wagenbrenner 2010).

Foltz and Copeland (2009) conducted laboratory rainfall simulations on unburned, remolded soil samples to evaluate the efficacy of woods shreds for mitigating erosion. Rainfall was simulated using a Purdue-type rainfall simulator where nozzles are used to achieve desired raindrop velocities. They found that increasing wood shred cover increased the time to runoff, reduced the runoff rate, and reduced the sediment delivery rate for a sandy loam soil when compared to a bare plot. Although each increase in wood shred coverage resulted in significantly less sediment loss, they suggested that 30% coverage would be sufficient to limit erosion. Foltz and Wagenbrenner (2010) conducted a similar study but, evaluated wood shred performance on burned soils. Burned soils were collected from a recently burned area, and samples were remolded with the ash mixed through-out the soil profile. They found that wood shreds were useful in mitigating erosion and runoff on burned soils and suggested that the increased surface roughness imparted by the wood shreds decreased the runoff energy, therefore, decreasing the sediment yields.

Larsen et al. (2009) and Woods and Balfour (2008) found that the ash layer created from burning was important in reducing runoff and erosion during rainstorms. Larsen et al. (2009) conducted rainfall simulations using a Purdue-type rainfall simulator on field and laboratory plots of unburned and burned soil. The results indicated that increases in erosion following a wildfire were primarily due to the loss of ground cover rather than fire-induced changes in soil properties. They also suggested that the ash layer reduced runoff and erosion by protecting the mineral soil surface from sealing. Woods and Balfour (2008) conducted rainfall simulations using an oscillating nozzle-type rainfall simulator on field plots of burned soil with and without an ash layer. The results suggested that the ash layer reduced runoff and erosion by providing additional water storage and by preventing soil sealing. Both studies addressed ash layers' susceptibility to eventual erosion by rain and wind, suggesting that ash may provide reductions in runoff and erosion for only a short time following a fire.

CHAPTER 3: METHODS AND MATERIALS

The experimental program for this study included slope-model experiments conducted under simulated rainfall and testing to assess soil characteristics and engineering properties. A summary of slope-model experiments conducted on the block samples is in Table 3.1. The following five scenarios were considered: (i) unburned with natural vegetation and ground litter; (ii) burned without straw mulch; (iii) burned with 0.06 kg/m^2 straw mulch; (iv) burned with 0.11 kg/m^2 straw mulch; and (v) burned with 0.22 kg/m^2 straw mulch. All burned block samples were burned under identical conditions in the laboratory.

A summary of the soil characteristics and engineering properties evaluated and corresponding test procedures is in Table 3.2. Soil characterization tests included particle-size distribution and Atterberg limits conducted on each of the eight grab samples, and specific gravity and compaction tests conducted on a single homogenized grab sample. Prior to each rainfall simulation on a block sample, Mini Disk Infiltrometer (MDI) and water drop penetration time (WDPT) tests were conducted. For each simulated rainfall event in a slope-model experiment, eroded sediment mass (i.e., sediment yield) and runoff volume were measured. In addition, three measurements were conducted for each intact block sample post testing: dry density, total organic carbon, and shear strength. Specimens for these tests were exhumed from the upper 6 cm of block samples after rainfall simulations using sampling procedures outlined in ASTM D7015-13 (ASTM 2013) and a thin-walled metal sampler.

3.1 Soil Sample Collection

Soil samples were collected in Roosevelt National Forest, Colorado, in a location north of Estes Park and west of Fort Collins (coordinates: 40.56856, -105.47370). The location represented soil and vegetation conditions in Colorado that have experienced wildfires. Soil composition in the area was similar to soil composition at historic Colorado wildfire burn areas, which are summarized in Table 3.3 (Moody and Martin 2001; Benavides-Solorio 2001;

MacDonald and Huffman 2004; Pietraszek 2006; Ebel et al. 2012; Robichaud et al. 2013). This location was also in close proximity to the High Park Fire, which occurred in 2012. Permission to obtain soil samples from the site was granted by the U.S. Forest Service. The sampling area was chosen to avoid large roots and rocks.

Seven undisturbed block samples and eight grab samples were collected. Block samples were collected within sheet metal boxes that were 91.4-cm long, 30.5-cm wide, and 30.5-cm tall following cubical block sampling procedures outlined in ASTM D7015-13 (ASTM 2013). An 11 gauge steel box with an open top and bottom was placed on the soil surface. Soil was excavated around the box so that the box could be pressed into the ground, continually enclosing the soil sample during excavation. Once the top of the box was inserted approximately 23 cm into the soil, the base of the block was separated from the parent material. The block was then moved onto a plywood pallet. Excavation for one block sample provided a starting location for the next block sample such that all block samples were collected adjacent to one another. Grab samples were collected in 20-L buckets intermittently during excavation of the block samples (see Appendix A).

Block samples were secured to the pallets used for collection and transported to CSU. The block samples were kept in a greenhouse and watered weekly to maintain healthy vegetation prior to testing.

3.2 Slope-Model Experiment with Simulated Rainfall

A simplified schematic of the slope-model experiment is shown in Fig. 3.1, which included a soil specimen container and rainfall simulator. The soil container was constructed from steel with dimensions of 76.2-cm long, 30.5-cm wide, and 30.5-cm deep. The container was designed with the ability to collect runoff and eroded sediment, drain infiltrated water from the bottom of the specimen, adjust slope of the specimen, and adjust location of the outflow plate. A non-woven geotextile was placed along the bottom of the soil container to allow drainage from the bottom of the specimen. To prevent sidewall water flow along the container-soil interface, bentonite paste (bentonite and water mixed at a ratio of 1:6) was placed around the specimen perimeter to a depth of 2.5 cm (Lee et al. 2010). If applicable, ground treatments were applied to soil specimens prior to rainfall simulations.

Rainfall was applied to the soil specimens with a rainfall simulator designed based on Regmi and Thompson (2000). A schematic of the soil rainfall simulator is shown in Fig. 3.1. Each raindrop former was a telescopic arrangement of a 21-ga. capillary tube inside a 9-ga. capillary tube. A total of 140 raindrop formers were spaced in an equilateral triangular grid on the bottom of the rainfall simulator. A stainless steel raindrop distribution screen was placed 71 cm below the raindrop formers to create a broader distribution of raindrop sizes (0.3 mm to 5.2 mm) that was more representative of natural rainfall than uniformly-sized raindrops. Rainfall intensity was controlled by adjusting the head of water above the raindrop formers. Water was primarily low-ionic-strength snowmelt runoff with pH between 6.8 and 7.3 and an electrical conductivity between 4 to 8 mS/m (Larsen et al. 2009). The height between the bottom of the rainfall simulator and soil specimen container was 7.6 m (25 ft), which allowed raindrops ≤ 2 mm in diameter to reach 95% of terminal velocity. The laboratory-scale slope-model experiment yielded repeatable measurements of sediment yield and runoff for replicate tests conducted on sand-silt mixtures (see Appendix B).

A summary of observed or simulated rainfall that produced runoff and erosion from burned Colorado hillslopes is in Table 3.4. Relationships of rainfall intensity versus rainfall duration from 23 Colorado Front Range NOAA weather stations are shown in Fig. 3.2. In this study, rainfall was simulated at an intensity of approximately 48 mm/h and experiments were conducted for 40 min. The rainfall intensity and duration were chosen to replicate a typical short-duration, high-intensity summer storm in Colorado that can lead to runoff and erosion on burned hillslopes (Robichaud and Brown 2005; Cannon et al. 2008; Larsen et al. 2009; Moody and Martin 2009; Foltz and Wagenbrenner 2010). A rainfall event in Colorado’s Front Range that is comparable to what was simulated in this study has a return period of 25 yr. The rainfall generator was calibrated prior to testing to determine the target rainfall intensity and the intensity applied during a given experiment was measured at the start and end of each experiment. Successive rainfall simulations conducted on a single specimen were conducted three days apart to allow for potential soil crust formation (Larsen et al. 2009).

Block samples were transferred from the metal collection boxes to the soil specimen container located beneath the rainfall simulator. The soil specimen container (Fig. 3.1) was then fixed at a slope of 27° for all experiments, which was representative of burned Colorado hillslopes that have produced runoff and erosion (Pietraszek 2006; Schmeer 2014). Plastic splashguards were placed on either side of the specimen parallel to the direction of slope to minimize loss of soil upon raindrop impact. Runoff, along with entrained sediment that had been eroded, was collected at the lower end of the soil specimen every five to ten minutes in 1.0-L bottles. The total water and sediment collected at each interval was weighed and then dried in an oven at 105 °C for 24 h. The eroded sediment mass (i.e., sediment yield) at each interval was the mass of sediment after drying. The runoff at each interval was taken to be the total mass collected minus the mass of eroded sediment, assuming the density of water = 1 g/cm^3. Initial soil moisture content was not measured; however, all samples were air-dried for one week prior to rainfall simulations.

3.3 Burn Simulation

Block samples were burned under controlled conditions to replicate a moderate to high soil-burn severity. Previous laboratory studies have shown that the hydrophobic layer in the soil subsurface is intensified at temperatures from 175 to 250 °C (DeBano and Krammes 1966; Doerr et al. 2000; Robichaud and Hungerford 2000; Zavala et al. 2010). These temperatures also correspond to a moderate to high soil-burn severity (Zavala et al. 2010). Prior to burning, the block samples were air-dried for 1 week to promote post-burning water repellency at shallow depths following recommendations in Robichaud and Hungerford (2000).

Hardwood lump charcoal was ignited and placed on a foil-lined, perforated metal sheet elevated 2.5 cm above the soil surface. Newly ignited charcoal was added to the metal sheet every 20 min until the soil at a depth of 2 cm from the surface reached 200 °C. The bottom and sides of the block sample were wrapped in an insulating fabric to promote soil heating from the surface down. The soil temperature 2 cm below the surface was monitored in real time using an Omega Type K thermocouple connected to a computer. Burning the soil using this approach required approximately 120 min to reach the target soil temperature (see Appendix C).

3.4 Block Samples Tested

A summary of the slope-model experiments conducted on burned and unburned block samples is in Table 3.1. Photographs of test specimens prepared from three unburned block samples with varying levels of vegetation and from four burned block samples with and without straw mulch as ground cover are shown in Fig. 3.3. The three unburned block samples were observed to have different amounts of vegetation and ground litter. These visual differences in surface cover were qualitatively described as low, medium, and high vegetation, where vegetation is used to imply intact surface vegetation and surface litter.

Straw mulch was applied to burned soil samples by hand, if applicable, prior to the first rainfall simulation. A straw mulch application rate of 0.22 kg/m^2 is commonly used as a post-fire ground treatment by BAER on Colorado hillslopes (Robichaud et al. 2000; BAER 2012). The straw mulch application rates of 0.06 and 0.11 kg/m^2 were evaluated to explore how reducing ground cover influenced runoff and erosion. Burroughs and King (1989) provided an equation to estimate the percent ground cover from mulch applications, whereby straw mulch application rates of 0.06, 0.11, and 0.22 kg/m^2 corresponded to ground cover percentages of approximately 40%, 50%, and 65%. However, the percent ground cover visually appeared higher (Fig. 3.3) than those predicted using the equation in Burroughs and King (1989).

Three replicates were considered for the unburned scenario and one replicate was considered for each burned scenario. A rainfall simulation was conducted on each unburned specimen prior to burning. Subsequent rainfall simulations were then conducted on burned specimens with the varying amounts of straw mulch (i.e., no cover to 0.22 kg/m^2). For each burned scenario, two rainfall simulations were conducted three days apart to explore changes in soil hydraulic properties due to potential soil crust formation (Larsen et al. 2009). Pictures of the test specimens in the slope-model experiments before and after each rainfall simulation are in Appendix D.

3.5 Soil Characteristic and Engineering Property Tests

A summary of geotechnical characteristics measured on the eight grab samples collected from the field is in Table 3.5. Particle-size distribution by sieve and hydrometer analyses (ASTM D6913-04 2009; ASTM D7928-16 2016) and Atterberg limits (ASTM D4318-10 2010) were conducted on each of the eight grab samples. Particle-size distribution curves for the eight grab samples and the average particle-size distribution curve are shown in Fig. 3.4. The eight samples yielded similar percent composition of gravel, sand, silt, and clay particles, and the soil classified as silty sand (SM) according to the Unified Soil Classification System. An equal mass of each grab sample was mixed together to create a representative, homogenized soil sample to assess specific gravity (ASTM D854-14 2014) and standard compaction (ASTM D698-12 2012).

Geotechnical testing also was conducted on unburned and burned soil samples to analyze the effect of burning on physical characteristics and hydraulic and mechanical properties. Changes in physical characteristics due to burning were analyzed by measuring dry density and total organic carbon. Changes in hydraulic properties due to burning were analyzed by measuring field saturated hydraulic conductivity and water repellency. Changes in mechanical properties due to burning were analyzed by measuring shear strength via direct shear. Unburned soil specimens were trimmed from block samples prior to rainfall simulations. Burned soil specimens were collected from burned block samples after rainfall simulations were complete.

3.5.1 Physical Soil Characteristics

Dry density and total organic carbon (TOC) were assessed on the upper 6 cm of block samples following sampling procedures outlined in ASTM D7015-13 (ASTM 2013) with a thin-walled metal sampler. Dry density was assessed on unburned and burned soil following ASTM D7263-09. A moist soil specimen was weighed, dried in a ceramic crucible at 105 °C for 24 h, and then re-weighed.

Total organic carbon was estimated using the loss-on-ignition (LOI) method. The LOI method involves the heated destruction of all organic matter in a soil specimen. A moist soil specimen was weighed and dried in a ceramic crucible at 105 °C for 24 h. The dry soil was then re-weighed and heated to 440 °C for 24 h. The specimen was then cooled in a desiccator and weighed again. Organic matter content was calculated as the difference between the initial and final dry masses divided by the initial dry mass. Furnace temperature for the LOI method was maintained below 450 °C to avoid destruction of any inorganic carbonates that may be present in the soil (Schumacher 2002).

3.5.2 Hydraulic Soil Properties

A mini-disk infiltrometer (MDI) was used to estimate the field saturated hydraulic conductivity (Decagon Devices). The MDI was placed on the soil surface after removing duff material from the unburned samples or ash from the burned samples. A negative pressure head of 0.5 cm was applied at the soil surface to promote water infiltration. Measurements of volumetric inflow versus time were recorded every 30 s for 15 min and then every minute until at least 15 mL of water infiltrated into the soil (Decagon Devices).

Field saturated hydraulic conductivity was calculated from the MDI data using a method proposed by Zhang (1997). Cumulative infiltration volume (I) versus time (t) was calculated using the following equation:

$$I = C_1 t + C_2 \sqrt{t} \tag{3.1}$$

where C_1 and C_2 are parameters related to hydraulic conductivity and soil sorptivity, respectively. Field saturated hydraulic conductivity (K_{fs}) was then calculated as

$$K_{fs} = \frac{C_1}{A} \tag{3.2}$$

where A is a van Genuchten parameter obtained from the instrument manual based on soil type and suction height. The MDI tests were conducted on block samples that had not been exposed to water for three days.

The water drop penetration time (WDPT) method was used to measure soil surface water repellency. The WDPT method is used widely as an indicator for determining the persistence of water repellency (Doerr et al. 2004), and was performed in conjunction with the MDI test.

Duff material was removed from the unburned and burned block sample surfaces in the area where the experiment was conducted. One droplet (≈ 80 µL) of de-ionized water was placed on the soil surface. The time required for the water droplet to infiltrate the soil was recorded. Repellency class intervals and associated ratings are summarized in Table 3.6. Penetration times greater than 5 s were recorded in 20 s intervals for the first 600 s, and then every 30 min. The WDPT tests were terminated after 5 h if a water drop had not penetrated (Doerr et al. 2004).

3.5.3 Mechanical Soil Properties

Direct shear tests were conducted under drained conditions on unburned and burned specimens following ASTM D3080. Intact specimens were collected from the upper 6 cm of the block samples using sampling procedures outlined in ASTM D7015-13 (ASTM 2013) with a thin-walled metal sampler. Specimens with a diameter of 64 mm and height of 33 mm were cut from the block samples and transferred to a circular direct shear box. Direct shear testing was conducted under effective normal stresses (σ'_n) of 17, 34, and 65 kPa, which were reasonably low stresses that could be applied in the direct shear apparatus to assess shear strength of the surficial soil deposit.

Specimens were inundated for 2 h immediately following application of normal stress. Drainage was permitted through porous metal disks and filter paper placed on the top and bottom of the specimens. Tests were conducted at a displacement rate of 0.08 mm/min using an ELE International Digital Shear Machine. Measurements of horizontal displacement, vertical displacement, and shear force were recorded every second using a National Instruments data acquisition card (NI USB-6009, 192256A-01), LABView software, and a laptop computer. Two linear variable displacement transducers (Novotechnik Models TR-0050 and TR-0025) were used to measure horizontal and vertical displacements. A load cell (Interface Force Transducer Model SSM-AJ-500) was used to measure shear force. Direct shear specimens were inspected post shearing to note if any gravel-sized particles were present within the shear plane.

Peak shear strengths were used to develop strength envelopes if a peak shear stress was observed in the shear-displacement data. Alternatively, the shear stress at 7 mm of horizontal displacement was selected as the shear strength for development of a strength envelope in the event peak shear strength was not observed.

Table 3.1. Summary of slope-model experiments conducted on block samples.

Test Group	***Scenario***	***Specimen Description***	***Straw Mulch Application (kg/m^2)***	***Test Specimen Replicates***	***Rainfall Simulations per Replicate***
Block Sample	1	Unburned block	0	3	1
	2	Burned block	0	1	2
	3	Burned block	0.06	1	2
	4	Burned block	0.11	1	2
	5	Burned block	0.22	1	2

Table 3.2. Summary of the soil characteristics and engineering properties that were evaluated and the experimental method for each.

Measurement	***Method***
Soil erodibility and runoff rate	Rainfall simulation
Soil characterization	Sieves, hydrometer, Atterberg limits, and specific gravity
Dry density	Mass loss by oven heating
Total organic carbon	Loss on ignition
Field saturated hydraulic conductivity	Mini Disk Infiltrometer
Water repellency	Water drop penetration test
Soil strength parameters	Drained direct shear

Table 3.3. Composition of soils in historic Colorado wildfire burn areas and soil collected from the block sample location.

Soil Texture	***Colorado Wildfire Burn Areas [a]***			***Block Sample Average (%)***
	Low (%)	***High (%)***	***Average (%)***	
Gravel	0	56	25	15
Sand	23	69	47	57
Silt	6	41	23	26
Clay	0	20	6	3

[a] Moody and Martin 2001; Benavides-Solorio 2001; MacDonald and Huffman 2004; Pietraszek 2006; Ebel et al. 2012; Robichaud et al. 2013

Table 3.4. References and locations of observed or simulated rainfall that produced runoff and sediment yield. Rainfall parameters include recurrence interval, storm duration, and storm magnitude.

Reference	***Location***	***Recurrence Interval (yr)***	***Storm Duration (min)***	***Storm Magnitude (mm/h)***
---	High Park Fire BAER	10	60	38
Robichaud et al. (2012)	Intermountain West	50	15	50
Foltz and Wagenbrenner (2010)	Intermountain West	50	25	51
Cannon et al. (2008)	Colorado [a]	< 2	< 180	1-32
Robichaud and Brown (2005)	Colorado Bobcat Fire [b]	5-10	30	48
Murphy et al. (2012)	Fourmile Creek Fire [b]	---	30	46
Moody and Martin (2009)	Plains rainfall regime	2	30	19-52
Verdin et al. (2012)	High Park Burn Area 1	2	60	25
Verdin et al. (2012)	High Park Burn Area 2	10	60	43
Verdin et al. (2012)	High Park Burn Area 3	25	60	51

[a] Debris flows that were produced from 25 recently burned basins in Colorado in response to 13 short-duration, high-intensity convective storms

[b] Actual storm event producing high sediment yields

Table 3.5. Summary of soil characteristics determined on the grab samples.

Characteristic	***Soil sample*** [a]
Gravel (%)	15 ± 3
Sand (%)	57 ± 2
Silt (%)	26 ± 3
Clay (%)	3 ± 1
Specific gravity	2.69
Plastic limit	1 ± 1
Max dry unit weight (kN/m^3)	16.4
Optimum gravimetric water content (%)	18

[a] Characteristics presented as X ± Y: X = mean and Y = standard deviation based on samples analyzed from each of the eight grab samples

Table 3.6. Water drop penetration time (WDPT) class increments and corresponding descriptive repellency rating (Doerr et al. 2004).

WDPT classes (s)	$\leq$***5***	***> 5, 20, 40, 60***	***80 - 600***	***> 600 - 3600***	***> 3600***
Repellency rating	Wettable	Slight	Strong	Severe	Extreme

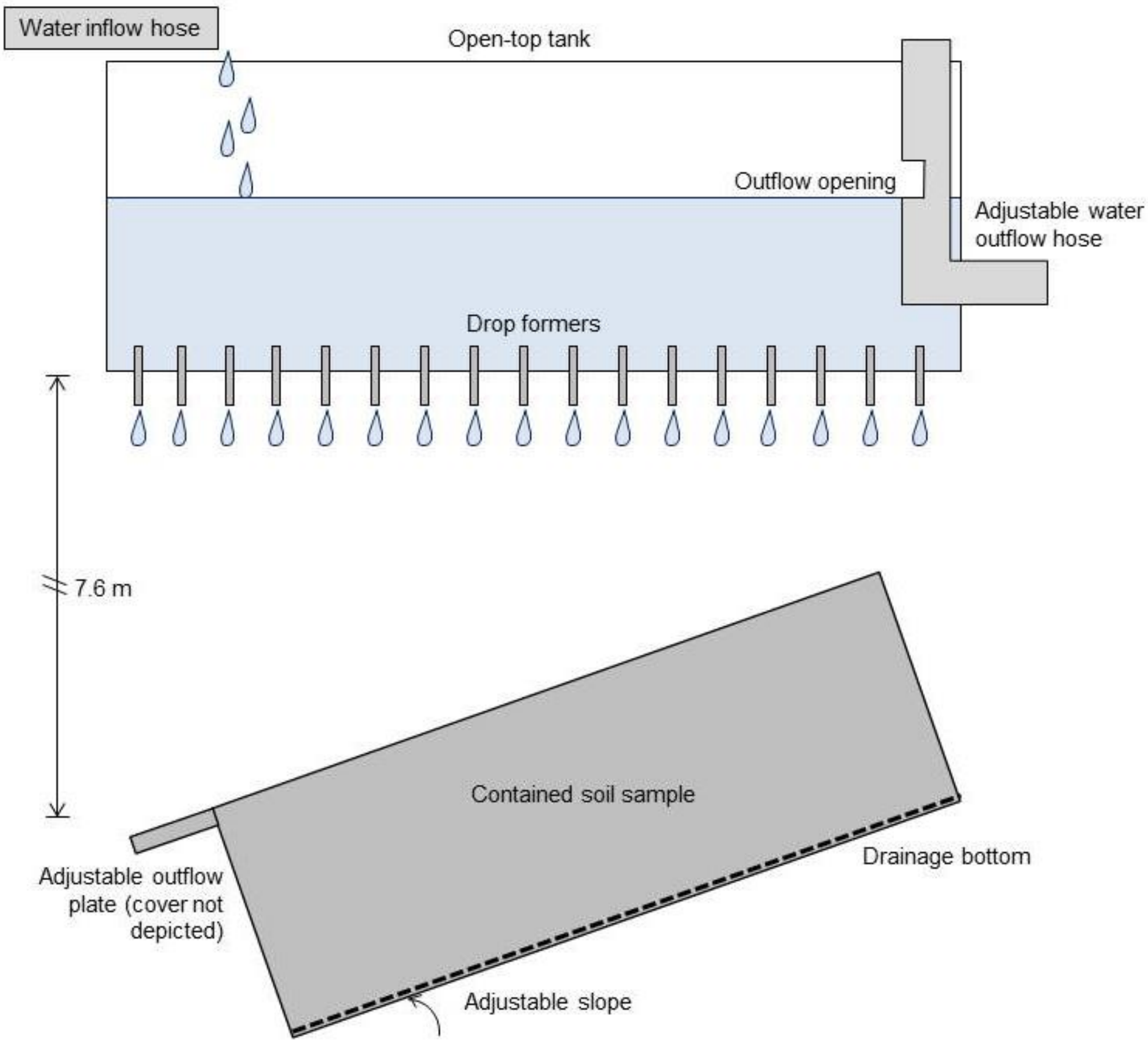

Fig. 3.1. Simplified schematic of the rainfall simulator (top) and soil container (bottom) used to conduct the slope-model experiments.

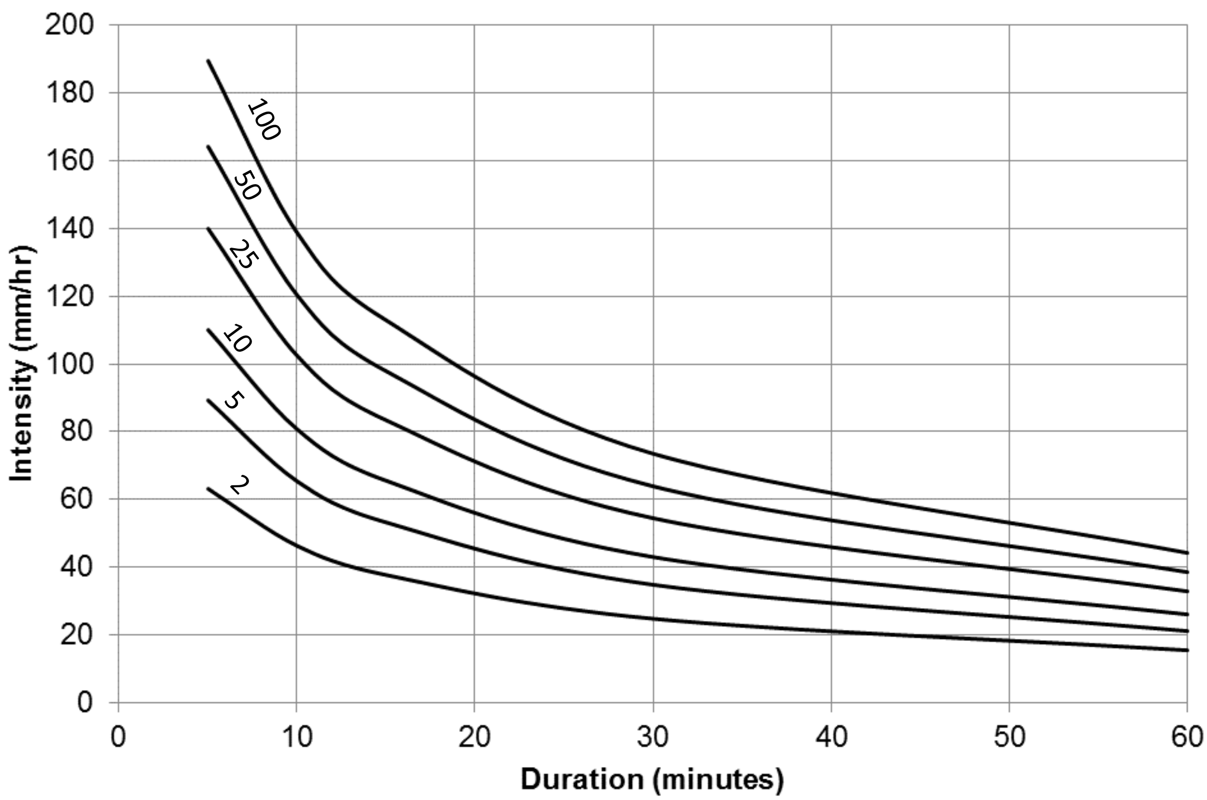

Fig. 3.2. Intensity-duration-frequency (IDF) plot based on average annual maxima data from 23 Colorado Front Range weather stations where each data series represents a return interval in years.

Fig. 3.3. Pre-rainfall simulation pictures of (a) low vegetation, unburned block, (b) medium vegetation, unburned block, (c) high vegetation, unburned block, (d) burned block, no straw mulch, (e) burned block, 0.06 kg/m^2 straw mulch, (f) burned block, 0.11 kg/m^2, and (g) burned block, 0.22 kg/m^2.

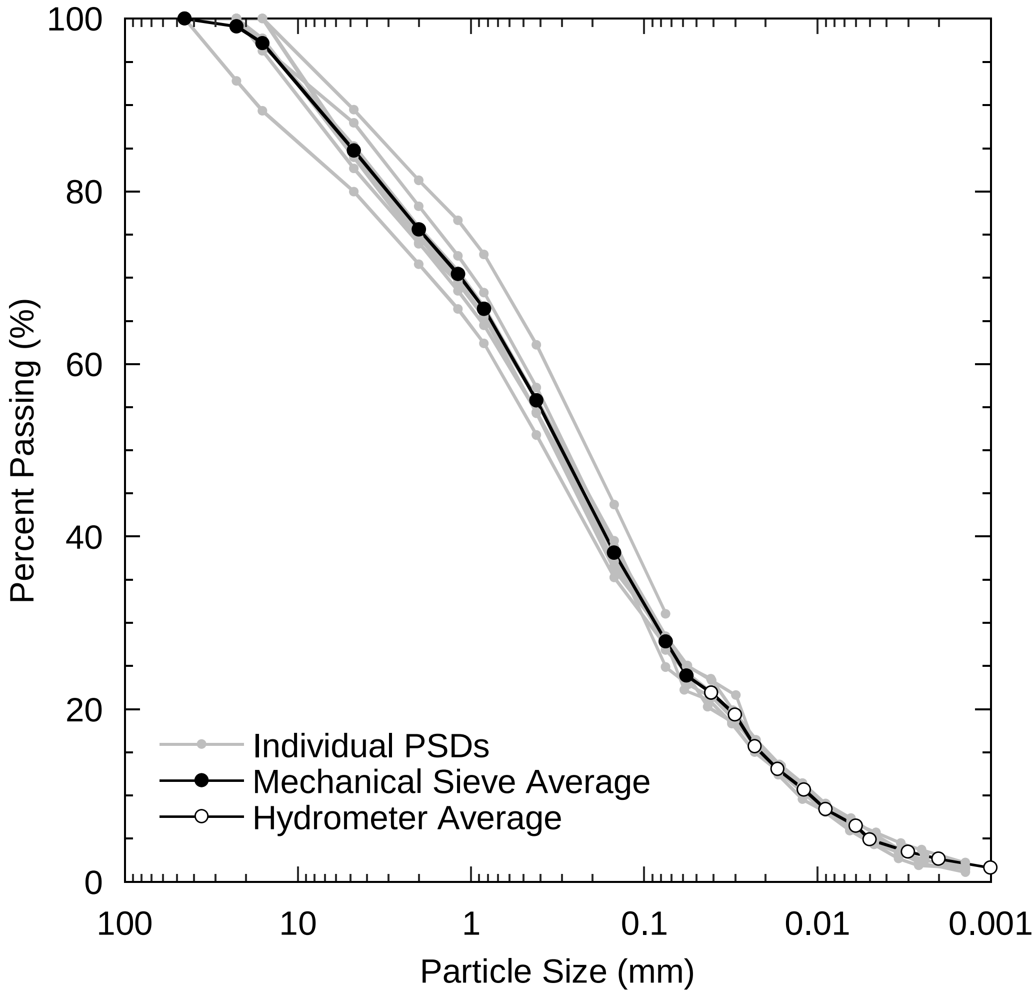

Fig. 3.4. Particle-size distribution (PSD) curves for eight grab samples collected alongside block samples and overall average particle-size distribution curve.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Rainfall Simulations

A summary of the rate of simulated rainfall, average runoff rate, ultimate runoff rate, and average percent runoff for the three unburned block samples and four burned block samples tested in the slope-model experiment is in Table 4.1. Average rainfall intensity for all rainfall simulations was 48 ± 2 mm/h. The average runoff rate was calculated as the total runoff collected during the simulated rainfall over the 40-min rainfall duration. The ultimate runoff rate was calculated as the runoff collected during the last 5 min of the simulated rainfall, which was approaching a constant runoff rate in all experiments. Average percent runoff was computed as the percent of cumulative precipitation falling on a soil specimen that resulted in runoff. Cumulative precipitation falling on a given specimen was computed based on surface area of the specimen, rainfall intensity, and duration of rainfall. Average infiltration capacities for unburned and burned soils (estimated using MDI) were less than the rainfall rate, which indicated that infiltration excess surface runoff occurred during the rainfall simulations, as opposed to saturation excess. Infiltration excess runoff is common during short duration, high intensity rainstorms analogous to the storm simulated in this study.

4.1.1 Effect of Burning on Runoff and Erosion

Temporal trends of runoff rate and sediment concentration from the slope-model experiments on the three block samples with intact natural vegetation and the one burned block sample with no ground cover are shown in Fig. 4.1. Runoff rate was computed incrementally as the volume of runoff occurring between subsequent measurements divided by specimen surface area and elapsed time. Sediment concentration was computed as the ratio of sediment yield to runoff between subsequent measurements.

The rate of runoff increased during the first 20-25 min of simulated rainfall for the burned soil and three soil specimens with natural vegetation, and subsequently approached an approximately consistent rate (i.e., ultimate runoff rate). The presence of natural vegetation directly influenced runoff, whereby the low vegetation, unburned specimen had the highest amount of runoff (50% of total rainfall), and the amount of runoff decreased with an increase in the amount of surface vegetation (Table 4.1, Fig. 4.1a). The amount of runoff measured for the burned soil with no ground cover was between the cumulative runoff measured on the medium and high vegetation block samples. The amount of runoff for the burned block sample was attributed to a wettable ash layer on the burned soil surface that acted as a water storage layer. Thus, during the first rainfall simulation the ash layer had the capacity to store precipitation since this ash layer was dry at the start of the rainfall simulation.

In contrast to similarities in runoff between unburned and burned block samples, the amount of erosion was considerably higher for the burned block sample (Fig. 4.1b). The amount of sediment eroded from the burned block sample increased by at least a factor of two relative to the low vegetation specimen and nearly an order of magnitude relative to specimens with medium and high vegetation (Fig. 4.1b). Although vegetation and bare areas on unburned soil surfaces can convey surface flow as runoff, the surface vegetation and corresponding root network helps protect the soil surface from raindrop impact and subsequent particle entrainment during runoff. Vegetation also aids to trap dislodged sediment or at least impede downslope movement, which reduces the amount of erosion. Soil particles on the burned soil surface with no ground cover were fully exposed to erosive forces of raindrop impact and surface water flow. Thus, the greater ability for soil particles to dislodge and transport on the burned soil surface increased erosion relative to the unburned block samples.

4.1.2 Effect of Straw Mulch on Runoff and Erosion

Temporal trends of runoff rate and sediment concentration measured in the slope-model experiments conducted on the four burned block samples with varying amounts of straw mulch are shown in Fig. 4.2. The presence of straw mulch was observed to directly influence the amount of runoff during the first and second rainfall simulations (Table 4.1, Figs. 4.2a and 4.2b). The amount of runoff generally decreased with an increase in the amount of straw mulch. Runoff measured for the burned block samples with 0.11 and 0.22 kg/m^2 straw mulch was approximately the same as the cumulative runoff measured on the high surface vegetation block sample (Fig. 4.2a). Also observed in the runoff measurements was an increase in the amount of runoff for the second rainfall simulation on the burned soil sample without ground treatment and with the burned soil samples with 0.06 and 0.11 kg/m^2 straw mulch. However, magnitude of the runoff increased from the first to second rainfall simulation and was highest for the burned sample without straw mulch. The straw mulch applied to the burned samples protected the ash layer from rainfall induced erosion, allowing the ash layer to continue to provide water storage during the second rainfall simulation.

The ultimate runoff rate generally decreased with increasing ground cover, whether the ground cover was natural vegetation or straw mulch (Table 4.1). A water balance analysis was conducted for each soil specimen during a given rainfall simulation. Water entering the system (i.e., a soil specimen) was simulated rainfall, and water leaving the system was in the form of infiltration, surface runoff, or water absorbed by surface cover. Burned block samples were exposed to similar rainfall rates and had similar infiltration capacities (discussed subsequently), and yet exhibited varying runoff rates. Straw mulch increased surface roughness for overland flow, which slowed down runoff and allowed more time for infiltration. Considering that runoff developed due to infiltration excess, increasing the amount of straw mulch decreased runoff rates by allowing more time for the water to infiltrate the soil. Straw mulch also reduced runoff by absorbing and storing water; however, this likely was not a major factor in runoff reduction. Based on the water absorption capacity of the straw mulch, the maximum amount of water the straw mulch could absorb was 1-4% of the total rainfall, depending on the rate of straw mulch application.

The amount of sediment eroded from the burned block sample with no straw mulch increased by a factor of seven relative to the burned samples with 0.06 and 0.11 kg/m^2 straw mulch and over an order of magnitude relative to the burned sample with 0.22 kg/m^2 straw mulch (Figs. 4.2c and 4.2d). In addition, sediment concentration measured on the burned block sampled increased from the first to the second rainfall simulation, whereas sediment concentration was approximately constant between the two rainfall simulations for the burned block samples with ground cover. The straw mulch used as ground cover acted similar to vegetation on the unburned samples in mitigating erosion. The straw mulch protected the burned soil surface from raindrop impact and provided an alternative flow path of water versus directly along the soil surface. Straw mulch also helped dissipate energy from raindrop impact, which reduced the potential for particle detachment. Dislodged particles were able to be trapped by the straw strands, which prevented the particles from being carried by water further downslope.

Temporal trends of the ratio of runoff rates during the second simulated rainfall (Q_2) to runoff rates during the first simulated rainfall (Q_1) for the four burned samples with varying amounts of straw mulch are shown in Fig. 4.3. Runoff rates during the first 20 min of the rainfall simulation increased considerably for the second rainfall simulation compared to the first simulation for burned block samples with no straw mulch and 0.11 kg/m^2 straw mulch. However, runoff rates for the second rainfall simulation when compared to the first simulation remained nearly the same for the burned samples with 0.06 and 0.22 kg/m^2 straw mulch, and Q_2/Q_1 for the 0.11 kg/m^2 sample was about 1.0 by the end of the rainfall simulation.

The increase in runoff for the second rainfall simulations was attributed to (i) an increase in soil saturation near the surface that decreased available soil water storage, and (ii) the development of soil hydrophobicity. Post-testing analysis on all four burned samples revealed a hydrophobic layer had formed 2 cm below the soil surface (classified as “extreme” using WDPT method). The hydrophobic layer inhibited infiltration, which resulted in a nearly saturated surface layer after the first simulation and start of the second rainfall simulation. The high degree of saturation in the surficial soil was qualitative and determined visually. The nearly saturated surface soil had limited available soil water storage during the second rainfall simulation, which increased runoff from the soil surface. The magnitude of the difference in runoff and erosion from the first rainfall simulation to the second was largest for the burned block sample with no straw and generally decreased with increasing straw mulch application rate. This was attributed to increased erosion of the wettable ash layer with decreasing cover as exposure to the erosive forces of raindrop impact and surface runoff increased. Erosion and subsequent removal of the ash layer reduced water storage provided by the ash layer (Woods and Balfour 2008).

Total sediment yield from successive rainfall simulations in the slope-model experiments on the four burned samples with varying amounts of straw mulch are shown in Fig. 4.4. Also included in Fig. 4.4 is the range of total sediment yield from the three unburned block samples with varying amount of surface vegetation. The addition of straw mulch to the surface of burned soil exponentially decreased the total eroded sediment during a rainfall simulation. All three straw mulch application rates (0.06, 0.11, and 0.22 kg/m^2) reduced total sediment yield to levels comparable with unburned samples. Erosion generally increased with successive rainfalls on burned samples, which was attributed to an increase in surface runoff (Fig. 4.3). However, the addition of straw mulch considerably reduced the difference between sediment yields measured for successive rainfall simulations when compared to the burned block sample with no ground cover. An increase in the amount of straw mulch applied to the surface of burned soil provided protection from erosive forces and was effective in decreasing erosion.

A plot of sediment yield versus percent runoff for all rainfall simulations on unburned and burned block samples is shown in Fig. 4.5. Unburned block samples with vegetation and burned block samples with straw mulch exhibited a similar trend of low sediment yield despite increasing percent runoff, which is depicted by the shaded area in Fig. 4.5. However, burned block samples with no straw mulch exhibited a trend of increasing sediment yield with increasing percent runoff. Although the trend identified in this study was only based on two measurements, a similar trend was observed by Wood and Balfour (2008), wherein sediment yield in burned plots with and without ash were positively correlated with runoff. The results suggest that straw mulch can prevent runoff from dislodging and transporting soil similar to vegetation on unburned soil. Results also suggest that for a given percent runoff, eroded sediment will be higher for burned soil with no straw mulch compared to burned soil with straw mulch. Comparing the two burned block samples that yielded approximately 45% runoff, the burned sample with straw mulch decreased sediment yield nearly an order of magnitude relative to the burned sample with no ground cover.

4.1.3 Comparison to Previous Studies on Wood Mulches

A compilation of runoff rate, runoff reduction, sediment concentration, and sediment concentration reduction for soils with and without ground treatments are summarized in Table 4.2. The runoff reductions and sediment concentration reductions were computed for soils with ground treatments relative tests on the same soil without ground treatment. All soils were sandy loam (SL) or silty sand (SM) tested in similar physical laboratory models with simulated rainfall. Runoff and sediment yield were determined from the referenced studies and this study after an elapsed time of 25-min of simulated rainfall to provide consistency between all studies. Runoff reduction (*RR*) was calculated using the following equation:

$$RR = \frac{(T-B)}{B} \tag{4.1}$$

where *T* and *B* are the runoff rates at 25 min of simulated rainfall from the treated sample (*T*) and bare sample (*B*), respectively.

Yanosek (2006) and Foltz and Copeland (2009) reported high runoff rates from unburned soils. For all studies, the addition of mulch generally reduced runoff for unburned and burned soils. Wood mulch appeared to be more effective at runoff reduction compared to agricultural straw mulch; however, it is difficult to make direct comparisons between studies due to differences in several variables. Both wood and straw mulch appeared equally effective at sediment concentration reduction. The mass of straw mulch used was 42-95% less than the mass of wood mulches used, suggesting straw mulch can provide similar erosion reduction at a lower cost. Yanosek (2006) suggested that the reduction in runoff, rilling, and erosion with the addition of wood strands was due to the strands slowing down water flow, which reduced shear forces of water against the soil. These observations made by Yanosek (2006) are similar to observations made in this study regarding the mechanisms of how ground cover on the surface of burned soil decreased soil erosion.

4.2 Soil Characteristic and Engineering Property Tests

4.2.1 Physical Soil Characteristics

Soil dry density and TOC measured for four unburned and four burned subsamples taken from the block samples are compiled in Table 4.3. Soil surface dry density did not change with high severity burning. Dry density for unburned samples varied from 1.0 to 1.2 g/cm^3, with an average dry density of 1.1 g/cm^3. Dry density for burned samples varied from 0.8 to 1.1 g/cm^3, with an average dry density of 1.1 g/cm^3. Although select studies reported that burning increased soil dry density due to aggregate breakdown and soil structure collapse (e.g. Moody and Martin 2001), other studies reported that average dry density did not change considerably between unburned and burned soils (Moody et al. 2005; Wieting et al. 2017).

Surface TOC did not change with high severity burning (Table 4.3). TOC estimated as the percent mass loss from LOI for unburned samples varied from 5% to 10%, with an average of 8%. Percent mass loss for burned samples varied from 8% to 11%, with an average of 9%. The LOI (TOC) values from this study are similar to those reported in literature, whereby Moody et al. (2005) reported LOI ranging from 6.0% to 7.3% for unburned Colorado soils and 5.8% to 7.4% for burned Colorado soils. Wieting et al. (2017) reported a high-temperature heated (high severity burned) sample average LOI value of 9%.

4.2.2 Hydraulic Soil Properties

Field saturated hydraulic conductivity of the soil surface (estimated using MDI) and water repellency (estimated using WDPT) measured on unburned and burned block samples are tabulated in Table 4.4. Surface K_{fs} slightly increased with high severity burning and slightly decreased between the first and second rainfall simulation on burned block samples. The K_{fs} for unburned samples prior to the first rainfall simulation varied from 5 x 10^{-5} to 1 x 10^{-3} cm/s, with an average K_{fs} = 5 x 10^{-4} cm/s. The K_{fs} for burned samples prior to the first rainfall simulation varied from 5 x 10^{-4} to 6 x 10^{-3} cm/s (average K_{fs} = 3x10^{-3} cm/s), whereas K_{fs} for burned samples prior to the second rainfall simulation varied from 8 x 10^{-4} to 1 x 10^{-3} cm/s (average K_{fs} = 1x10^{-3} cm/s). An increase in K_{fs} with burning was not expected based on previous studies that suggest K_{fs} decreased with burning (e.g. Ebel et al. 2012). However, Wieting et al. (2017) also showed an increase in K_{fs} between unburned and burned soils with average values of 3.7x10^{-5} cm/s and 1.4x10^{-4} cm/s, respectively.

Based on the WDPT class ranges proposed by Doerr et al. (2004), the water repellency rating was wettable for both unburned and burned soil surfaces. However, the repellency rating 2 cm below the soil surface for unburned soils was wettable, where for burned soils was extremely repellent. This result implies the subsurface formation of a hydrophobic layer with burning developed and was attributed to the condensation of organic hydrophobic coatings. The wettable surface on burned samples was likely due to presence of an ash layer, since the ash layer was not removed prior to testing. Ebel et al. (2012) found that ash layers had a much larger infiltration capacity than burned soil. Thus, the ash layer can create a temporary storage layer above a subsurface hydrophobic layer. Similarly, Woods and Balfour (2008) and Larsen et al. (2009) found that the ash layer created by burning provided additional water storage capacity and prevented soil surface sealing. The hydrophobic layer created with burning in this study was not at the soil surface, which left a highly wettable ash layer above the hydrophobic layer to temporarily store water.

4.2.3 Mechanical Soil Properties

Shear strength of intact samples excavated from unburned and burned block samples as well as unburned remolded samples was measured in direct shear. A summary of the direct shear tests conducted is in Table 4.5 along with the σ'_n, peak shear strength (τ_p), and horizontal displacement to peak shear strength. The τ_p listed in Table 4.5 are actual peak shear strengths if a peak shear stress was observed or represent the shear stress at a horizontal displacement of 7 mm. The purpose of testing unburned, remolded soil (dry density = 1.2 g/cm^3) was to analyze the effect of roots on shear strength parameters. This collection of direct shear tests aided in evaluating the hypothesis that high severity soil burning reduced shear strength due to loss of surface vegetation.

Relationships of τ_p versus σ'_n for direct shear tests conducted on intact unburned soil, intact burned soil, and unburned remolded soil are shown in Fig. 4.6. Peak shear strength of the unburned remolded soil coincided with lower-bound τ_p plotted in Fig. 4.6, such that nearly all τ_p measured on intact burned and unburned soil specimens plotted above the strength envelope for the unburned remolded soil. At least three replicate direct shear tests were conducted on intact burned and unburned soil specimens at each σ'_n (Table 4.5). Considerably more scatter was observed in τ_p measured on the intact burned soil samples relative to the intact unburned soil. Furthermore, τ_p for the intact burned soil at a given σ'_n ranged from as high as τ_p measured on intact unburned soil and as low as τ_p measured on unburned remolded. This scatter in τ_p measured on intact burned soil specimens was attributed to variability in surface burning. Select locations on the surface retained roots after burning that led to τ_p similar to the unburned intact specimen. In contract, other locations on the burned soil surface had completely destroyed root structures after burning that reduced τ_p to levels comparable with the unburned remolded soil.

The burned block outlier was due to an observed rock in the shear plane and was not included in the development of the burned strength envelope. Only 2 tests are presented for intact, unburned soil tested at σ'_n of 63.6 kPa due to testing equipment error during the 3 test.

Strength envelopes determined for each of the data sets in Fig. 4.6 exhibited a high degree of linearity, with coefficients of determination (R^2) ranging from 0.92 to 0.99. Effective cohesion intercepts ranged from 0 kPa for unburned remolded soil, to 6 kPa for unburned intact soil. The effective stress friction angle (Φ') for unburned and burned intact soil and unburned remolded soil were similar, ranging from 40° to 44°. These similarities in Φ' but differences in *c*' were expected. Burning and remolding did not necessarily alter the mineral properties of the soil, which contribute to frictional strength. However, burning does, compromise root strength and the action of remolding completely removed roots. These results suggest that unburned soil can be remolded at a representative surficial dry density and evaluated in direct shear to estimate frictional strength that would be anticipated to be present within the soils following a wildfire.

4.2.4 Summary of Effects of Burning on Soil Characteristics

Considerable changes in soil physical characteristics and hydraulic and mechanical properties between unburned and burned soil samples were not found in this study. Similarities in surface dry density, organic matter, field saturated hydraulic conductivity, and shear strength between unburned and burned soil samples imply that the observed increases in erosion on bare burned samples during rainfall simulations was mainly caused by the destruction of surface cover with burning. This result is similar to that drawn by Larsen et al. (2009) who found post-fire sediment yields were likely not due to fire-enhanced soil water repellency, but were attributed to the loss of ground cover. Several studies (e.g. Neary et al. 1999; DeBano 2000; Doerr et al. 2000) have suggested that observed increases in runoff and erosion following high severity wildfires are due in large part to changes in soil characteristics and properties; however, results from this study suggest that soil properties may not change considerably with burning.

Table 4.1. Rate of simulated rainfall, average runoff rate, ultimate runoff rate, and average percent runoff for unburned and burned block samples tested in the slope-model experiment.

Condition	***Rainfall Simulation***	***Cover/ Straw Mulch (kg/m²)***	***Rainfall Rate (mm/h)***	***Average Runoff Rate (mm/h)***	***Ultimate Runoff Rate (mm/h)***	***Percent Runoff (%)***
Unburned block	1st	Low vegetation	48	24	32	50
		Medium vegetation	48	13	22	27
		High vegetation	47	11	18	23
Burned block	1st	0	48	15	25	31
		0.06	49	20	23	41
		0.11	49	9	17	18
		0.22	50	11	20	22
	2nd	0	47	21	29	45
		0.06	49	21	23	43
		0.11	49	14	18	29
		0.22	46	11	16	24

Table 4.2. Compilation of runoff rate, runoff reduction, sediment concentration, and sediment concentration reduction from treated samples with respect to bare samples for laboratory slope-model experiments of sandy loam (SL) or silty sand (SM) soils with different ground treatments after 25-min of simulated rainfall.

Study	***Soil***	***Slope (%)***	***Rainfall Intensity (mm/h)***	***Cover Mass (kg/m^2)***	***Cover Material***	***Runoff Rate (mm/h)***	***Runoff Reduction (%)***	***Sediment Conc. (g/L)***	***Sediment Conc. Reduction (%)***
This study [a]	SM, unburned	50	48	0	Bare	21		4	
	SM, burned	50	48	0	Bare	23		16	
				0.06	Straw	25	- 9 [b]	2	88
				0.11		14	39	7	56
				0.22		15	35	2	88
Yanosek (2006) [c]	SL, unburned	30	50	0	Bare	31			
				0.38	Wood strand	14	55		66 [d]
Foltz and Copeland (2009) [c]	SL, unburned	30	50	0	Bare	28			
				0.49	Wood shred	8	71		74 [d]
Foltz and Wagenbrenner (2010) [c]	SL, burned	40	51	0	Bare	12			
				0.64	ASIS wood	4	67		82 [d]
				1.12	ASIS wood	3	75		95 [d]

[a] Runoff rate and runoff reduction for first rainfall simulation
[b] Negative value indicates increase in runoff when compared to bare sample
[c] Runoff rates and sediment concentrations after 15-min of simulated rainfall and 10-min of pre-wetting prior to rainfall simulation
[d] Reported sediment concentration reduction values from Foltz and Wagenbrenner (2010)

Table 4.3. Dry density and total organic carbon (TOC) measured on intact unburned and burned subsamples exhumed from block samples tested in the slope-model experiment.

Sample	***Replicate***	***Dry density (g/cm^3)***	***TOC (%)***
Unburned block	1	1.1	5
	2	1.0	9
	3	1.0	8
	4	1.2	10
	Average	1.1 ± 0.1	8 ± 2
Burned block	1	1.1	8
	2	1.1	11
	3	0.8	9
	4	1.1	10
	Average	1.1 ± 0.1	9 ± 1

Table 4.4. Saturated field hydraulic conductivity (K_{fs}) and wettability index measurements conducted on burned and unburned block samples tested in the slope-model experiment.

Sample	***Replicate***	***Time***	***K_{fs} (cm/s)*** [a]	***WDPT (s)*** [b]
Unburned block	1		$3x10^{-4}$	<5
	2		$5x10^{-5}$	<5
	3		$2x10^{-4}$	<5
	4		$1x10^{-3}$	<5
	Average		$5x10^{-4}$	<5
Burned block	1	Before rainfall	$2x10^{-3}$	<5
		After rainfall	$1x10^{-3}$	<5
	2	Before rainfall	$4x10^{-3}$	<5
		After rainfall	$8x10^{-4}$	<5
	3	Before rainfall	$6x10^{-3}$	<5
		After rainfall	$1x10^{-3}$	<5
	4	Before rainfall	$5x10^{-4}$	<5
		After rainfall	$8x10^{-4}$	<5
	Average	Before rainfall	$3x10^{-3}$	<5
		After rainfall	$1x10^{-3}$	<5

[a] Average value from 2 MDI tests
[b] Average value from 3 drops

Table 4.5. Shear strength measured on intact unburned and burned subsamples exhumed from block samples tested in the slope-model experiment and unburned, remolded samples tested in drained direct shear.

Sample	*Effective Normal Stress (kPa)*	*Peak Shear Strength (kPa)*	*Horizontal Displacement at Peak Shear Strength (mm)*
Unburned block	17.2	20.5	7.0
		23.8	7.0
		19.5	7.0
	32.7	38.9	7.0
		39.8	7.0
		37.9	7.0
	63.6	67.6	7.0
		65.3	7.0
Burned block	17.2	12.1	7.0
		29.3 [a]	7.0
		19.8	7.0
		26.4	6.9
	32.7	33.4	7.0
		29.7	7.0
		41.7	7.0
		37.2	7.0
	63.6	55.8	7.0
		69.2	7.0
		69.3	7.0
		62.2	7.0
Unburned, remolded	17.2	13.6	7.0
	32.7	33.1	6.4
	63.6	52.3	7.6

[a] Outlier

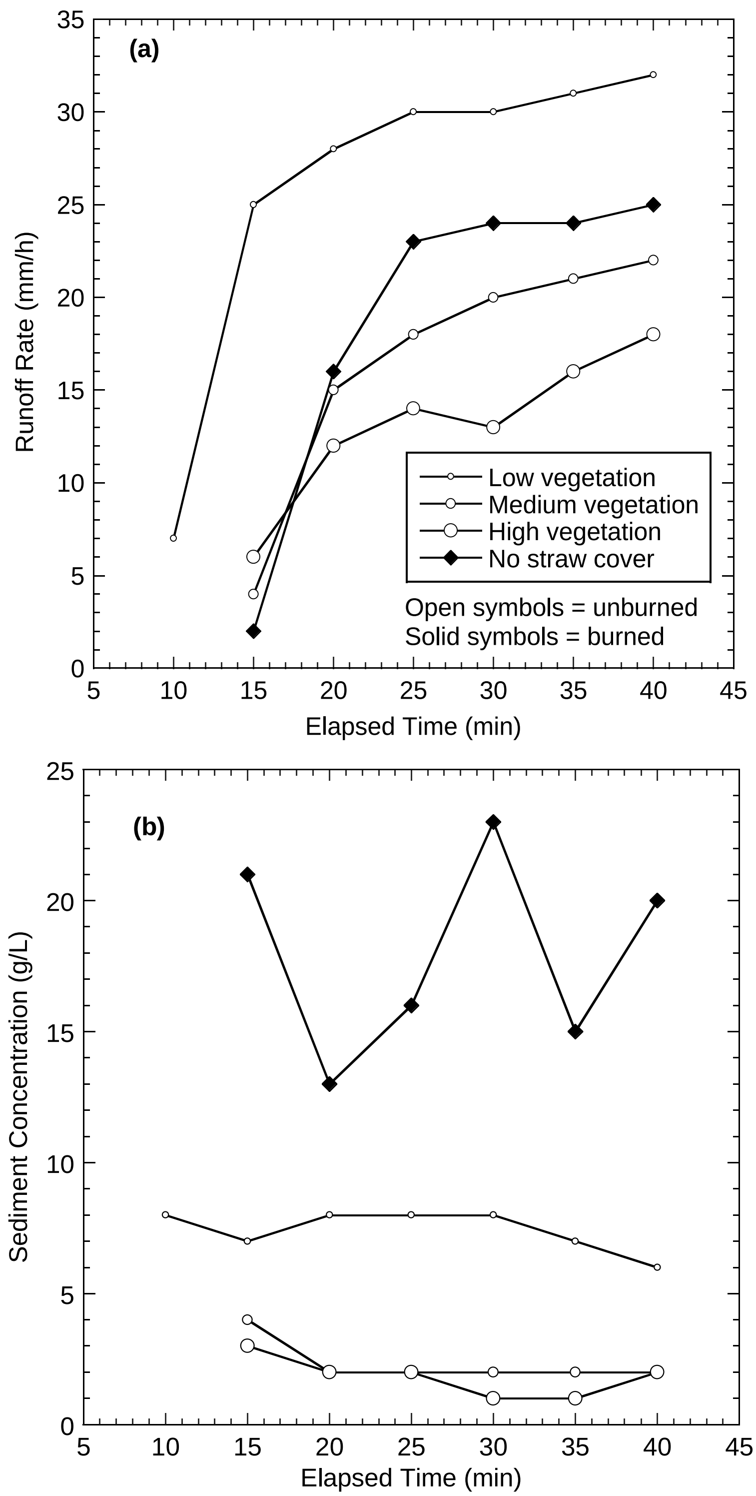

Fig. 4.1. Temporal relationships of (a) runoff rate and (b) sediment concentration for slope-model experiments conducted on three unburned block samples and one burned block sample with no straw mulch cover.

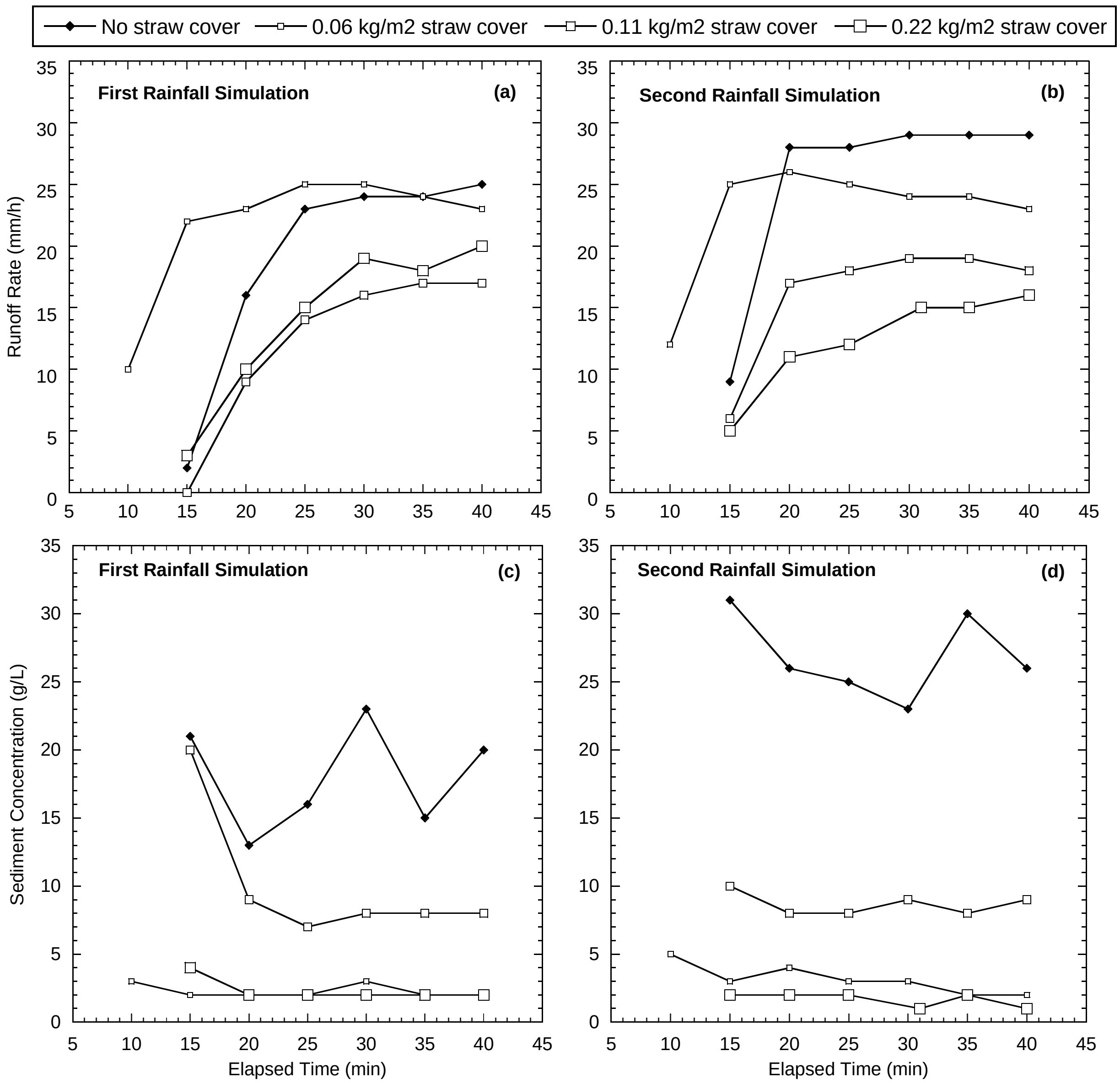

Fig. 4.2. Temporal trends of runoff rate for the (a) first rainfall simulation and (b) second rainfall simulation, and temporal trends of sediment concentration for the (c) first rainfall simulation and (d) second rainfall simulation from the slope-model experiments conducted on the burned block samples with varying amounts of straw mulch.

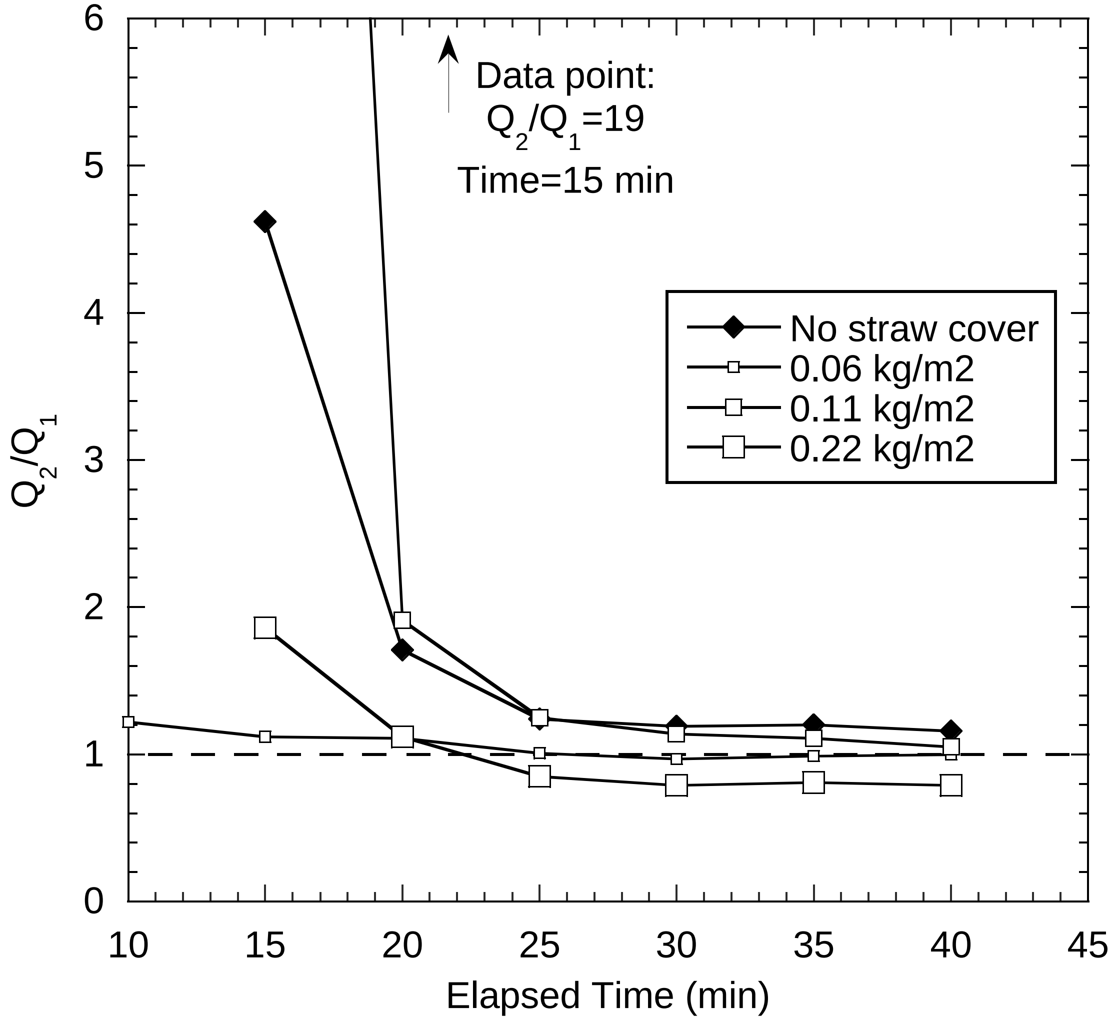

Fig. 4.3. Temporal trends of the ratio of cumulative runoff during the second simulated rainfall (Q_2) to cumulative runoff during the first simulated rainfall (Q_1) for four burned samples with varying amounts of straw mulch application.

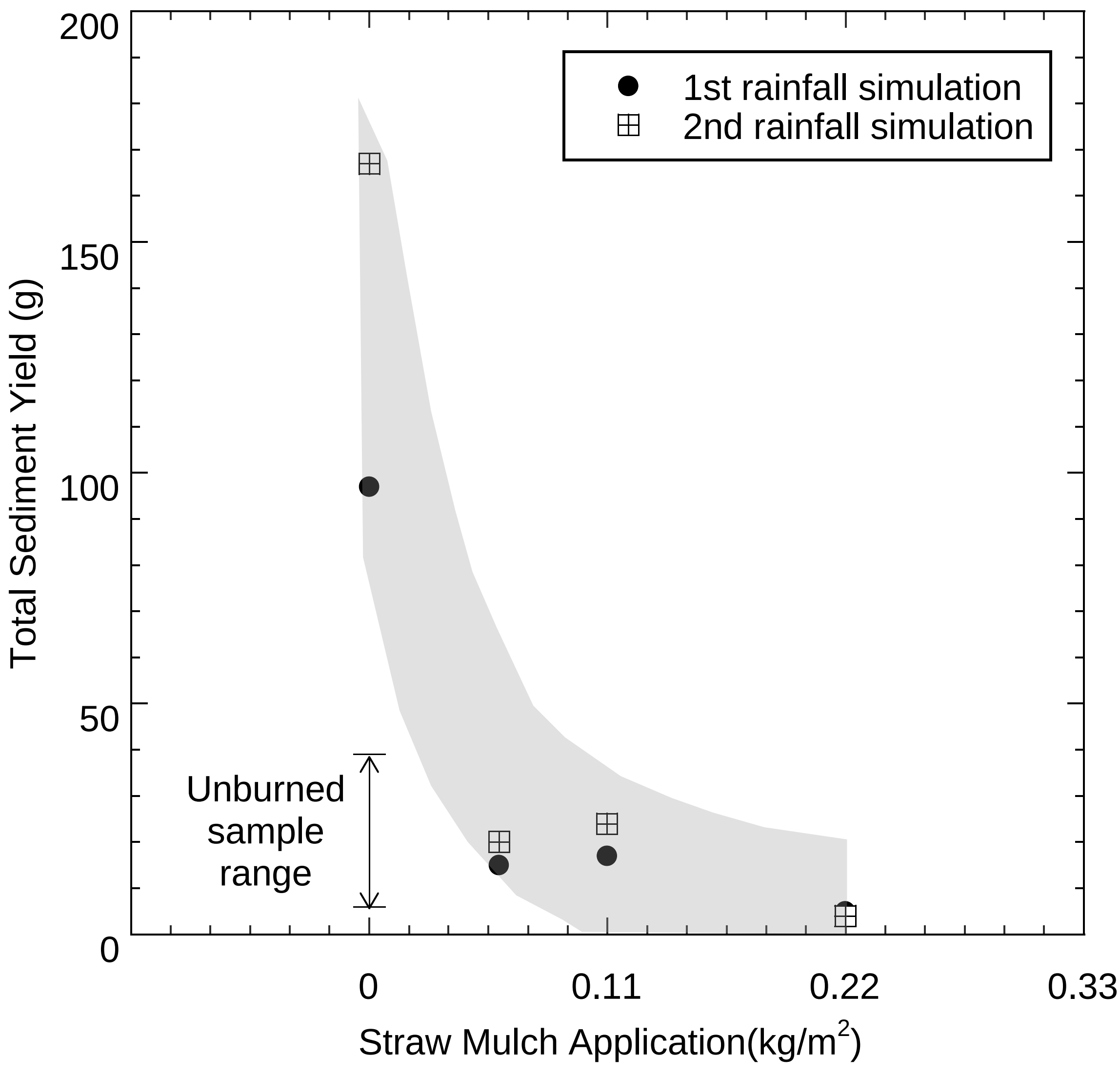

Fig. 4.4. Relationships of total sediment versus straw mulch application for successive simulated rainfalls on four burned samples with different amounts of straw mulch. Range of sediment yield included from the unburned samples with natural vegetation.

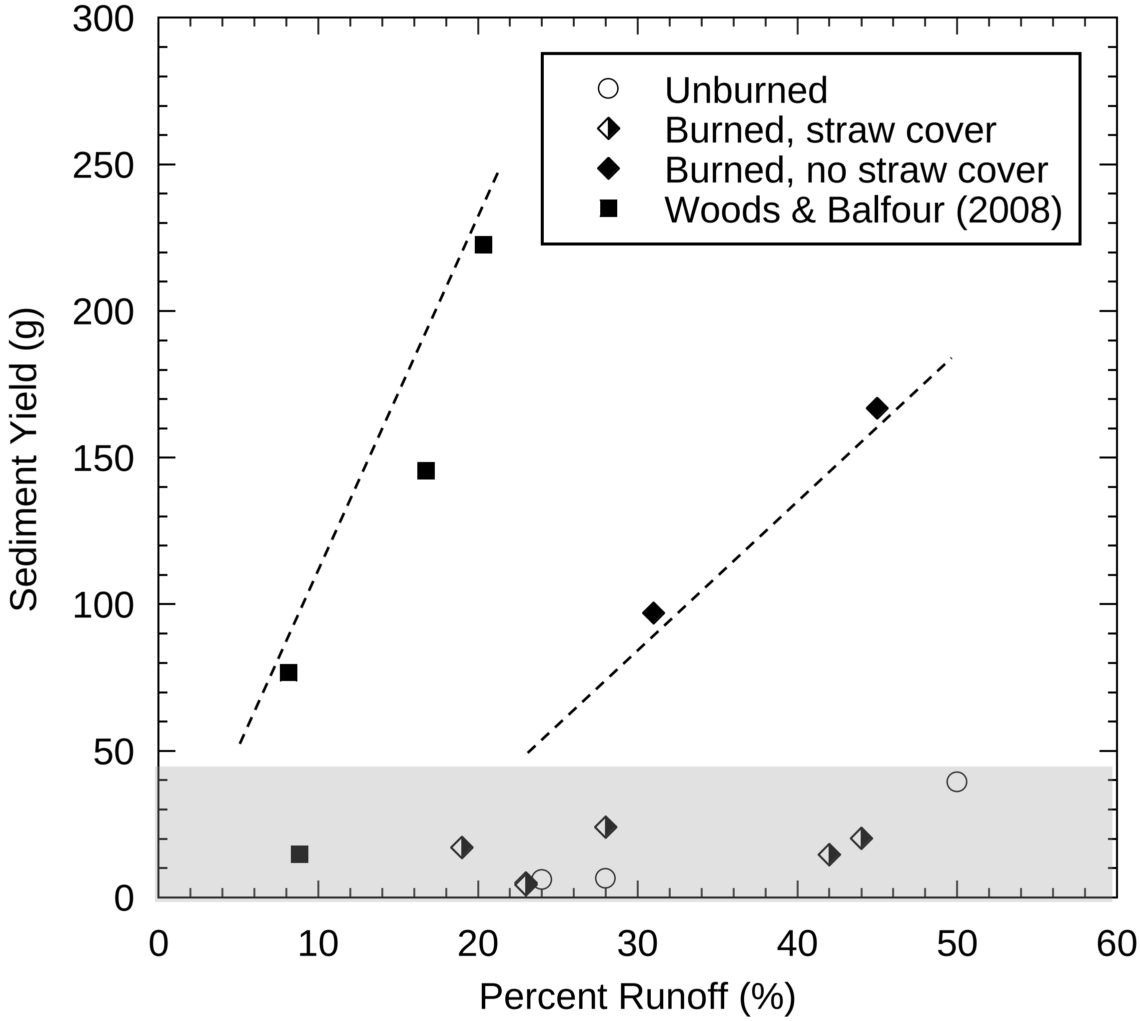

Fig. 4.5. Scatter plot of sediment yield versus percent runoff for all rainfall simulations on unburned and burned block samples. Burned soil, no cover data from Woods and Balfour (2008) was included to build on the trend observed for the limited burned soil, no cover data from this study.

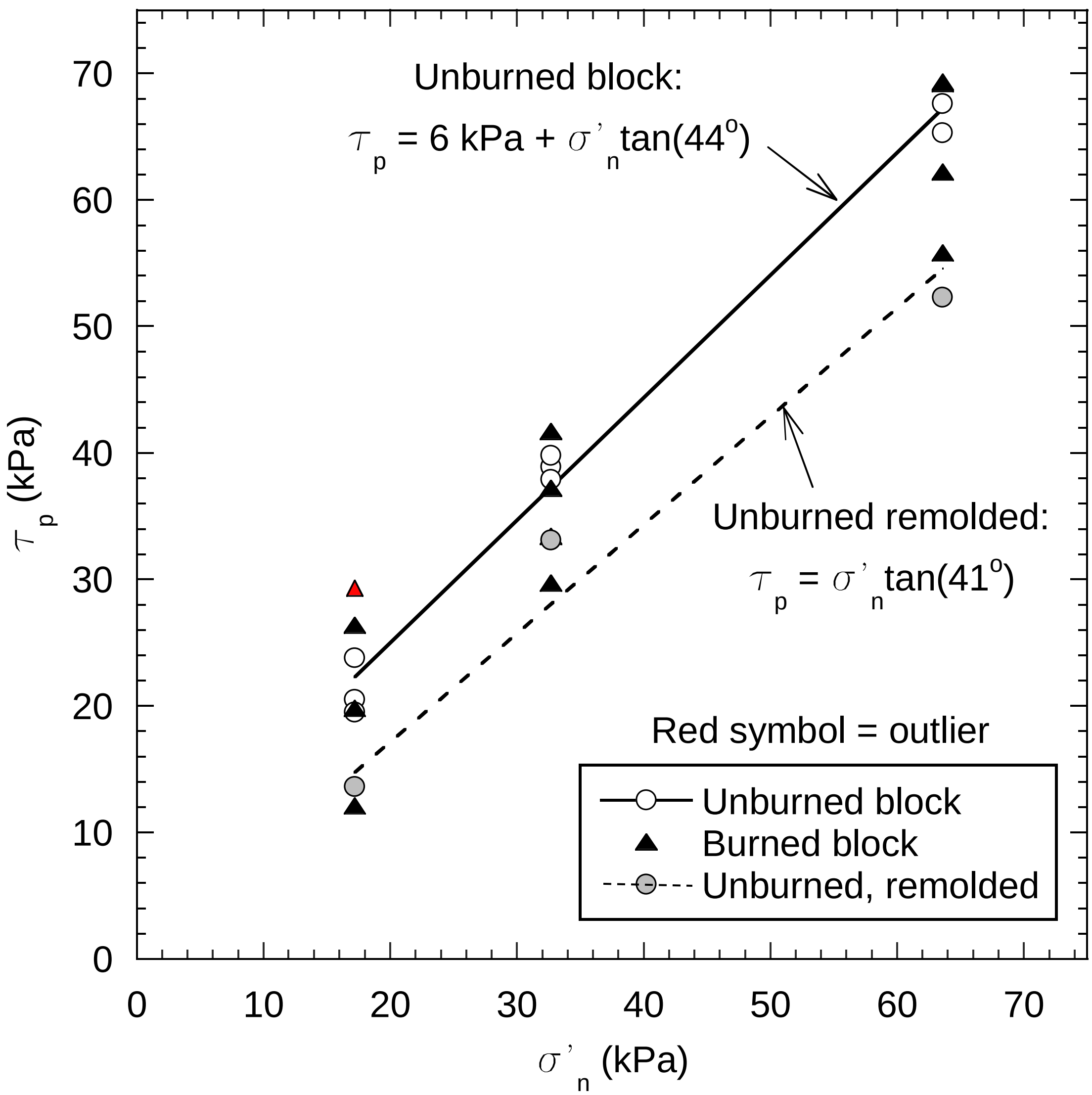

Fig. 4.6. Strength envelopes for undisturbed surface samples of unburned and burned soil and unburned, remolded soil using direct shear. The burned block outlier was due to an observed rock in the shear plane.

CHAPTER 5: SUMMARY, CONCLUSIONS, AND FUTURE RESEARCH

5.1 Summary and Conclusions

The effects of soil surface vegetation burning and straw mulch application on runoff and erosion of soil surfaces was evaluated using a laboratory-scale slope-model experiment. A series of rainfall simulations was conducted on intact block samples with natural vegetation, burned vegetation, and burned vegetation and straw mulch applied as ground cover. Geotechnical property tests were also conducted on unburned and burned subsamples to evaluate changes in physical characteristic and hydraulic and mechanical properties due to burning. The following observations and conclusions were drawn from this study.

- The amount of runoff and erosion increased with a decrease in the amount of natural surface vegetation on the block samples. Burning the surface vegetation did not directly increase runoff, but burning did lead to an increase in erosion.
- The presence of straw mulch on the surface of a burned block sample reduced runoff rates and sediment concentrations relative to burned block samples without ground cover by providing layer above the soil to dissipate energy of raindrop impact and temporary store precipitation. Straw mulch also reduced erosion via acting as a barrier to entrap dislodged soil particles, preventing them from moving further downslope.
- Burned block samples generally produced higher runoff and erosion during a subsequent rainfall simulation (second simulation) when compared to a prior rainfall simulation (first simulation).
- Burning exponentially increased erosion compared to unburned conditions. Also, straw mulch reduced burned soil erosion to levels consistent with unburned samples that had natural vegetation.

- Increasing runoff from burned block samples with no ground cover resulted in increased sediment yield. Surface cover, whether natural vegetation or straw mulch, prevented increasing runoff and increasing sediment yields.
- The ash layer on the burned soil surfaces had high infiltration capacity and acted as a water storage layer. A hydrophobic layer was identified below the ash layer on the burned soil surfaces. This hydrophobic layer prevented water infiltration from the wettable ash layer deeper into the soil, which increased runoff from burned samples during the second rainfall simulation. Straw mulch helped protect the ash layer from eroding during rainfall simulations, which helped maintain the ability of the ash layer to provide water storage.
- Notable changes in soil physical characteristics and hydraulic and mechanical properties with high severity burning were not found in this study. Similarities in surface dry density, organic matter, field saturated hydraulic conductivity, and shear strength between unburned and burned soil samples suggest that the observed increases in erosion on bare burned samples during rainfall simulations could be attributed to destruction of surface cover with burning.

5.2 Future Research

There were several limitations of this research project due in large part to limited resources. These limitations can be used to steer future research that would expand on the results from this study. A key limitation was the number of block samples that could be collected for testing. Due to the limited number of samples, statistical analyses could not be conducted on the results. For this reason, result trends could be suggested but not proven to be statistically significant. Future studies with increased sample collection permitting and sample collection labor would be useful in conducting rainfall simulations on replicates, therefore, making statistical analyses possible.

Another limitation was only being able to test one post-fire ground treatment. Although this research focused on agricultural straw mulch as a post-fire ground treatment, additional studies on wood mulch will be useful since erosion materials derived from natural and available materials native are becoming more prevalent (Yanosek et al. 2006).

Due to the limited sample size, the only variables that were changed were burning and rate of straw mulch application. Straw mulch at any application rate was shown to decrease erosion on burned soil samples considerably in this study. However, this conclusion may not hold true once other variables such as rainfall intensity, rainfall duration, slope, and soil type are changed. Additional studies using the slope-model experiment while changing the variables that were held constant in this research could be useful in further understanding how post-fire ground treatments mitigating runoff and erosion.

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APPENDIX A: SOIL SAMPLE COLLECTION

Fig. A.1. Soil sample collection area and process.

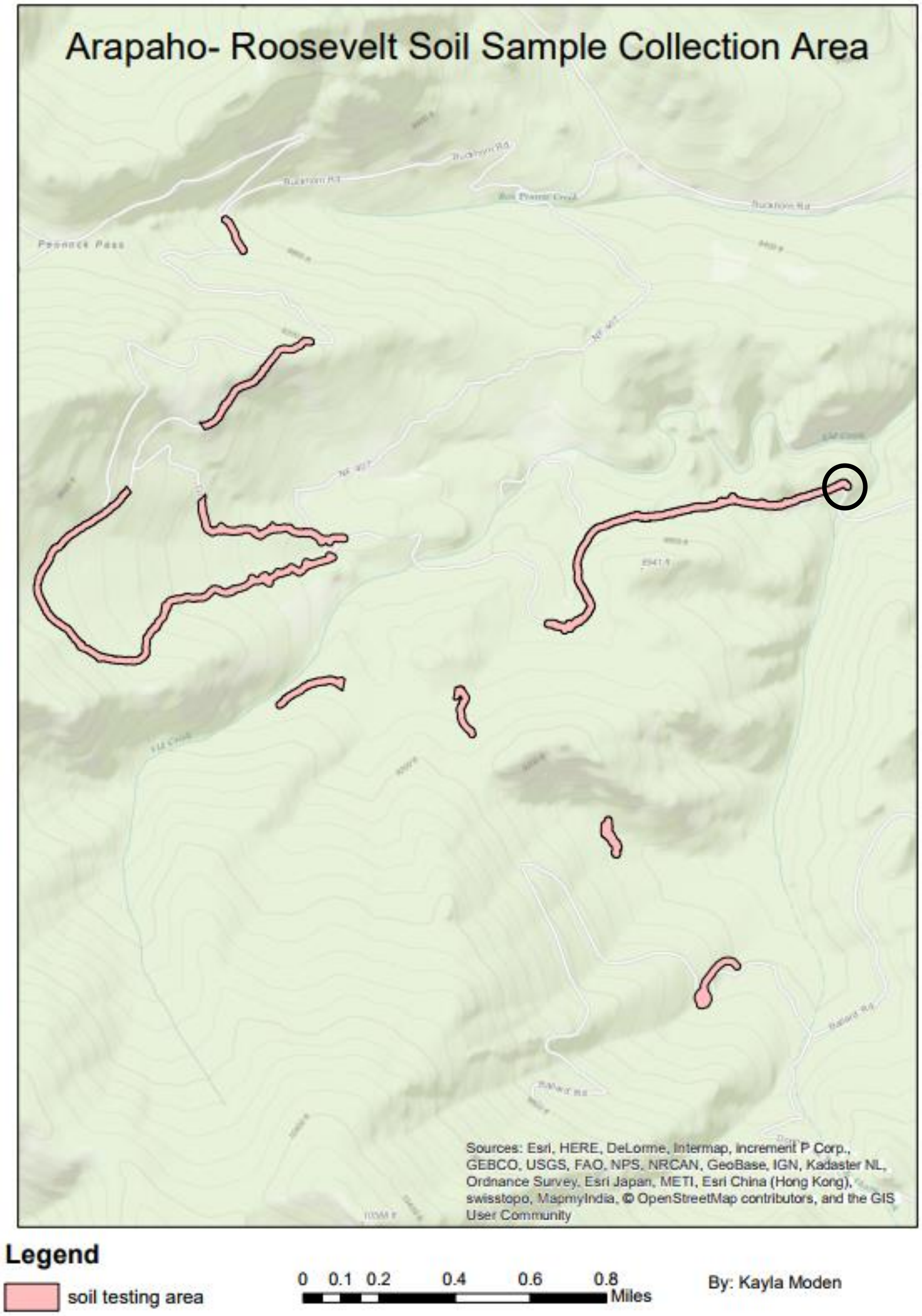
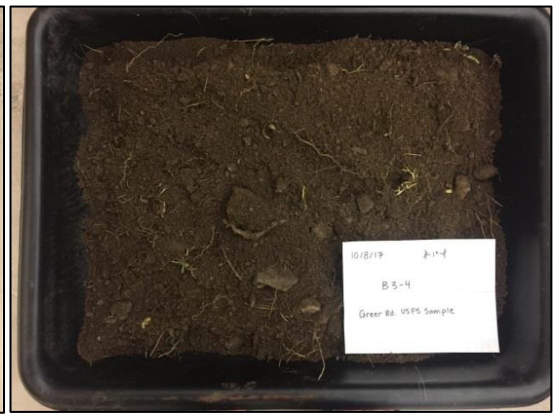
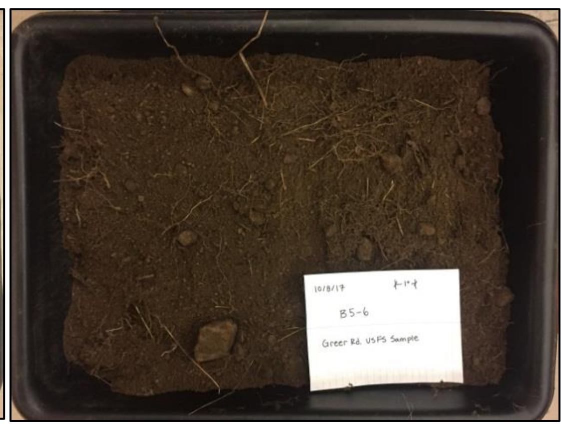
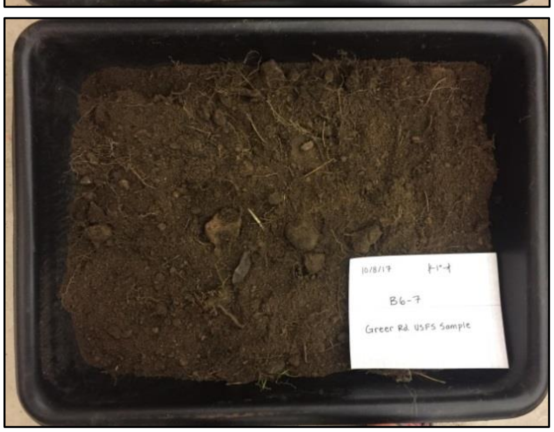


Fig. A.2. Permitted soil testing areas (pink) and location of soil sample collection (black circle).


10/8/17
B1
Greer Rd. USFS Sample

B1-2
Greer Rd. USFS Sample

10/8/17
B2-3
Greer Rd. USFS Sample

10/8/17
B3-4
Greer Rd. USFS Sample

10/8/17
B4-5
Greer Rd. USFS Sample

10/8/17
B5-6
Greer Rd. USFS Sample

10/8/17
B6-7
Greer Rd. USFS Sample

10/8/17
B7
Greer Rd. USFS Sample

Fig. A.3. Grab samples collected in between each of the seven block samples.

APPENDIX B: SAND-SILT MIXTURE TESTS

A summary of the slope-model experiments conducted on sand-silt mixture is in Table B.1. These baseline experiments were conducted on replicate sand-silt mixtures composed of 10, 20, 30, and 40 percent non-plastic silt with the other fraction made up of quartz sand. Sand-silt mixtures were prepared my manually mixing air-dried sand and silt, and then preparing the specimen in four, 2-inch lifts while the soil container was lying horizontal. The average dry density of the sand-silt mixtures was 1.75 g/cm^3. Each specimen was subjected to one simulated rainfall (intensity of about 4.5 cm/h for 40 minutes), and each mixture was tested twice. The first specimen of each mixture was hand-compacted until the soil would not compress any further with moderate effort. After testing, the upper 2 inches of soil comprising the specimen were removed (a depth well below depth of maximum erosion). The second specimen of each mixture (i.e., replicate) included a single fresh surface layer compacted on the underlying soil after scarifying the interface.

An additional set of experiments was conducted using 70 percent sand, 30 percent silt mixture and straw mulch as ground treatment. The straw mulch was spread on the soil surface at application rates of 0.22 kg/m^2 and 0.44 kg/m^2. A straw mulch application rate of 0.22 kg/m^2 has been used on Colorado hillslopes by BAER (BAER 2012). The straw mulch application of 0.44 kg/m^2 was evaluated as this application has been used in previous post-fire ground treatment studies (Schmeer 2014). Each slope-model experiment with straw mulch was subjected to one simulated rainfall (intensity of 4.5 cm/h for 40 minutes), and each mulch application rate (i.e., 0.22 or 0.44 kg/m^2) was tested twice.

Effect of Silt Content on Runoff and Erosion

Temporal relationships of the cumulative water runoff from the slope-model experiments conducted on sand-silt mixture with different silt contents are shown in Fig. B.1. Each sand-silt mixture was tested in duplicate, and in general, the replicate experiments on a given sand-silt mixture yielded similar results. The general trend of increasing runoff with increasing elapsed time, which corresponded to increasing duration of rainfall, was observed for all sand-silt mixtures except the mixture with 10 percent silt. Negligible runoff was collected for the 10 percent silt content since all rainfall infiltrated rapidly due to the high permeability of the mixture.

Table B.1. A summary of slope-model experiments conducted on sand-silt mixtures.

Test Group	***Scenario***	***Specimen Description***	***Straw Mulch Application (kg/m^2)***	***Test Specimen Replicates***	***Rainfall Simulations per Replicate***
Sand-Silt	1	90% sand, 10% silt	0	2	1
	2	80% sand, 20% silt	0	2	1
	3	70% sand, 30% silt	0	2	1
	4	70% sand, 30% silt	0.22	2	1
	5	70% sand, 30% silt	0.44	2	1
	6	60% sand, 40% silt	0	2	1

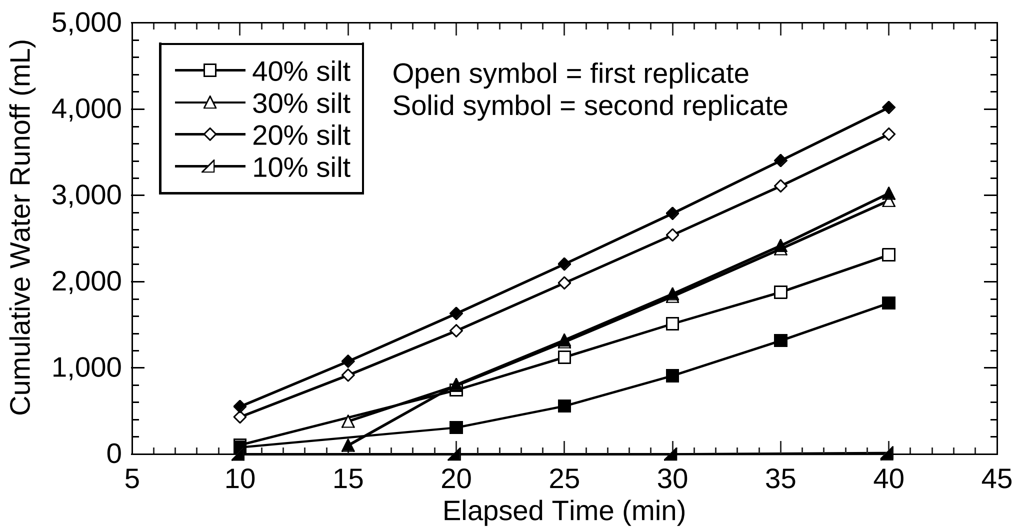


Fig. B.1. Temporal relationships of cumulative runoff in the slope-model experiments on sand-silt mixtures.

Relationships of percent runoff and total sediment yield versus silt content for the sand-silt mixtures are shown in Fig. B.2. The percent runoff was computed as the percent of cumulative precipitation falling on the soil specimen that resulted in runoff. Cumulative precipitation falling on a given specimen was computed based on surface area of the specimen, rainfall intensity, and duration of rainfall. The highest percent runoff and largest sediment yield were measured for the 80 percent sand, 20 percent silt mixture. A more pronounced reduction in percent runoff and total sediment yield was observed via decreasing silt content from 20 percent to 10 percent as conducted on the sand-silt mixtures were consistent with one another, which suggested that the slope-model experiment was capable of yielding repeatable measurements of runoff and erosion. The larger variation between replicate specimens for total sediment yield (Fig B.2b) compared to runoff (Fig. B.2a) was attributed to localized sloughing that occurred during some rainfall simulations.

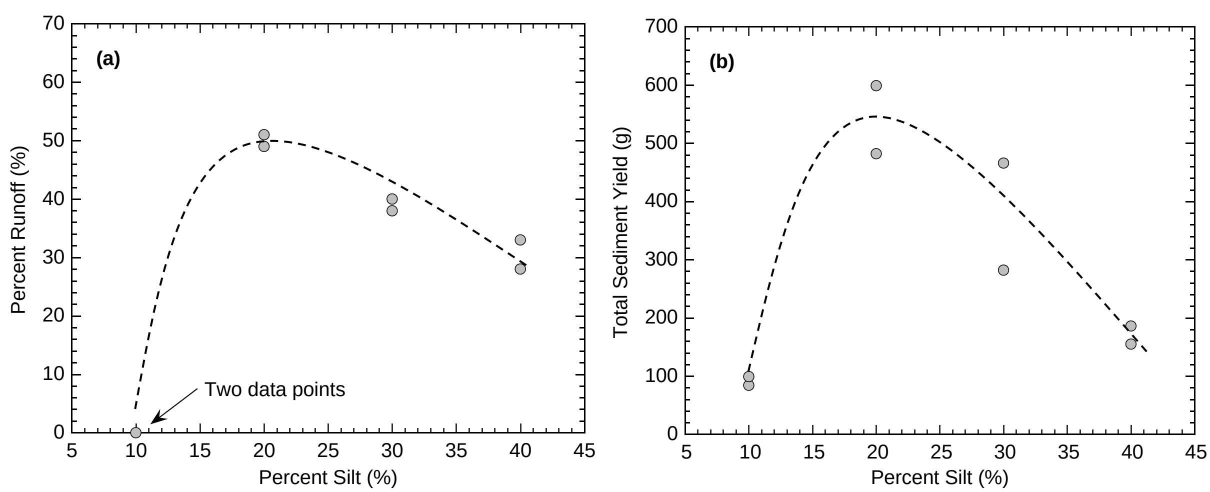


Fig. B.2. Relationships of (a) percent runoff versus percent silt content and (b) total sediment yield versus percent silt content from slope-model experiments conducted on sand-silt mixtures.

The trends of runoff and erosion as a function of silt content observed in Fig. B.2 were attributed to the influence of silt on infiltration and soil water storage. As silt is mixed with sand, the silt particles begin filling void space between sand particles, and subsequent addition of silt will eventually surpass the total volume of voids between the sand particles such that sand particles act as inclusions in the silt matrix. The transitional fines content has been shown to exist between approximately 20 percent and 30 percent silt content (i.e., non-plastic fines) for sand-silt mixture (e.g., Lade et al. 1998). Thus, at silt contents below 20 percent, the sand fraction dominates behavior, whereas silt contents above approximately 30 percent the silt fraction dominates behavior. The slope-model experiments primarily dealt with hydraulic behavior and the hydraulic conductivity of pure sand can be assumed orders of magnitude higher than pure silt. Thus, for soils with a silt content of 10 percent, the soil hydraulic behavior was governed by the sand, which resulted in high infiltration and low runoff. In contrast, at silt contents of 20 percent or greater, soil hydraulic conductivity and infiltration decreased. The reducing trend of runoff and erosion as silt content increased above 20 percent was attributed to increased soil water storage that allowed some raindrops to be retained by the silt matrix.

The experiments on sand-silt mixtures suggest that there was a threshold soil matrix that reduced infiltration capacity and also had limited soil water storage such that rainfall resulted in increased runoff that also increased erosion. The water runoff acted as an erosion agent, which dislodged soil particles and carried them downslope, resulting in high sediment yields.

Effect of Straw Mulch on Runoff and Erosion

Temporal relationships of cumulative water runoff from slope-model experiments on 70 percent sand, 30 percent silt mixtures with different amounts of straw mulch used as ground cover are shown in Fig. B.3. Similar trends of increasing runoff with increasing elapsed time were observed between the sand-silt mixtures with straw mulch and the sand-silt mixture without straw mulch. Similar magnitudes of runoff were measured for the sand-silt mixture without straw mulch and the 0.22 kg/m^2 straw mulch application, whereas an increase in straw mulch to 0.44 kg/m^2 decreased the amount of runoff.

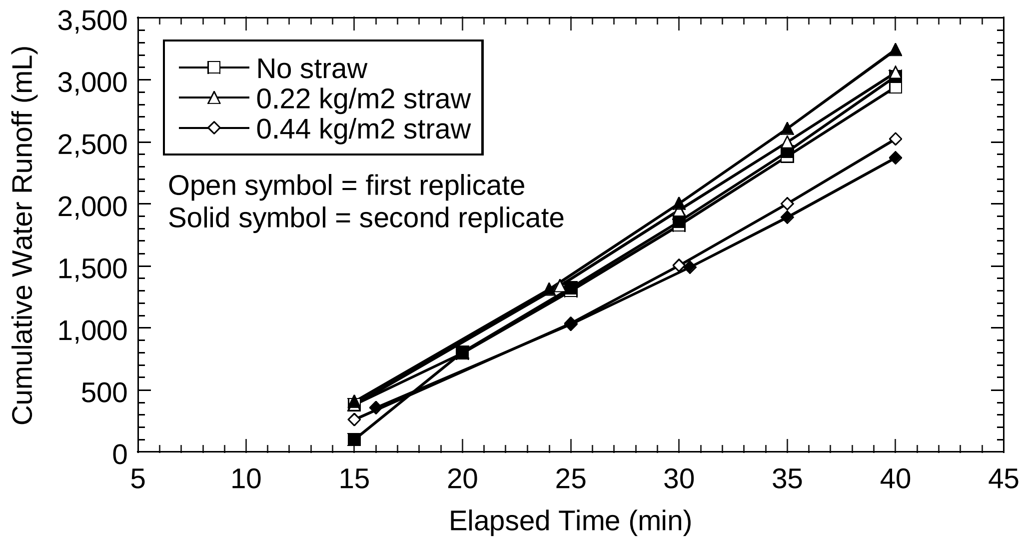


Fig. B.3. Temporal relationships of cumulative runoff in the slope-model experiments on sand-silt mixtures (70 percent sand and 30 percent silt) with and without straw mulch applied as ground treatment.

Relationships between the percent runoff and total sediment yield versus the amount of straw mulch application for the 70 percent sand, 30 percent silt mixtures are shown in Fig. B.4. Although limited differences in runoff were measured as a function of the amount of straw mulch (Fig. B.4a), the presence of straw mulch considerably decreased total sediment yield that was eroded during the experiment (Fig. B.4b). The high rates of runoff measured for the sand-silt mixture with straw mulch were attributed to the porous network of straw strands during testing. The straw mulch application rates of 0.22 and 0.44 kg/m^2 covered the majority of the specimen surface, and the modest reduction in runoff for the increase in ground cover was attributed to increased moisture holding capacity within a thicker straw layer for the 0.44 kg/m^2 ground treatment.

The pronounced decreased in soil erosion for the two straw mulch applications supports the premise that the presence of ground cover decrease erosion. The straw mulch acted to shield the soil surface from raindrop impact, as well as, prevent subsequent particle dislodgment and entrainment during surface flow. In addition, the straw mulch acted as a barrier to resist particle detachment in the event that surface flow occurred. The set of experiments on sands-silt mixtures with and without straw mulch used as ground cover support observations from field applications of post-fire ground cover that the presence of ground cover can reduce surface erosion.

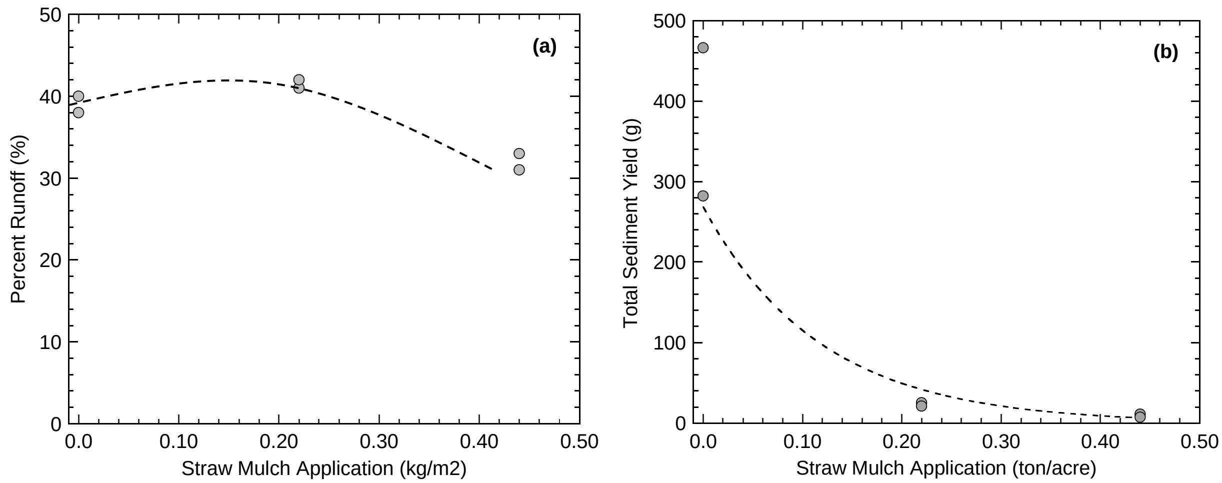


Fig. B.4. Relationships of (a) percent runoff versus rate of straw much application and (b) total sediment yield versus straw-mulch application from slope-model experiments conducted on sand-silt mixtures (70 percent sand and 30 percent silt).

Several conclusions were drawn from the rainfall simulations conducted on sand-silt mixtures. The main conclusion was that the laboratory-scale slope-model experimental setup yielded repeatable measurements of erosion and runoff for replicate tests on sand-silt mixtures.

APPENDIX C: LABORATORY BURNING

The thermocouple software was not available for the fourth burn simulation so, the thermocouple was not able to be used. The outside temperature at the start of the fourth burn was -4 ^{o}C. The fourth sample was burned for 120 min to ensure the temperature 2.5 cm below the soil surface reached at least 175 ^{o}C.

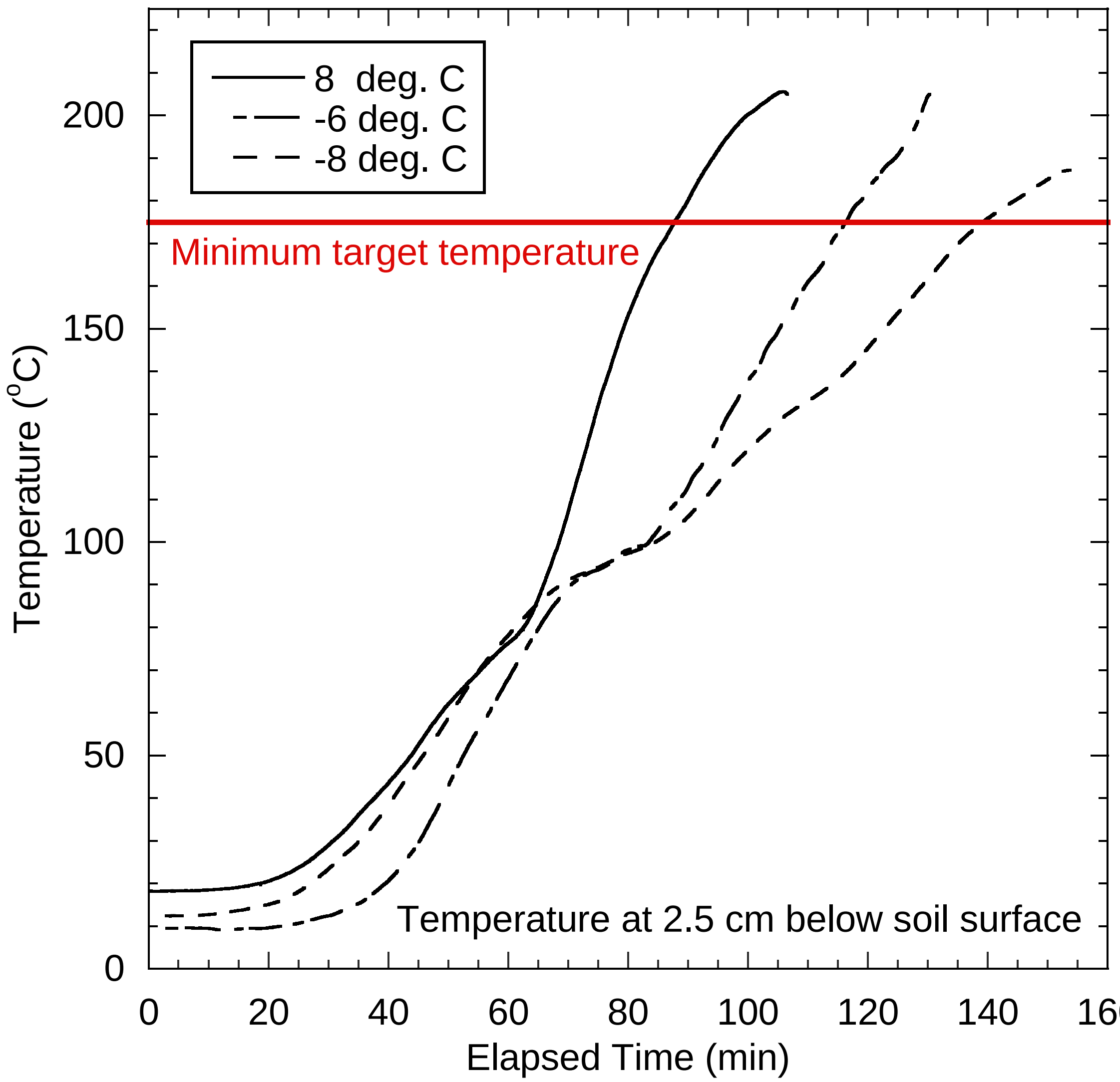


Fig. C.1. Time-temperature curves collected during the burning of three block samples. Each data series represents different outside temperatures at the start of the burn simulation.

APPENDIX D: PRE- AND POST-RAINFALL SIMULATION PICTURES

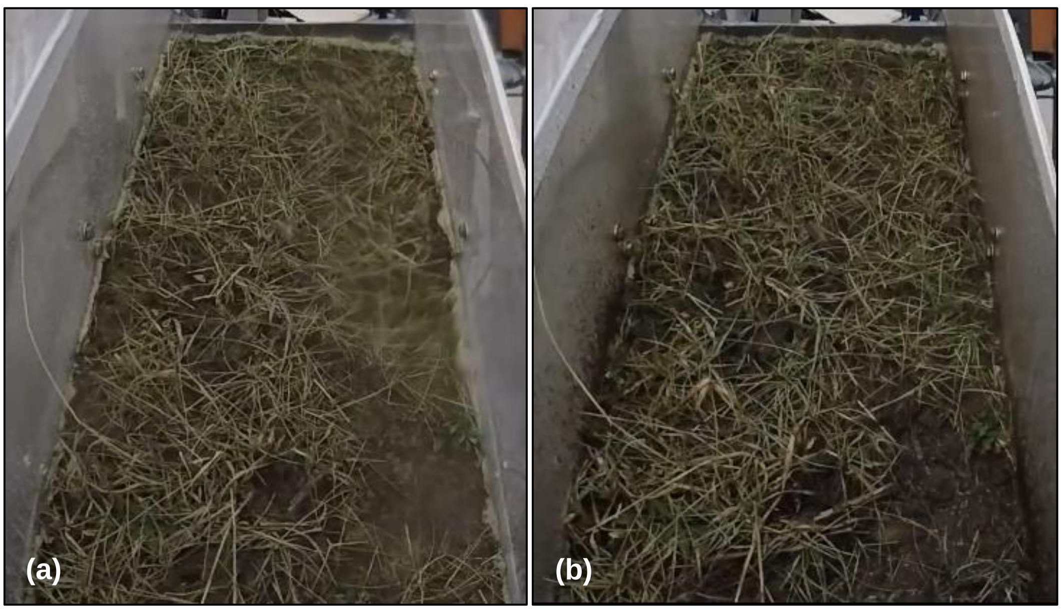


Fig. D.1. Unburned block, low vegetation (a) before rainfall simulation and (b) after rainfall simulation.

Fig. D.2. Unburned block, medium vegetation (a) before rainfall simulation and (b) after rainfall simulation.

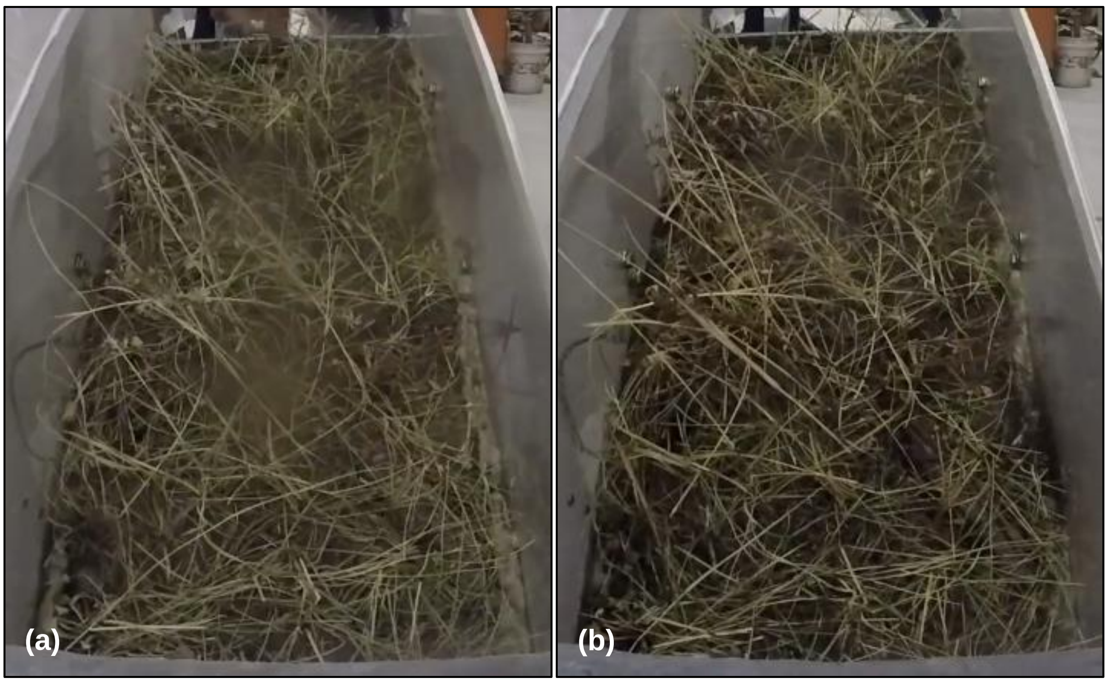


Fig. D.3. Unburned block, high vegetation (a) before rainfall simulation and (b) after rainfall simulation.

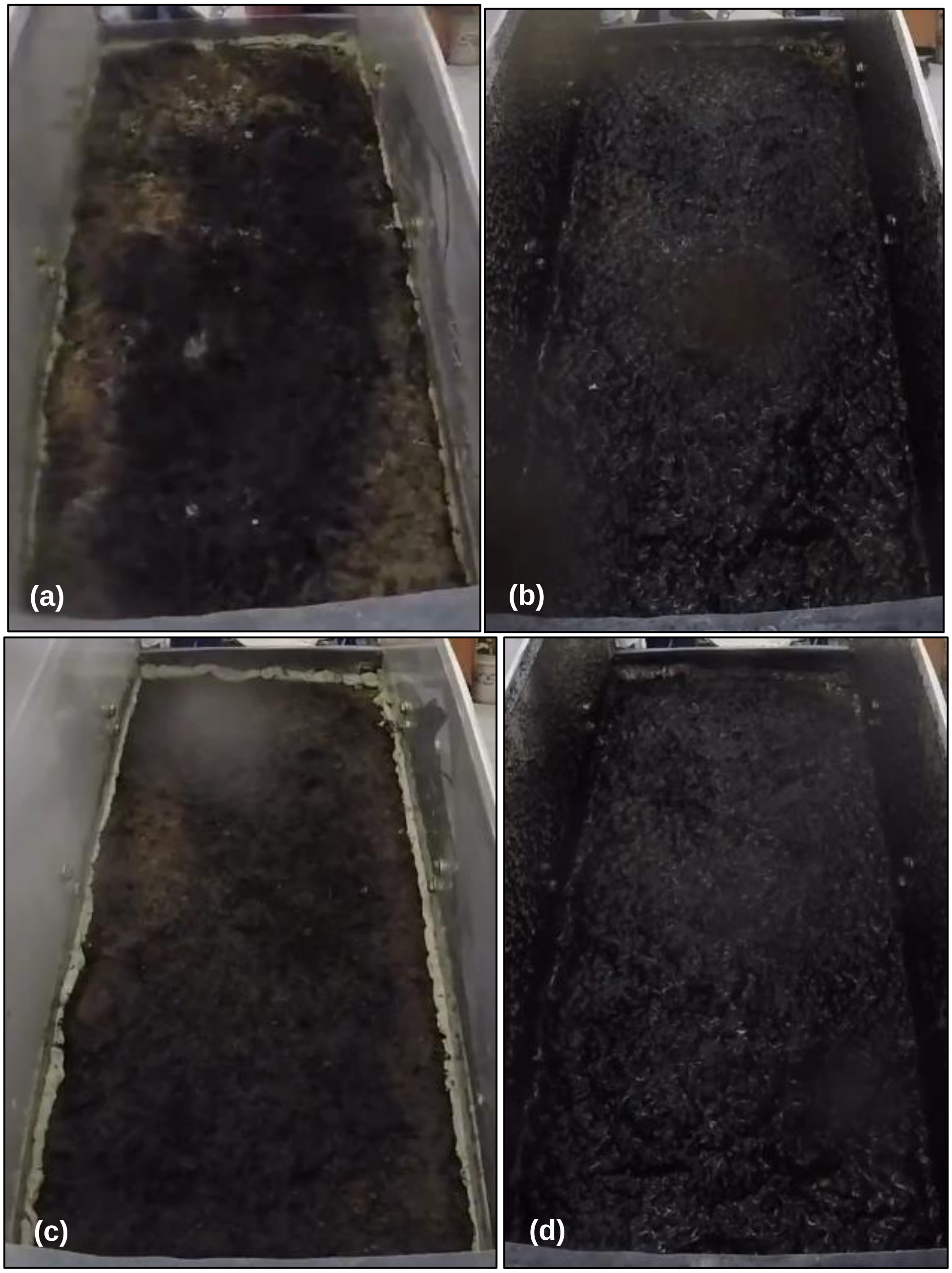


Fig. D.4. Burned block, no straw mulch (a) before 1st rainfall simulation, (b) after 1st rainfall simulation, (c) before 2nd rainfall simulation, and (d) after 2nd rainfall simulation.

Fig. D.5. Burned block, 0.06 kg/m^2 straw mulch (a) before 1st rainfall simulation, (b) after 1st rainfall simulation, (c) before 2nd rainfall simulation, and (d) after 2nd rainfall simulation.

Fig. D.6. Burned block, 0.11 kg/m^2 straw mulch (a) before 1st rainfall simulation, (b) after 1st rainfall simulation, (c) before 2nd rainfall simulation, and (d) after 2nd rainfall simulation.

Fig. D.7. Burned block, 0.22 kg/m^2 straw mulch (a) before 1st rainfall simulation, (b) after 1st rainfall simulation, (c) before 2nd rainfall simulation, and (d) after 2nd rainfall simulation.