# POST-FIRE EROSION FOLLOWING THE CZU LIGHTNING COMPLEX FIRE: QUANTIFYING HILLSLOPE EROSION AND PROVIDING GUIDANCE TOWARDS IMPROVING POST-FIRE RESPONSE

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| TITLE: | Post-Fire Erosion Following the CZU Lightning Complex Fire: Quantifying Hillslope Erosion and Providing Guidance Towards Improving Post-Fire Erosion Control Policy |
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# ABSTRACT

## Post-Fire Erosion Following the CZU Lightning Complex Fire: Quantifying Hillslope Erosion and Providing Guidance Towards Improving Post-Fire Erosion Control Policy

Matthew Crockett

The size and severity of wildfires have increased in California during recent decades. This trend is highlighted through the CZU Lightning Complex fire of August 2020 which burned over 86,000 acres in the Santa Cruz mountains of California. The fire greatly impacted the Little Creek watershed, a roughly 1,300-acre watershed that exists largely within Cal Poly San Luis Obispo's Swanton Pacific Ranch (SPR). The current trends of California's increased wildfire regime are expected to continue, raising concerns regarding the direct and secondary effects on forest watersheds and the effectiveness of current post-fire erosion control management. Accelerated rates of erosion following wildfire have been found to occur due to the loss of vegetation cover and changes in soil physical properties. We measured hillslope erosion from ten plots at SPR using a silt fence erosion trap approach to study regional post-fire erosion dynamics in the second winter following the CZU Lightning Complex fire. Slope steepness, percent soil cover, and percent canopy coverage were found to be significant factors driving changes in post-fire hillslope erosion in a multivariate model ($R^2$=0.88). Field-collected data from the erosion plots was used to inform spatial extrapolation of hillslope erosion and sediment delivery rates for the entire Little Creek watershed under different soil cover and precipitation scenarios using the Universal Soil Loss Equation (USLE). A watershed average hillslope erosion rate was found to be 4.23 tons/acre/year during the study period from October 2021-March 2022, a 53-fold increase when compared to pre-fire erosion rates and surpassing the watershed average soil loss tolerance factor. Annual sediment delivery to streams within the Little Creek watershed was quantified at 1.16 tons/acre from contributing hillslopes, a 58-fold increase from pre-fire sediment delivery. Using the information obtained from the results from this study, a review of scientific literature, and interviews with relevant stakeholders, we also identify current issues limiting the effectives of post-fire erosion control and provide recommended policy changes and best management practices to mitigate these problems. The results of this study provide valuable information and context regarding post-fire erosion dynamics in the Santa Cruz region and inform future managing decisions aimed mitigating accelerated rates of erosion following wildfire.

**Keywords:** Post-fire erosion, Hillslope erosion, Post-fire response policy, Universal Soil Loss Equation

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# Chapter 1

# INTRODUCTION

## 1.1 Statement of Problem

Wildfire severity, frequency, and scale have drastically increased over the past three decades in California, resulting in environmental degradation, property damage, and the loss of human life (Miller et al, 2020). The extent of the wildfire problem in California highlights an urgent need to better understand the severity of subsequent environmental impacts to inform and guide policy makers and land managers. One such post-fire impact, accelerated rates of soil erosion, is of large concern in California due to its capacity to threaten human infrastructure and damage ecosystems through reducing water quality and degrading soil health (Cui et al, 2018).

Variability in post-fire hillslope erosion has led researchers to search for patterns between landscape features and wildfire characteristics with intent of better predicting post-fire impacts at the regional level (Shakesby, 2011). However, limited data across a broad range of ecosystem types have limited our overall understanding post-fire soil erosion dynamics (Shakesby, 2011). Current research also focuses on analyzing the effectiveness of post-fire mitigation practices towards reducing soil erosion and downstream sedimentation (Cerda & Robbichaud, 2009). Yet, some argue that current post-fire erosion management is insufficient in adequately mitigating accelerated rates of erosion following wildfire.

## 1.2 Research Space

The CZU Lightning Complex Fire of August 2020 burned through 86,509 acres of coastal forest and rangeland north of Santa Cruz (Sannigrahi et al., 2020). Cal Poly’s 3,200-acre Swanton Pacific Range lies within the burned area and experienced significant losses to timber resources and infrastructure.  While the status of the ranch is perceived as shocking by those tied to it, a prime opportunity existed to study post-fire soil erosion in a region where this data has been previously limited. Local land managers and public agencies are greatly invested in understanding the magnitude and drivers and severity of soil erosion and downstream sedimentation following the CZU Lightning Complex Fire. In addition, these groups seek to understand how to best manage for accelerated rates of erosion following wildfire.

### 1.3 Project Overview

This study seeks to quantify post-fire hillslope soil erosion and stream sediment contributions within the Little Creek watershed at Cal Poly's Swanton Pacific Ranch during the second winter after the CZU Lightning Complex Fire of August 2020. We utilize a silt fence erosion trap approach to measure soil erosion from ten plots with varied physical and biological characteristics to better understand the dynamics between wildfire and soil erosion in this region of California. In addition, these erosion measurements are incorporated into a spatial model used to predict total erosion at the watershed level, allowing for a comparison between pre-fire and post-fire annual erosion and sediment yields. Using the results of this study, conducting interviews with stakeholders, and reviewing the literature, we also identify current problems related to post-fire erosion control and provide policy recommendations and best management practices in response to these issues.

The three objectives of this study were:

1. Develop a multivariate statistical model to identify the significant drivers of post-fire erosion in the context of our study area.
2. Use field-collected erosion data to calibrate the Universal Soil Loss Equation to spatially estimate erosion for the entire Little Creek watershed to compare changes in hillslope erosion and sediment delivery from pre-fire to post-fire conditions.
3. Inform post-fire response management decisions through identifying current problems and identifying feasible policy changes and best management practices.

## 1.4 Project Broader Impacts

The findings from this research will improve our understanding of post-fire hillslope erosion within the geographic context of coastal forests of California, while also informing how to effectively respond to and address post-fire impacts.

### 1.4.1 Advance Knowledge and Understanding

Post-fire soil erosion response is highly variable, episodic, and dependent on many combined processes (Moody et al, 2013). Our analysis will identify the leading drivers of post-fire erosion, allowing for highly erosive areas to be identified following wildfires.  Further, this study will contribute valuable data to inform post-fire soil erosion knowledge within the geographic area of the California coastal range, a region where this research is insufficient (Shakesby, 2011).

The silt fence approach used in this study to quantify post-fire erosion highlights this method as an affordable and effective approach.  The methods of this study can be replicated by others across a broad range of ecosystems to better understand the geographic variability of post-fire erosion. The field methods employed in this research can be undertaken by groups lacking substantial funding, reducing barriers to entry for studying post-fire soil erosion and increasing data related to this topic.

This study also advances our ability to integrate field data into the Universal Soil Loss Equation to estimate erosion at a watershed scale. The scenario analysis used within the spatial model allows for post-fire erosion to be quantified in the context of varying environmental parameters, advancing our ability to predict post-fire impacts across landscape changes.

### 1.4.2 Improving Management

With wildfire impacts increasing in scale and severity, the findings of this study will be useful towards informing future responses and estimations of post-fire erosion in coastal forests of California. Our research will inform local policy makers and land managers of how erosion two years after a wildfire compares to pre-fire conditions, providing essential context and guidance during post-fire management practices if they are conducted. Land managers currently experience little guidance for how to reasonably mitigate post-fire erosion impacts (Chen et al., 2013). Our findings will provide reasoning, or lack thereof for continuing erosion mitigation two years post-fire. In addition, our findings can be used to guide post-fire forest practices in a manner that reduces soil erosion impacts. The factors leading to accelerated erosion can be managed for when conducting common practices such as salvage logging and hazardous fuels reduction.  Further, problems facing post-fire response as identified through literature review and interviews with stakeholders and the resulting policy recommendations will inform how to improve post-fire erosion control.

## Chapter 2

## LITERATURE REVIEW

In this chapter, we present the relevant information pertaining to post-fire soil erosion and management. We begin with an overview of the current wildfire problem in California and its outlook. The dynamic between wildfire and hillslope erosion is explained in addition to the associated environmental impacts. We provide an overview of the current state of post-fire erosion research, while also highlighting the current research issues within the field. Finally, we synthesize the barriers preventing effective post-fire soil response. Through covering these relevant topics, we identify a knowledge gap pertaining to the understanding of post-fire soil erosion at the regional level of our study. In addition, we identify key issues that limit greater effectiveness of post-fire policy and wildfire erosion risk assessment.

### 2.1 California’s Wildfire Regime: Current Status and Predictions

Wildfire is a critical component for many ecosystems throughout California. The state’s Mediterranean climate involves warm and dry summers where fuels are highly receptive to fire (Miller et al., 2012). These climatic conditions have facilitated fire adaptation in areas of the state with historically short fire frequency intervals. Historic frequent low intensity fire, either natural or from indigenous burning, reduced forest fuel loads and fostered moderate density, healthy forest stands. Further, frequent low severity fire occurrence facilitated forest regeneration in species which require fire to instigate seed dispersal and germination (Kimmerer and Lake., 2001). While wildfire’s presence within the California landscape was maintained through natural events and indigenous burning practices, California's wildfire regime been altered severely in the past century (Lorimer et al., 2009). A long history of successful fire suppression, the absence of indigenous burning, and certain forest management practices have limited the ability for wildfire to perform essential ecosystem services (Syphard et al., 2007). Instead, we now observe a substantial increase in the size and severity of wildfire events in California (Westerling et al., 2011). While historical wildland fire and forest management are large contributors to the current wildfire problem in the state, the effects of a changing climate and its effect on wildfire characteristics must also be emphasized (Williams et al., 2019). Prolonged periods of drought, warmer and drier summers, and longer fire seasons have heightened the risk of severe fire throughout California (Steel et al., 2015). Fifteen of the twenty largest wildfires in the state's history have occurred since 2000, and six of the twenty largest fires in state history occurred in 2020 (Kane, 2019). The past few years alone have experienced unprecedented wildfire behavior. The Dixie fire burned 963,310 acres, an area larger than the entire state of Rhode Island, in the summer of 2021, burning the majority of the structures in the town of Greenville, California (Weber and Berger, 2020). California's most deadly fire, the Camp fire, left 85 people dead after decimating the town of Paradise (Brewer and Clements, 2020). In Santa Cruz California, the CZU Lightning Complex of 2020 burned an unprecedented acreage of costal redwood forests (Choy, 2021). Unfortunately, the current state of wildfire in California is expected to continue, if not intensify in coming years (Westerling et al., 2011). While the direct impacts of large and severe wildfires are substantial and are experienced at many levels, the acceleration and increased magnitude of the state's wildfire regime mandates a reevaluation of post-fire impacts and response.

### 2.2 Wildfire's Influence on Erosion and Sedimentation

Wildfire's impacts to soil are far reaching, and in some locations, it is considered the single most important cause of geomorphological change (Shakesby and Doerr, 2006). While low severity burning can aid in beneficial nutrient cycling and even enhance soil organic properties, higher burn temperatures can result in negative impacts to forest soils (Boerner, 1982; Vieira et al., 2015). Wildfire has been found to cause increased rates of soil erosion and downstream sedimentation due to a loss of cover, hydrophobic soil conditions, and a lack of precipitation interception from the forest canopy (Ice et al., 2004; Debano, 2000). Soil erosion occurs via a two-step process. First, soil particles must be detached from the soil surface. Detachment drivers are rain splash, overland flow, or wind. Second, these detached particles must be transported away from their source, most commonly travelling downslope by overland flow (Scott et al., 2009). Wildfires have direct impacts on these processes as they cause conditions which increase both soil detachment and transport.

Previous studies highlight the removal of vegetation cover following wildfire as among the main drivers of increased soil erosion (Shakesby, 2011). During high intensity wildfires, complete combustion of soil protective vegetation litter can occur. This increases the amount of rain splash detachment and correlates to greater chances for overland flow to occur (Cerda and Doerr, 2008). Detachment can be further exacerbated by reductions in soil structure due to the degradation of organic cements (Mataix-Solera et al., 2011). Overland flow following wildfires is often in response to changes in soil water infiltration capacity. Soil infiltration capacity is mostly driven by physical changes in soil properties (Cerda and Robichaud., 2009). While chemical and biological changes such as increased soil pH, nutrient volatilization, and sterilization of soil biomass occur after severe wildfires, these changes are believed to be insignificant towards increasing post-fire soil erosion (Hohner et al., 2019; Smith et al., 2008; Murphy et al., 2006).

The absence of protective vegetation and tree canopy coverage has been found to increase the rate that water reaches the soil surface, leading to increased overland flow velocities due to minimal physical obstruction from vegetation (Beeson et al., 2001). While ash has been found to increase infiltration capacity, its presence on the soil surface is short-lived (Bodi et al., 2014). Combustion of surface vegetation and soil heating also increase soil water evaporation following wildfire. This leads to soil compaction and higher bulk density which decreases soil porosity and prevents infiltration (Verma and Jayakumar, 2012). These hydrophobic soil conditions have been found to reduce soil hydraulic conductivity by 40% (Robichaud, 2000). This water repellant soil layer rarely exceeds 6-8 cm in depth, and the duration of its persistence is variable but short-lived (Chen et al., 2020). Huffman et al, 2001 noted a weakening of the hydrophobic layer three months after a fire, and Henderson and Golding found no evidence after two years (Huffman et al., 200, Henderson & Golding, 1983). While hydrophobic soil conditions and the absence of soil vegetation cover are both contributors to increased rates of soil erosion, the latter is most often more detrimental. Shakesby et al., (1993) found soil losses to be two orders of magnitude greater in stands burned 0-2 years before compared to those burned 3-4 years prior (Shakesby et al., 1993).

Increased rates of stream sedimentation have been found to occur in response to higher rates of soil erosion in watersheds directly impacted, or downslope of wildfires (Shakesby and Doerr, 2006). Transported soil material can be transported at greater rates to watercourses and alter stream characteristics including physical habitat and turbidity (Rhoades et al., 2011; Gresswell, 1999). Sediment deposition following a wildfire has been found to be three times greater than that in unburned forests (Wagenbrenner & Robichaud, 2013). The sediment delivery ratio increases following a wildfire, as the removal of vegetation limits the capacity for sediment to be deposited within the hillslope. However, there lacks a uniform sediment delivery ratio across location, spatial scales, and ecosystem types (Walling, 1983). While sediment delivery ratios following a wildfire are troublesome to estimate, the impacts of increased sediment deposition can be extreme. The Buffalo Creek fire in Colorado caused the closure of a major water treatment plant and required substantial cleanup efforts of a water supply reservoir due to high sediment loads (Ice et al., 2004; MacDonald and Larsen, 2009). In Oregon, post-fire mitigation practices captured roughly 140 $m^3$/ha of sediment within the impacted area of the Bridge Creek fire (Robichaud et al., 2008). Increased rates of soil erosion and downstream sedimentation can lead to negative environmental impacts across ecosystem components.

## 2.3 Issues Arising from Post-Fire Erosion

The issues stemming from post-fire erosion have the capacity to impact the environment, human life, and property. We provide an overview of these impacts highlighting particular areas of concern for both society and ecosystem health.

### 2.3.1 Water Quality and Supply

Federal forests in California supply 65% of the state's water (Brown et al., 2008). Forests aid in both the quantity and quality of fresh water, while also substantially lowering water treatment costs (Ernst et al., 2004). Forest soils act as a natural filter removing pollutants as water travels into groundwater aquifers or streams (Blum, 2005). In addition, forest soils also regulate the supply of fresh water by storing water and slowing the delivery of water into streams (Neary et al., 2009). Worsened water quality and fresh water supply issues have been found to occur across the western United States following wildfires. Eroded soil which is deposited in streams can alter the physical and chemical makeup of stream waters (Hohner et al., 2019; Smith et al., 2008; Murphy et al., 2006; Cerda and Robichaud, 2009). Increased sediment loads in watercourses cause significant issues for water managers and suppliers. Large sediment deposits fill water-supply reservoirs limiting their water storage capacity and increasing maintenance costs (Randle et al., 2017). These decreases in water storage capacity are especially concerning in California given current drought conditions and an already limited surface water supply (Mann and Gleick, 2015). In addition, wildfires can severely alter the timing of snowmelt and storm water runoff (Bladon et al., 2014). This phenomenon can overwhelm and limit the trap effectiveness of water-supply reservoirs, reducing annual water storage. Post-fire erosion is also found to alter the chemical makeup of streams. Eroded soils increase nutrient concentrations in streams and upsurge the concentration of heavy metals and major ions (Randle et al., 2017). While these physical and chemical changes in water quality increase water treatment costs and threaten municipal fresh water supplies, they also cause concern regarding the health of sensitive aquatic species (Rieman and Clayton, 1997).

### 2.3.2 Risks to Sensitive Aquatic Species

While minimally severe wildfires can be beneficial to aquatic ecosystems through the deposit of woody debris and the formation of new habitats via morphological stream changes, severe wildfires, and correlating downstream sediment deposition present challenges to sensitive aquatic species (California Department of Fish and Wildlife, 2014). Risks to sensitive species can be described by two processes, the first being physical and chemical changes that directly impact species, and second, through habitat alterations that change the physical structure of stream habitats (Rhoades et al., 2017). Coho salmon (*Oncorhynchus kitsutch*) are a noteworthy example of an aquatic species that may be adversely impacted by post-fire soil erosion in the context of this project’s study area. San Vincente creek in Santa Cruz County once harbored robust populations of spawning Coho salmon. However, numbers have been nearly reduced to zero in recent decades (Kogan, 2018). The neighboring Scotts creek has been identified as the most important fisheries system within the Santa Cruz region given its minimally impacted physical and biological conditions and its harboring of both Coho and Steelhead salmon (Dietterick, 2019). While restorative measures are underway and the future of Coho salmon in Santa Cruz is hopeful, secondary impacts from wildfires threaten the rebound of these sensitive species. Coho salmon are sensitive to water pollutants, which are likely to leach from post-fire soils and be deposited in streams (Chapman and Stevens, 1978). Further, elevated rates of stream sedimentation, particularly in the form of fine sediment, can smother and kill salmon eggs, while also filling in critical pool habitats juveniles need for survival (Cordone and Kelley, 1961; Wood and Armitage, 1997). While the long-term impacts to aquatic species are dynamic and complex, accelerated rates of sediment deposition are likely to prevent the short-term success of sensitive species through reducing the likelihood of colonization and establishment.

### 2.3.3 Post-Fire Erosion Hazards

Alterations in erosive and hydrologic processes following severe wildfires have the capacity to lead to hazardous events such as debris flows. Debris flows resemble fast moving landslides that occur without warning and pose threats to human safety (Cannon and DeGraff, 2009). Rapid rates of soil erosion following substantial and high intensity rain events in areas recently impacted by wildfire are often the leading cause of debris flows (Cannon et al., 2011) Debris flows often occur following the first large storm since a wildfire, however, they have been also found to occur in the second year post-fire (Cannon and DeGraff, 2009). During these events, elevated levels of eroded soil, rocks, and organic material funnel into stream channels where they are rapidly transported downstream (Wall et al, 2020). To understand the hazardous potential of debris flows, one can look to the Southern California debris flows of 2018. This event led to the death of twenty-three people in Montecito, CA, and occurred after 0.54 inches of precipitation fell in five minutes within the burn scar of the recent Thomas fire (Weather

Underground, 2018). These considerable threats to human health due to accelerated soil erosion following wildfires highlight the urgent need to research the drivers of these hazardous events.

## 2.4 Current Status of Post-Fire Erosion and Sedimentation Research

The current state of wildfire size and severity has influenced researchers throughout various parts of the world to study how soil erosion and downstream sedimentation is influenced by wildfire. Most of this work is geographically centered in three regions including the western United States, Mediterranean region of Europe, and Australia (Shakesby, 2011). This geographic variability in post-fire research increases the diversity of wildfire behavior and environmental characteristics such as soil type, forest structure and composition, and climate. We examine the status of post-fire soil erosion research through analyses of different measurement techniques, the variability in erosion response following wildfire, and finally, highlight the current issues preventing further understanding and an effective post-fire response.

### 2.4.1 Measuring Post-Fire Soil Erosion

Accurate and repeatable measurements of post-fire soil erosion and sedimentation are crucial for understanding post-fire environmental impacts and informing management responses. Measuring soil erosion often takes two forms: field measurements and computer modelling. Each method has its unique appeals and drawbacks relating to accuracy, efficiency, and affordability.

#### 2.4.1.1 Field Methods

A review of the literature relating to post-fire soil erosion highlights two main methods for collecting field data including silt fence traps and sediment storage tanks (eg., Robichuad, 2005; Spigel and Robichaud, 2007; Marques and Mora, 1998; Prats et al., 2016). Both methods utilize plot designs which seek to isolate erosion measurements to a defined area. The silt fence method utilizes geotextile fabric to capture eroded soil and sediment for measurement. This silt fence is curved upslope to provide maximum catchment. Straw log barriers are placed on the upslope margin of the plot to confine erosion to the plot area. Following rain events, trapped sediment is removed from the silt fence and dried and weighed to gauge erosion totals (Robichaud, 2002). Research into the trap effectiveness of silt fences found that this method retained 93% of eroded soil during the first year after fire on a storm-by-storm basis, and 92% at the end of second year following wildfire (Robichaud et al., 2001). This method is affordable and relatively simple to implement (Robichaud, 2002).

Select post-fire studies use a gutter and storage tank methodology for quantifying soil erosion (Marques and Mora, 1998; Prats et al., 2016). Study plots capture runoff and eroded soils in large, sealed storage tanks which receive inputs via a long open drain-gutter at the most downslope portion of the plot. Eroded soil and sediment are removed from the tanks and dried and weighed. This methodology is argued to better withstand significant erosion events due to sturdiness of the storage tanks as compared to the silt fence material (Prats et al., 2016). It is argued that this approach is less effective in trapping eroded material from the study plot compared to the silt fence approach (Marques and Mora, 1998). Therefore, this methodology is best suited for comparison studies which examine the effectiveness of different post fire treatments or land uses, rather than for gathering baseline data.

#### 2.4.1.2 Spatial Modeling

Spatial modeling is also used to predict post-fire soil erosion. The three most common models are the Revised Universal Soil Loss Equation (RUSLE), Disturbed WEPP (Water Erosion Prediction Project) (Larsen and MacDonald, 2007,) and the Erosion Risk Management Tool (EMRiT). The USLE model was originally used for predicting erosion from agricultural fields. This model utilizes six variables including the rainfall-runoff erosivity factor, the soil erodibility factor, slope length factor, slope steepness factor, cover management factor, and the support practice factor. Particle detachment, sediment transport, infiltration, and overland flow are represented through these six variables (Ghosal and Bhattacharya, 2020). This model is most commonly used at the hillslope level (Renard and Ferreira, 1993).

The Disturbed WEPP is an internet-based soil erosion predictive model that succeeds the physical WEPP model.  The WEPP model uses stochastically generated daily weather data to inform models of water infiltration, evapotranspiration, plant growth, plant decomposition, and the detachment, transport, and deposition of soil particles (Elliot et al, 2000). Predictions of peak rainfall intensity and duration are paired with soil erodibility to determine the amount of rill detachment and corresponding soil and sediment transport. Mean annual sediment yield is calculated by summing daily totals and dividing by the simulation period (Elliot, 2004). While the previous WEPP model requires 400 input variables, the Disturbed WEPP model only requires seven including climate station selection, slope length, slope steepness, soil texture, percent rock fragments in the soil, percent surface cover, and the specification of one of eight land use and land cover types (Elliot, 2004).

The Erosion Risk Management Tool (ERMit) is a web-based model that integrates WEPP to predict probabilistic sediment delivery from hillslopes. ERMiT provides precipitation event sediment delivery from inputs including regional climate data, soil burn severity, soil texture, and hillslope characteristics. Storm-level hillslope sediment deliveries are produced from one to five years post-fire. ERMiT also allows produces sediment delivery estimates following mitigation measures including seeding, mulching, and erosion barriers (Robichaud et al., 2007).

While predictive soil erosion models are commonly utilized by land managers to predict the significance of post-fire soil erosion, their accuracy remains debated. In a study by Larsen &

MacDonald, predictions via the Disturbed WEPP and RUSLE models were compared to hand collected field data. They found that the R-squared value for the RUSLE model for grouped hillslopes was 0.56, and 0.59 for the Disturbed WEPP model suggesting only moderate prediction of soil erosion variability (Larsen and MacDonald, 2007). These discrepancies raise concern regarding the predictive effectiveness of these models, which could have implications for the future of post-fire response policy. These discrepancies between actual and predicted erosion levels highlights the need to better calibrate spatially driven erosion models. Utilizing field-collected data and parameters may be essential for improving the accuracy of commonly used models.

### 2.4.2 Variability in Post-Fire Soil Erosion

A survey of the literature related to post-fire soil erosion research highlights great diversity and variability in erosion responses following wildfire. Erosion dynamics following wildfire seem to vary case by case, and it is argued that a 'one-size fits all' approach to predicting post-fire response is insufficient and fails to address the array of unique details present in different regions impacted by wildfire (Shakesby, 2011). To highlight the variability in post-fire erosion, we present multiple studies which seek to understand the drivers of accelerated erosion.

#### 2.4.2.1 Variability Relating to Burn Severity

Wildfire behavior, especially burn severity, is believed to greatly influence the significance of post-fire erosion (Vieira et al., 2015). Classifications of burn severity are non-uniform and are variable across agencies and scientific studies. The USFS classifies soil burn severity as either high, moderate, or low. According to this classification method, soils which have experienced high burn severity are absent of vegetation cover, are covered by ash, and often undergo structural changes (Parsons, 2003). High burn severity is argued to facilitate high levels of soil erosion due to the complete combustion of organic binding agents, while also increasing the likelihood for a hydrophobic soil layer to develop. In addition, complete soil exposure is more likely following severe wildfires due to the loss of vegetation cover. Moderately burned soils are those which have roughly 20% of vegetation cover remaining and topsoil layers intact. Low burn severity soils have recognizable litter layers that have not been consumed, and surface roots are generally unburned (Parsons, 2003).

A correlation between burn severity and soil erosion at the hillslope scale during the first year after a wildfire was measured in NW Spain (Vega et al., 2015). Soil burn severity was estimated via an operational classification system based on visual indicators and was highest in study plots where the soil organic layer was completely consumed and alterations in soil structure existed less than 1cm deep. In their meta-analysis of rainfall simulation experiments which compared burnt and unburnt conditions, Vierra et al. (2015) sought to understand how soil burn severity effects post-fire runoff and interrill erosion rates. While burn severity was found to influence levels of erosion, it was not fount to influence rates of overland flow. Although burn severity is argued by many to be the leading cause of accelerated post-fire soil erosion, it may be lacking in its ability to explain intricacies of post-fire hydrologic responses (Lopez et al., 2021).

#### 2.4.2.2 Variability Relating to Changes in Precipitation

Because precipitation is the major driver of soil erosion, storm characteristics following wildfires influence the scope and significance of post-fire soil erosion and downstream sedimentation (Kampf et al., 2016). Soil erosion risks are highest during high intensity rainfall shortly after wildfire (Scott et al., 2009). This is particularly consistent with regions resembling a Mediterranean climate such as California, as fire occurrence often occurs in late summer just prior to high intensity autumn rainfall (Wittenberg, 2021). First, vegetation regrowth is unlikely to be present shortly after wildfires, reducing soil cover completely in severe wildfires (Cerda and Doerr, 2005). Second, high intensity rainfall often exceeds the infiltration capacity of the soil resulting in a rapid occurrence of overland flow, leading to high rates of soil detachment and transport (Scott et al., 2009). In their study comparing the effects of two different storms on hillslope sediment production, Wilson et al. (2020) found a low intensity and long duration storm to produced lower hillslope sediment yields than a high intensity and short duration storm.

#### 2.4.2.3 Variability Relating to Topography

In addition to storm characteristics, topographical characteristics such as slope steepness influence post-fire impacts to soil erosion. Steep slopes are likely to experience greater rates of soil erosion following wildfires (Pereira, 2018). Overland flow occurs at higher velocities, increasing channeling and soil detachment. Detachment is further exacerbated on steep soils due shallow soils with poor stability (Sidle et al., 2006). Stability concerns are further heightened on slopes that experience high intensity wildfire, as plant roots that contribute to soil structure are combusted. These soils are more likely to experience hazardous mass movements. The aspect of the hillslope may also influence hillslope erosion. Long term soil impacts to steep slopes are most likely with a south facing aspect. South facing slopes are much drier, and experience slower rates of vegetation recovery, limiting the capacity for soil cover and structure to develop (del Pino and Ruiz-Gallardo, 2015).

#### 2.4.2.4 Variability Relating to Forest Practices

Post-fire forest activities are also studied to understand their impact on soil erosion (e.g., Wagenbrenner et al., 2016; Cole et al., 2020; Marques and Mora, 2009; Silins et al., 2009). Post-fire salvage logging occurs in regions with valuable timber (Fernandez and Vega, 2016). In

California, salvage logging occurs on both private and federal lands and contributes to a large portion of the state's total timber production annually. Salvage logging and the use of heavy equipment is believed to compact soils, increasing the bulk density and lowering soil infiltration capacity leading to accelerated overland flow and soil erosion (Prats et al., 2019). Higher rates of overland flow and hillslope erosion have been found to occur in some cases. In fact, Wagenbrenner et al. (2016) found rill erosion to be 190% greater on occasion in logged areas versus unlogged control plots. However, higher rates of soil erosion are not always found in response to post-fire logging. In their comparison between clear-cut forests and forests with non-intervention, Marques and Mora (1998) found no significant differences between the two regarding soil erosion. Similar findings were observed in a study performed by Fernandez and Vega (2016). Following the Valley fire in northern California, hillslope sediment production was found to be greater in areas where salvage logging did not occur (Cole et al., 2020). While the impact of salvage logging on soil erosion seems to vary, covering soil with logging slash has been shown to reduce overland flow and soil erosion in logged areas (Prats et al., 2019).

## 2.5 Research Issues

Post-fire soil erosion response is highly variable, episodic, and dependent on many combined processes (Moody et al, 2013). These attributes have created certain research issues that hinder our ability to link wildfire characteristics, environmental conditions, and different land uses to their impacts in hillslope soil erosion. We highlight three problem areas in post-fire research that are most relevant to the goals of this project and the study site location.

### 2.5.1 Lack of Synthesis

Post-fire soil erosion has been studied for 80 years in the United States, and then later in other regions of the world (Shakesby, 2011). Therefore, the opportunity exists to synthesize this data as to better understand post-fire soil response and the processes influencing its significance. However, this synthesis is currently lacking. Measuring the similarities and differences in post-fire soil response from across regions and ecosystem types is needed to synthesize the significant factors driving accelerated soil erosion following wildfires (Moody et al., 2013; Chen et al., 2013).

### 2.5.2 Variability in Study Methods

Studies relating to post-fire soil erosion and sediment production utilize various methods and definitions, preventing a standardized approach (Parsons, 2003).  As mentioned earlier, measuring post-erosion in the field is conducted in two main ways. The same is true for computer modelling methods which utilize different predicting variables and equations to predict soil erosion impacts and hazards (Larsen and MacDonald, 2007; Renard and Ferreira, 1993; Elliot et al., 2000).  Standardizing post-fire assessment methods would remove potential discrepancies between methods and better serve policy makers.

### 2.5.3 Competing Definitions

Different definitions are also used when measuring post-fire erosion, most notably burn severity. Burn severity is classified using both different methods, including aerial imagery, vegetation combustion, or physical characteristics (Rogan and Franklin, 2001; Miller and Thode, 2007; Cocke et al., 2005; Shin et al., 2019; Parks et al., 2014). Variability in the way fire severity is classified poses issues when comparing scientific studies where different classification metrics were used.  Standardizing burn severity classification would increase uniformity when predicating post-fire erosion post-fire impacts.

### 2.5.4 Geographic Limitations

While post-fire soil impacts are studied throughout different regions of the world, data remains geographically limited (Shakesby, 2011) While post-fire erosion data is abundant in the Mediterranean region of Europe, Australia, and portions of the western United States, our understanding of post-fire impacts remains limited in certain ecosystems, notably, the coastal forests of Northern California. A review of scientific literature highlighted that this region is significantly understudied.  Strong variability exists in regards to ecosystem response following wildfire. While vegetation regrowth, an important factor for controlling post-fire erosion, may be quite slow in high altitude or arid ecosystems, vegetative response may occur much quicker in ecosystems with wetter climates (Bright et al, 2019). While the drivers and severity of post-fire erosion vary across location and ecosystem types, the extent and duration of post-fire erosion is likely differ across ecosystem types.

## 2.6 Conclusion

The current state of post-fire erosion research involves studying both the drivers influencing the severity of soil erosion, predicting and modeling post-fire soil impacts, and seeks to understand the effectiveness of mitigation strategies. The scientific literature suggests great variability in soil impacts arising from differing land management practices and environmental characteristics such as soil burn severity, soil type, topography, and others. While wildfire’s impact on soil erosion varies from case to case, consistent factors that can be used to predict post-fire soil impacts are lacking due to insufficient data and monitoring.  In addition, post-fire erosion data is limited in many ecosystem types including the coastal forests of Northern California.  These issues and gaps in knowledge relating to post-fire soil erosion and management highlight current research needs in the field and act as a guide for the goals of this study.  We seek to better understand post-fire soil erosion from hillslopes within the geographical context of the California Coastal range.  Through a standardized approach, we measure post-fire hillslopes erosion rates following the CZU Lightning Complex fire in the Santa Cruz mountains and identify the significant factors which influence the amount of soil eroded annually from burned hillslopes. Further, we employ a predictive model calibrated with field collected post-fire erosion rate inputs to spatially predict post-fire hillslope erosion and sediment delivery at the watershed scale. We use these finding to depict spatial post-fire erosion variability and to quantify the watershed average post-fire hillslope erosion and sediment delivery rates. Our results provide interested stakeholders with essential context regarding the drivers and severity of post-fire erosion in the region to promote scientifically guided post-fire management.

Chapter 3

# METHODS

## 3.1 Site Description

### 3.1.1 Location

This study was conducted at Swanton Pacific Ranch (SPR), a 3,200-acre property owned and managed by California Polytechnic State University San Luis Obispo (Figure 1). SPR is located roughly fifteen miles north of Santa Cruz adjacent to Swanton, California. The property was donated to Cal Poly in 1993 by the late Al Smith who intended "…the ranch be maintained as a working ranch and used exclusively for agriculture, recreational, and educational purposes ." Swanton Pacific Ranch is mixed use and includes rangelands, agricultural fields, and forestlands (Cal Poly San Luis Obispo, n.d.). Current uses of the ranch include forest management, grass-fed beef production, crop production, and education. SPR is also a center for research on environmental and agricultural resources.

The specific location of the research site exists just south of Little Creek within Schoolhouse Gulch adjacent to Old Schoolhouse Gulch Road (37.064, -122.223). The roughly 11-acre study area exists within the Little Creek watershed, a 1,305-acre watershed within the greater Scotts Creek Watershed.

### 3.1.2 Wildfire Impacts at Study Site

The CZU Lightning Complex Fire began on August 16th, 2020 after a large thunderstorm led to over 11,000 dry lightning strikes within the Santa Cruz peninsula (Mountain Parks Foundation, 2020). The fire was classified as a complex fire when the Warnella fire, Waddell fire, and other small fires combined and rapidly grew in size. The CZU Lightning Complex burned roughly 86,000 acres, driven by winds as high as 74 mph on ridgetops and heavy fuels exacerbated by decades of fire suppression (Santa Cruz Museum of Natural History, 2022). The fire destroyed 1,049 structures and led to the death of one individual (California Department of Forestry and Fire Protection, 2020).  Recreational areas including Big Basin Redwoods and Butano State Parks were highly impacted by this fire, experiencing immense losses to infrastructure and forest resources (Mountain Parks Foundation, 2020). The intensity of this wildfire is further seen through the large proportion, 43% of the burn area, designated with moderate or high burn severity (Watershed Emergency Repsonse Team, 2020). The size and severity of the CZU Lightning Complex was unprecedented within the region. Previous fires in the region include the Lockheed fire which burned roughly 8,000 acres in 2009 and parts of the Little Creek watershed, and the Summit fire of 2008 which burned 4,500 acres (Niebrugge, 2012; Potter, 2016).

The CZU Lightning Complex fire impacted the majority of Swanton Pacific Ranch (Figure 1). Highest severity fire impacts are seen atop higher elevation ridges where fire behavior was most intense, while riparian corridors experienced significantly less mortality. Multiple structures were lost in addition to loss of SPR’s timber resources.   While Swanton Pacific Ranch managers are currently planning for rebuilding and post-fire forest treatments, a prime opportunity exists was created for researchers to study post-fire impacts.

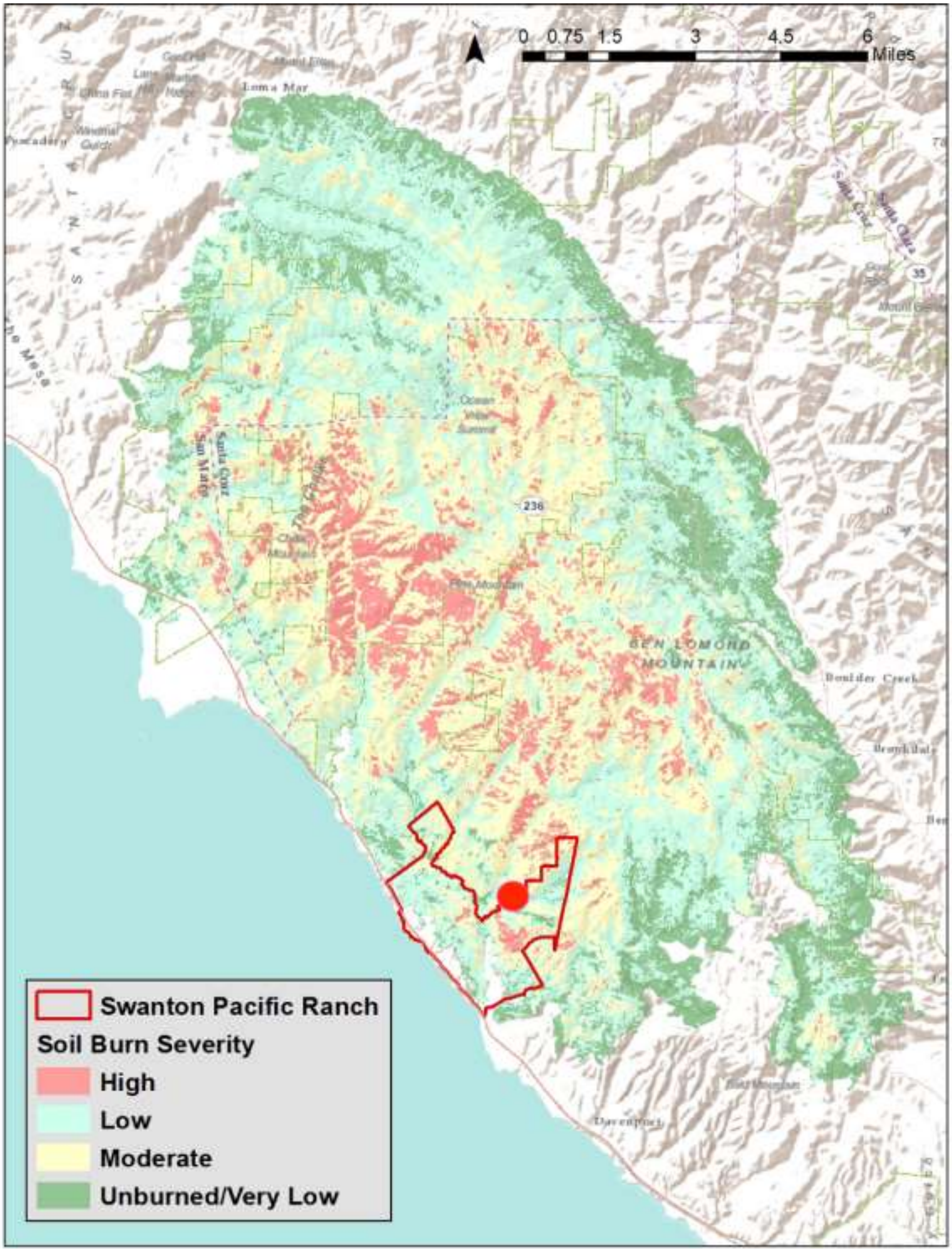


*Figure 1 Soil burn severity map from CZU Lightning Complex fire of 2020 with study site location shown as the red dot (WERT, 2020). Burn severity designations are classified using the normalized burn severity approach (dNBR).*

### 3.1.3 Slope and Geology

Slopes are highly variable in the Little Creek watershed ranging from 0-50 degrees. Steepest slopes within the study site peak at 38 degrees, with the majority of hillslopes ranging from 12-18 degrees (Figure 2).

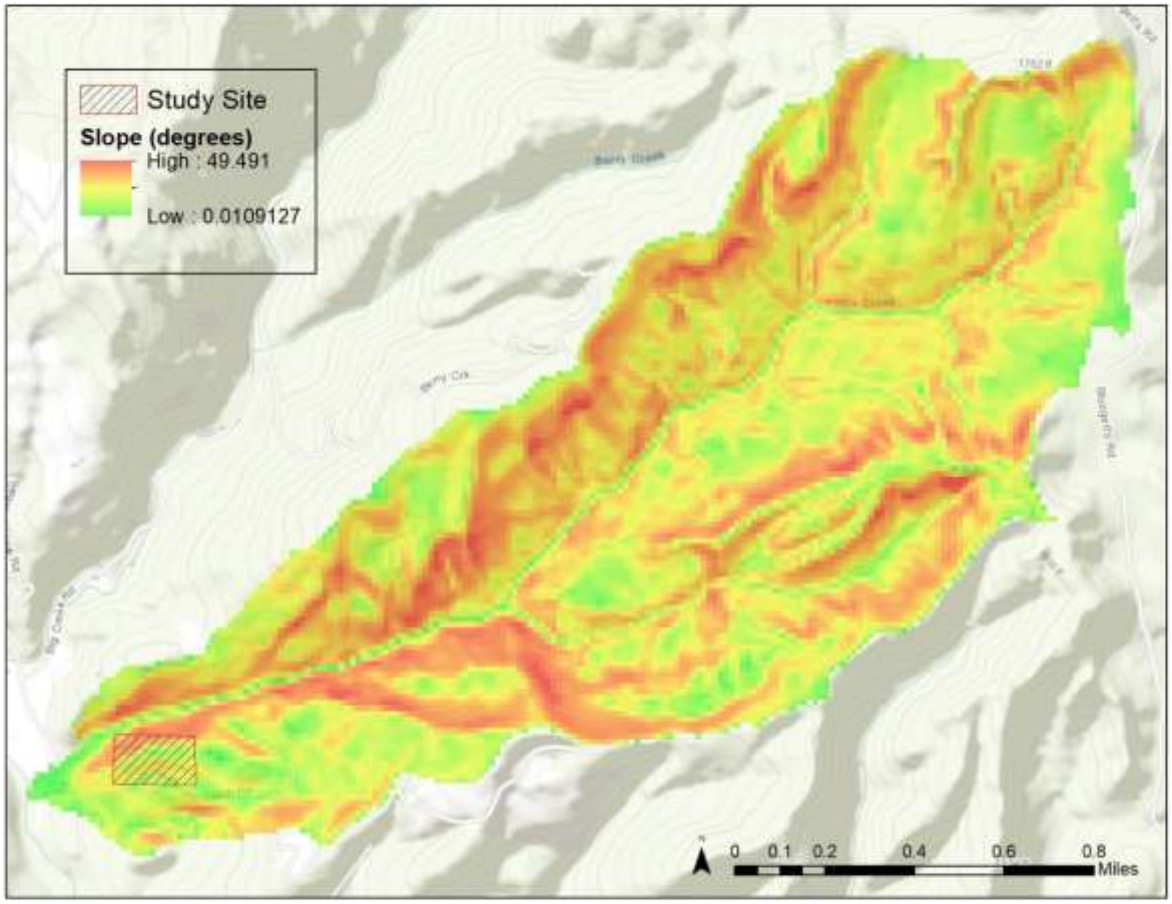


*Figure 2. Slopes of Little creek map derived from 20 meter Digital Elevation Model (DEM).*

The Little Creek watershed lays within the Coast Ranges geologic province. Granitic and metamorphic basement bedrock is overlaid with marine sedimentary rocks. Surface geology in the watershed includes Santa Cruz Mudstone, Santa Margarita Sandstone, quartz diorite, and metasedimentary rocks (Figure 3).

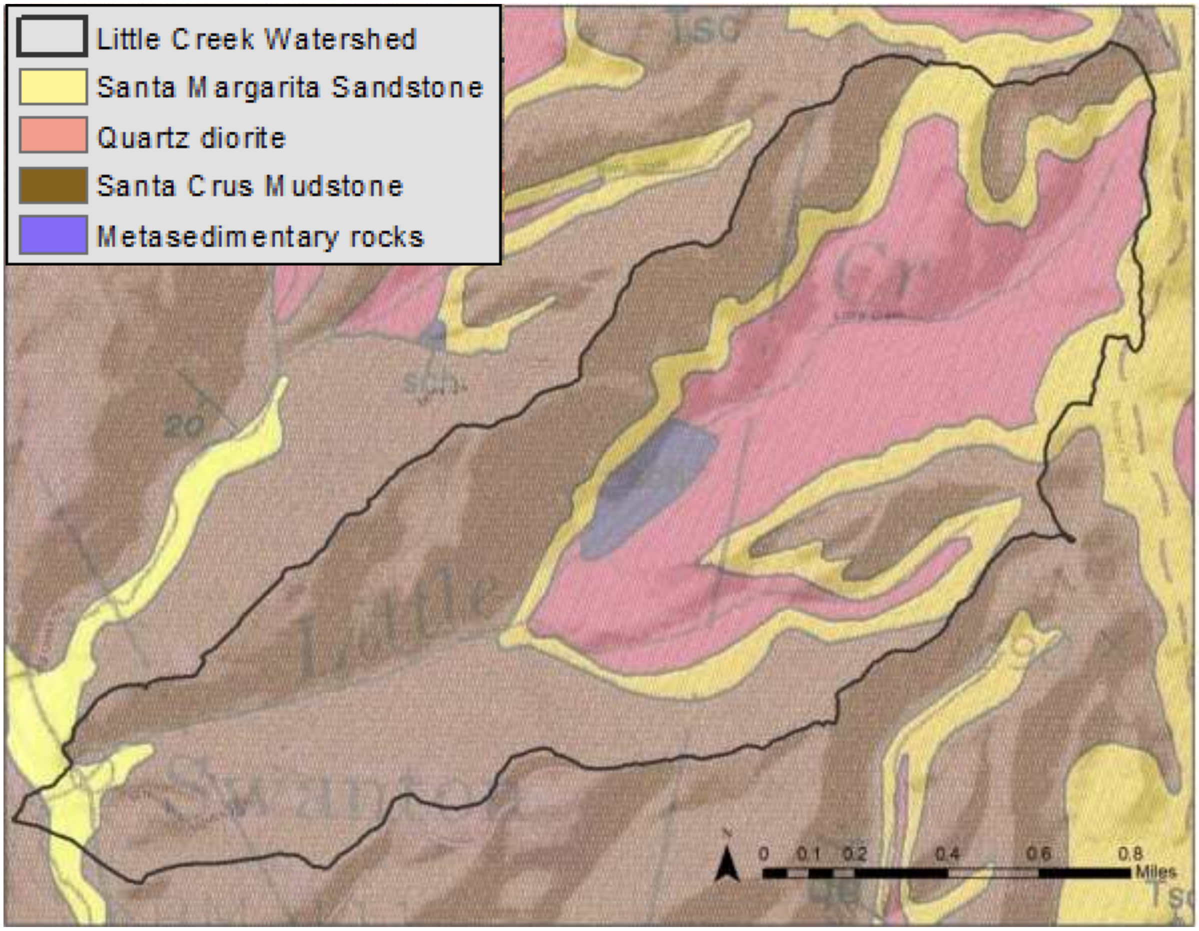


*Figure 3. Geologic map of Little Creek watershed (Brabb, 1977)*

### 3.1.4 Climate

The climate resembles a Mediterranean climate with coastal influence leading to cool, wet winters and cool, foggy, and dry summers. Annual temperatures generally range from 45-75 degrees Fahrenheit.  Mean annual precipitation is roughly 122 cm (48 inches), the majority of which falling between the months of November and April (PRISM Climate Group, 2011). The majority of precipitation falls as rain, seldom snow.

### 3.1.5 Vegetation

The Little creek watershed includes a variety of vegetative communities including coastal redwood forest, mixed conifer forests, chaparral, coastal oak woodlands, and grasslands. The study site within the watershed features mixed coastal forest with dominant species including Monterey pine, Douglas fir, Coastal redwood, Tan oak, and Coast live oak (Figure 4). Understory species include California blackberry, Poison oak, and Ceanothus. Revegetation of understory species is dominated by California blackberry and Ceanothus.

*Figure 4. Photograph of study area taken October 2nd 2021*

### 3.1.6 Soils

The study area encompasses two main soil types including Ben Lomond-Catelli-Sur Complex and Santa Lucia shaly clay loam. The greater Little creek watershed features eight soil types (Figure 5). Ben Lomond soils are the most common soils within the watershed area, are classified as well drained with moderately rapid permeability decreasing their susceptibility to erosion (Table 1). These soils are formed from weathered sandstone or granitic rocks, and possess greater than 1% organic matter. A full description of all soils present within the watershed can be found through the USDA National Cooperative Soil Survey.

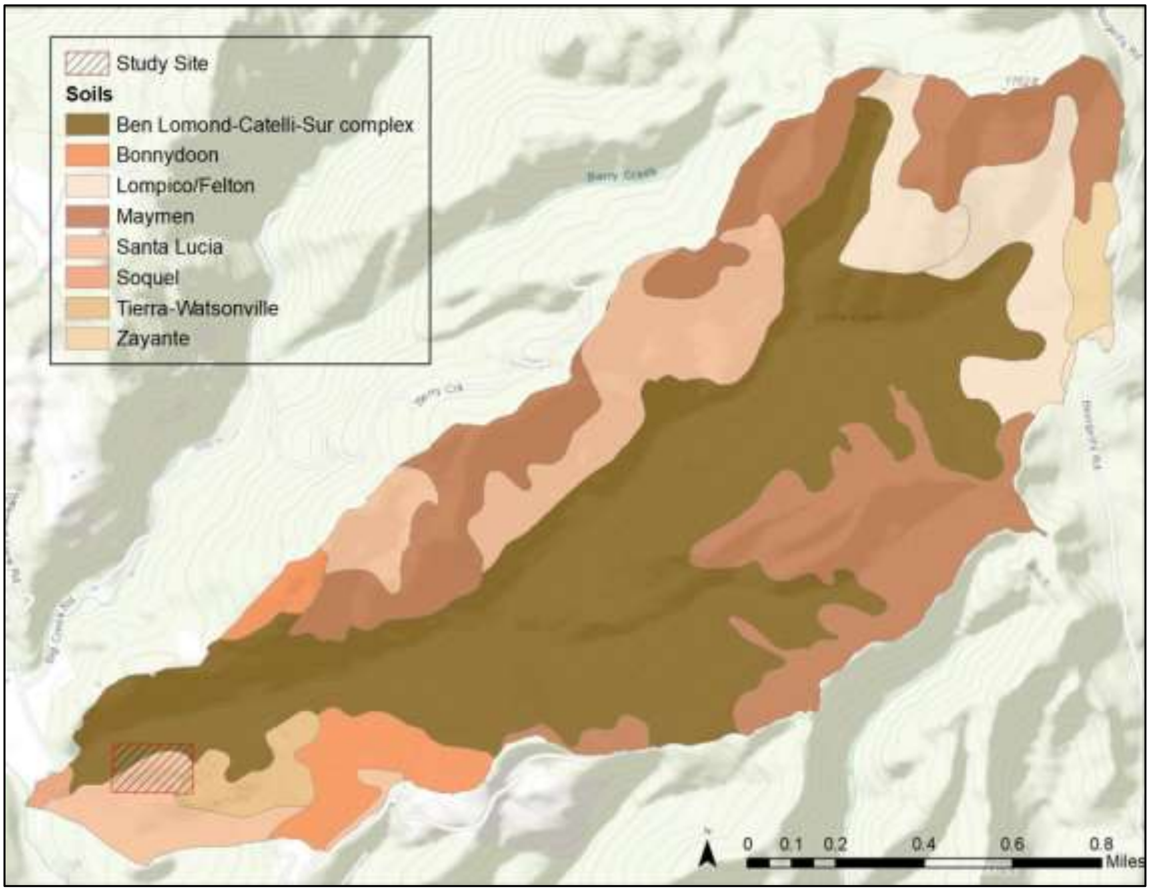


*Figure 5. Soil types present within the Little Creek watershed and the research site.*

*Table 1. Family classifications of soils found within Little Creek watershed.*

| Soil Series Name | Family Classification |
|---|---|
| Ben Lomond-Catelli-Sur Complex* | Coarseloamy, mixed, superactive, mesic Pachic Ultic Haploxerolls/ Coarse-loamy, mixed, superactive, mesic Ultic Haploxerolls/ Loamy-skeletal, mixed, superactive, mesic Entic Haploxerolls |
| Santa Lucia* | Clayeyskeletal, mixed, superactive, thermic Pachic Ultic Haploxerolls |
| Lompico/Felton | Fineloamy, mixed, superactive, mesic Ultic Argixerolls/ Fine loamy, mixed, superactive, mesic Ultic Argixerolls |
| Maymen | Loamy, mixed, active, mesic, shallow Typic Dystroxerepts |
| Soquel | Fineloamy, mixed, active, mesic Cumulic Haploxerolls |
| Tierra/Watsonville* | Fine, smectitic, thermic Mollic Palexeralfs/ Fine, smec thermic Xeric Argialbolls |
| Bonneydoon | Loamy, mixed, superactive, thermic, shallow Entic Haploxerolls |
| Zyante | Sandy, mixed, mesic Humic Dystroxerepts |

*Note: Soils marked with * occur within the research site.*

Soil loss tolerance, or the maximum annual amount of soil erosion that can occur before productivity is reduced, ranges from 2-3 tons/acre within the study site and 1-5 tons/acre within the overall watershed area (Figure 6**)** (Natural Resource Conservation Service, 2019). Also referred to as a soil’s T-value, this number is important when considering post-fire impacts regarding soil heath and productivity.

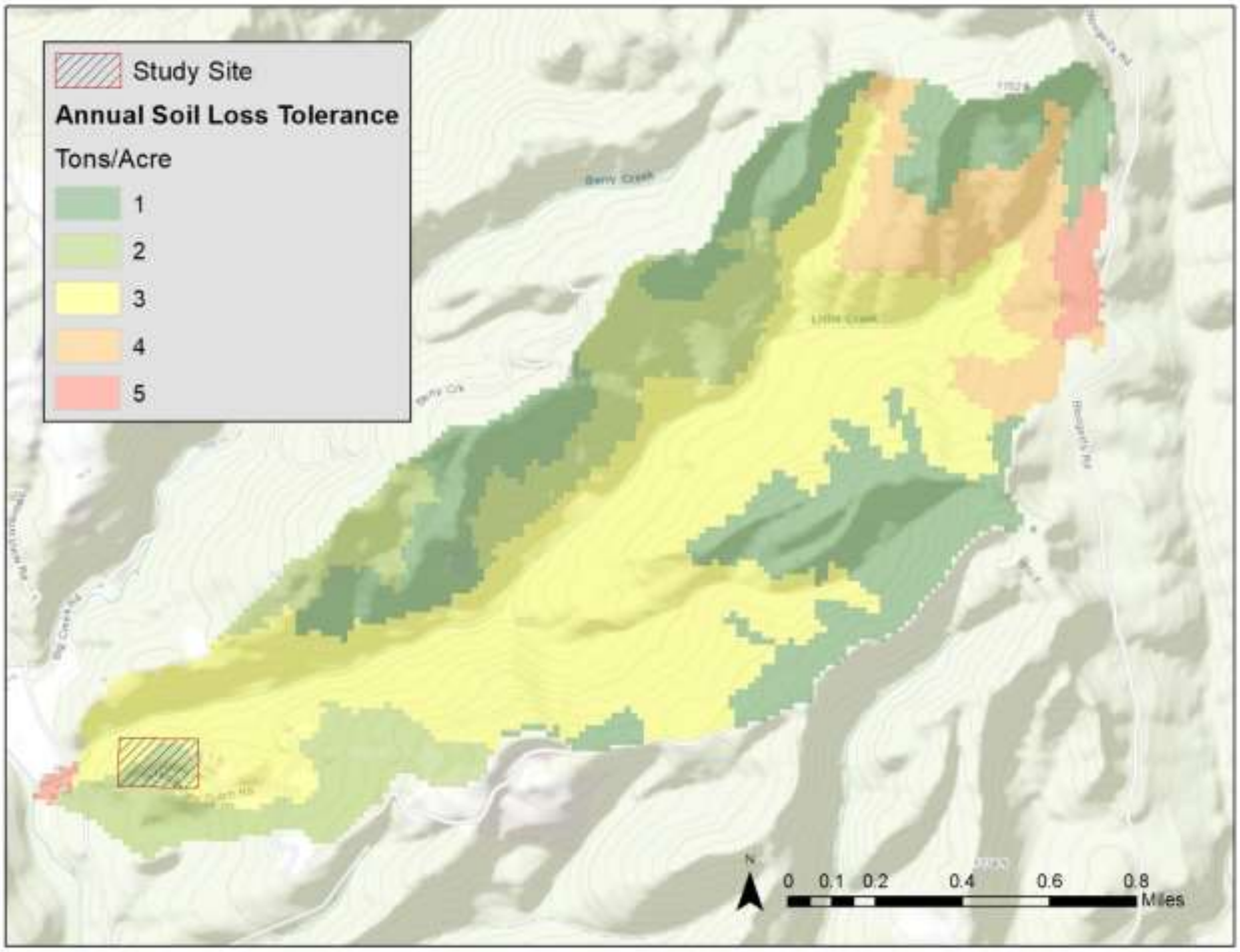


*Figure 6. Variability in soil loss tolerance across the Little Creek watershed. Data obtained from NRCS SSURGO soils database and compiled in ArcGIS Pro.*

### 3.2 Site Selection

The location of the research site was selected based on both environmental factors and access. The site was partly chosen due to its reflection of the predominant landscape features observed at a broader watershed level. Vegetative communities, slopes, and soil types present at the study site are common regionally. In addition, close access to a paved road made this site location desirable for field data collection while also reducing safety concerns associated with conducting field work in a burned forest. This site also had varying soil burn severities to research if different mapped soil burn severity affected soil erosion.

## 3.3 Measuring Erosion: The Silt Fence Erosion Trap Approach

This study follows the procedures for constructing and collecting erosion from silt fence plots as described by Robichaud and Brown (2002).  Silt fences trap eroded sediment from a confined plot area and express high hydraulic performance with sediment trap efficiencies ranging from 68-98 % (Robichaud et al, 2001).

### 3.3.1 Silt Fence Plot Construction

Silt fence plots utilize synthetic geotextile fabric to capture eroded sediment from the defined plot area. Silt fence plot construction began by defining the plot area and digging a ‘U’-shaped trench 6-10 inches in diameter along the downhill boundary. The curved form increases the capturing capacity and prevents eroded soil from depositing outside the plot area. The geotextile material was placed within this trench and laid downhill and held vertically in place with metal t-posts and wooden stakes (Figure 7). The silt fence material was fastened to the posts with metal twist ties.

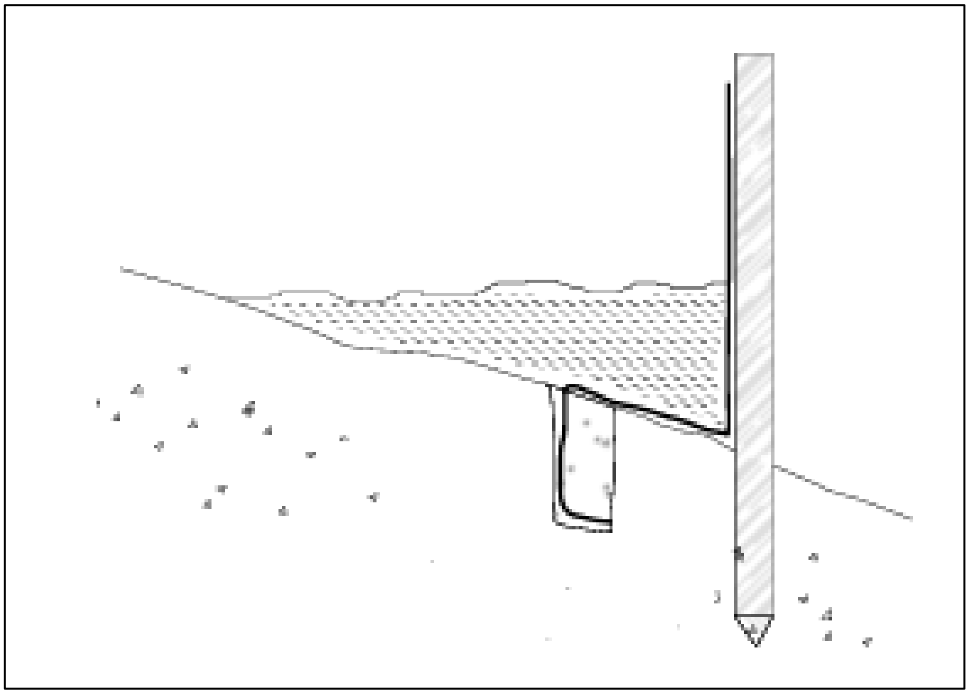


*Figure 7. Profile view of silt fence showing the placement of the geotextile material (Robichaud & Brown, 2002).*

The trench was then filled and backfilled from the downslope side to prevent sediment from passing underneath the silt fence (Robichaud, 2002). Another opposite facing ‘U’-shaped trench of similar size was dug along the uphill plot boundary where straw logs were placed and secured using wooden stakes (Figure 8- 9). This upslope erosion barrier was constructed to ensure that the eroded soil captured had originated from a known area.  Finally, red construction chalk was added to the soil surface along the sediment trap material to allow for delineation between eroded sediment and the intact soil surface during data collection (Robichaud, 2002).

*Figure 8. Upslope view of fully constructed silt fence plot.*

*Figure 9. Downslope view of fully constructed silt fence plot and highlighting the red chalk.*

### 3.3.2 Silt Fence Plot Maintenance

Maintenance was required for most plots following significant rain events and from general wear and tear over time. This included patching holes in the silt fence with plumbing tape and re-staking the t-posts and wooden posts securely in the soil. T-posts posts were added to all plots alongside the outer wooden stakes after this was found to be a common weak point for all plots. Maintenance was performed without disturbing the soil surface within the plot area.

## 3.4 Plot Locations

Ten erosion plots were constructed within the study site (Figure 10). Plot locations were selected with a goal of accommodating a variable range of environmental parameters. Plots were constructed at locations with varying burn severity classifications, slope steepness, percent soil cover, and aspect. Locations with multiple slopes were avoided to isolate erosion at the individual hillslope level.

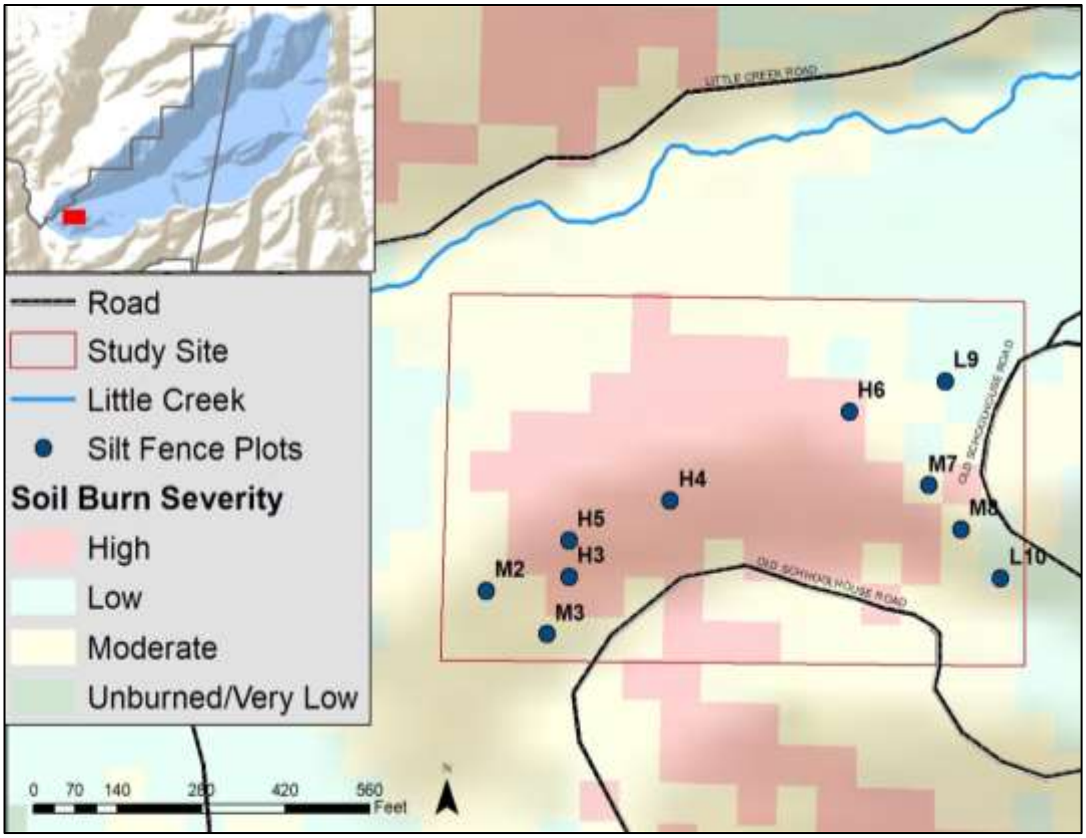


*Figure 10. Location of erosion plots within the study area in relation to the Little Creek watershed and SPR property boundary. The H.M,L designations before the plot number represent the mapped soil burn severities of High, Moderate, or Low respectively.*

## 3.5 Measuring Site Characteristics at Each Plot

Site characteristics at each plot were measured in the field. These include the plot area, slope steepness, aspect, percent canopy cover, percent ground cover, bulk density, and gravimetric water content. Soil burn severity was classified from the Watershed Emergency Response Team (WERT) dNBR soil burn severity map in ArcGIS Pro (Figure 1-2).

### 3.5.1 Plot Area

The physical area of each plot was calculated in square-feet by multiplying the average length and width of the plot. Average lengths and widths were determined by measuring each dimension five times at evenly spaced increments and averaging these values. The plot areas were then converted to acres for erosion representations per acre.

### 3.5.2 Slope

Slope was measured as a percentage using a clinometer. Readings were taken simultaneously from the upslope boundary shooting downslope and the downslope boundary shooting upslope to confirm an accurate reading.

### 3.5.3 Aspect

Aspect was measured in degrees using a conventional compass. Readings were taken from the upslope boundary of the plot while facing directly in line with the plot area. Expressing aspect in degrees creates issues during statistical analysis because slopes with similar aspects may be assigned significantly different numerical values as observed when comparing slopes facing 359 degrees and 1 degree. Therefore, aspect measurements were converted from degrees to degree of northness by converting degrees into radians and then applying a cosine function.

### 3.5.4 Canopy Cover

Percent canopy cover, or the proportion of the sky covered by vegetation when viewed from a single point, was determined using a densiometer. Densiometer measurements were collected at three locations within the plot including the center of the uphill boundary, center of the plot, and center of downhill boundary. Four measurements were taken at each location facing each cardinal direction and averaged to quantify overall canopy coverage for the plot area.

### 3.5.5 Soil Cover

Determining percent soil cover was the most time intensive and utilized a transect approach. Five transects were laid horizontally across each plot. Data was recorded at foot increments along the transect identifying if the soil surface was covered or uncovered. Soil coverage was determined by placing a pencil vertically at each foot mark and assessing if it met either live vegetation, leaf litter, or large stones. Coverage data was recorded as either “yes” or “no” into a field journal. The number of “yes” data points was then divided by the sum of data points to calculate the percent ground cover for each plot. This process was conducted twice; October 2nd , 2021 and March 15, 2022. Due to substantial changes in soil cover over time during the study period, the average value between both soil cover measurements was used to represent the ground cover for the study period.

### 3.5.6 Soil Burn Severity

Soil burn severity was classified as either high, moderate, or low. Burn severity data was obtained from the WERT soil burn severity map using the rapid Normalized Burn Ratio (dNBR) approach. The normalized burn ratio (NBR) is a measure of reflectance from healthy vegetation. This is determined through the use of near infrared (NIR) and shortwave infrared wavelengths (SWIR).

## 3.6 Measuring Erosion

Eroded soil was removed from the silt fence plots following precipitation events which were significant enough to cause erosion. In general, storms of two inches or more were required to produce enough eroded material to require cleanout. Silt fence cleanout occurred two times; November 6th and December 27th. At each plot, the eroded material was removed from the silt-fence using a hand trowel. Soil was not collected beyond the depth of the red chalk marker. A fresh layer of chalk was re-applied following cleanout. Eroded soil was placed into a five-gallon bucket and then weighed on-site using a USGS certified hanging scale. The weight of the bucket was weighed before-hand and subtracted from the total weight. The total weight was recorded in pounds, and a sample of the eroded material was placed into an airtight bag for use in the laboratory. In the laboratory, the samples of soil collected from the silt fences were weighed and then dried in a soil drying oven at 105 degrees for 24 hours. The dried samples were re-weighed to quantify the percent water content of the sample. Percent water content values were accounted for to determine the oven-dry mass of the eroded material from each plot and allow for even comparison between plots.

## 3.7 Statistical Analysis

Soil erosion and its relationship to environmental conditions was analyzed in a free statistics software package manufactured by Jump (JMP). Analysis involved both univariate and multivariate testing to determine how single and combined explanatory variables predict rates of hillslope erosion.

### 3.7.1 Univariate Analysis

Univariate analysis between each explanatory variable and hillslope erosion rates was conducted to understand the significance of single variables towards influencing hillslope erosion rates. Linear correlations were performed for quantitative explanatory variables, while ANOVA was used for burn severity, a categorical explanatory variable.

### 3.7.2 Multivariate Analysis (Stepwise Regression)

Stepwise regression was performed to assess how multiple explanatory variables influence hillslope erosion. Stepwise regression functions by adding or removing explanatory variables and testing for their combined significance towards influencing the dependent variable in a multi-regression model. This statistical method was chosen for its ability to identify statistically significant explanatory variables (Table 2), and how these variables combine to influence post-fire hillslope rates. A mixed variable selection method was chosen, using a p-value threshold of 0.25 for variable selection. The minimum AIC (Akaike information criterion) approach was used to choose the appropriate model. The AIC approach compares the quality of a model and is useful when comparing many model outputs. Low AIC values correspond to low prediction error in the model and assists in choosing the most parsimonious model of the drivers of post-fire erosion. A total of seven explanatory variables were tested for their influence on soil erosion (Table 2).

*Table 2. List of all covariates tested during statistical analysis.*

| **Explanatory Variables** | **Data Type** |
|---|---|
| Burn Severity (High, Moderate, or Low) | Categorical |
| Slope (percent) | Quantitative |
| Percent Soil Cover (%) | Quantitative |
| Percent Canopy Cover (%) | Quantitative |
| Aspect (northness) | Quantitative |
| Bulk Density (g/ml) | Quantitative |
| Gravimetric Water Content | Quantitative |

### 3.8 Spatial Extrapolation: Employing the Universal Soil Loss Equation (USLE)

Erosion collected from silt-fence plots was used to spatially extrapolate erosion measured erosion rates to the entire Little Creek watershed. Spatial extrapolation allows for understanding post-fire erosion dynamics at the watershed scale and is useful for assessing post-fire erosion beyond the borders of the study area. The Universal Soil Loss Equation (USLE) was employed to model erosion throughout the Little Creek watershed. The USLE was chosen for its ability to calibrate soil erosion based on field-collected data. Known levels of erosion can be used to finetune predictive variables to correct inaccuracies in the model. This model multiplies five variables to predict annual soil loss in tons/acre as shown in equation 1 below.

$$A = R * K * LS * C * P \qquad (1)$$

Where:

A= *Soil loss (tons/acre/year)*

R= *Rainfall erosion index, in 100 feet – tons/acre*in/hr*

K= *Soil erodibility factor, tons/acre per unit of R*

LS= *Slope length and steepness factor, dimensionless*

C= *Vegetative cover factor, percentage of bare soil*

P= *Erosion control practice factor*

The methodology used for spatially extrapolating erosion rates follows that identified by Surfleet (2022). This methodology incorporates the USLE into GIS software to calculate and map erosion estimates. We utilized the USLE to extrapolate hillslope erosion for the Little creek watershed under four different scenarios.

These include:

1) Scenario 1 uses C factor values based on the percent soil cover present for each erosion plot measured 14 and 19 months post-fire. R factor values are based on precipitation which occurred during the duration of this study.
2) Scenario 2 uses C factor values based on the percent soil cover present for each erosion plot measured 14 and 19 months post-fire. R factor values are based on long-term average precipitation.

3) Scenario 3 uses C factor values assuming complete soil cover to resemble pre-fire conditions. R factor values are based on precipitation which occurred during the duration of this study.
4) Scenario 4 uses C factor values assuming complete soil cover to resemble pre-fire conditions. R factor values are based on long-term average precipitation.

This scenario analysis allows for comparing changes in the severity of hillslope erosion from pre-fire to post-fire conditions for different levels of precipitation, lower than average precipitation during this study period and average precipitation. Model outputs for each of the ten plots were averaged for each scenario to identify average hillslope erosion in tons/acre/year. across the Little Creek watershed.

### 3.8.1 Determining Values for Variables used in the USLE

We provide the methodology for determining the values for each of the variables used in the Universal Soil Loss Equation.

#### 3.8.1.1 Soil Erodibility Factor (K)

The soil erodibility factor measures the susceptibility of soil particles to detach and transport. The K-factor was determined from soil attributes including soil texture, drainage capacity, soil structure, and the amount of soil organic matter. These attributes were used within an equation determined by Renard et al. (1997) to identify the K-factor for different soil types. The K-factor for use in spatial extrapolation was calculated on the basis of the soil characteristics of the two soil types present in study area; Santa Lucia series and the Tierra-Watsonville series. K-factor values for use during spatial extraction were 0.3 and 0.13 respectively for plots with these respective soil types.

### 3.8.1.2 Slope Length and Steepness (LS)

A 20-meter Digital Elevation Model (DEM) was used to determine the flow accumulation and slope corresponding to each pixel across the watershed area. LS-factors for each pixel were calculated based on the relationship between flow accumulation and slope factor using equation 2 created from Stone and Hilborn (2012).

$$LS = (\text{“flow accumulation count”} * (65.62/72.5)^{0.4} * \text{Sine}(\text{“slope degrees”} * 0.01745)/0.09,1.4)^{1.4} \tag{2}$$

### 3.8.1.3 Rainfall Erosivity Index (R)

The rainfall erosivity index is calculated from monthly cumulated rainfall. Two different R-factors were used depending on whether the scenario utilized long-term average local precipitation, or the precipitation observed over the course of this study. Long-term average R-factors were gathered from the RUSLE2 software (United States Department of Agriculture (USDA), 2016). This software provides regional precipitation data in mm/month of precipitation for specified climate regions. The Santa Cruz climate file was selected with 46 inches of annual precipitation to reflect the climate of the study area.

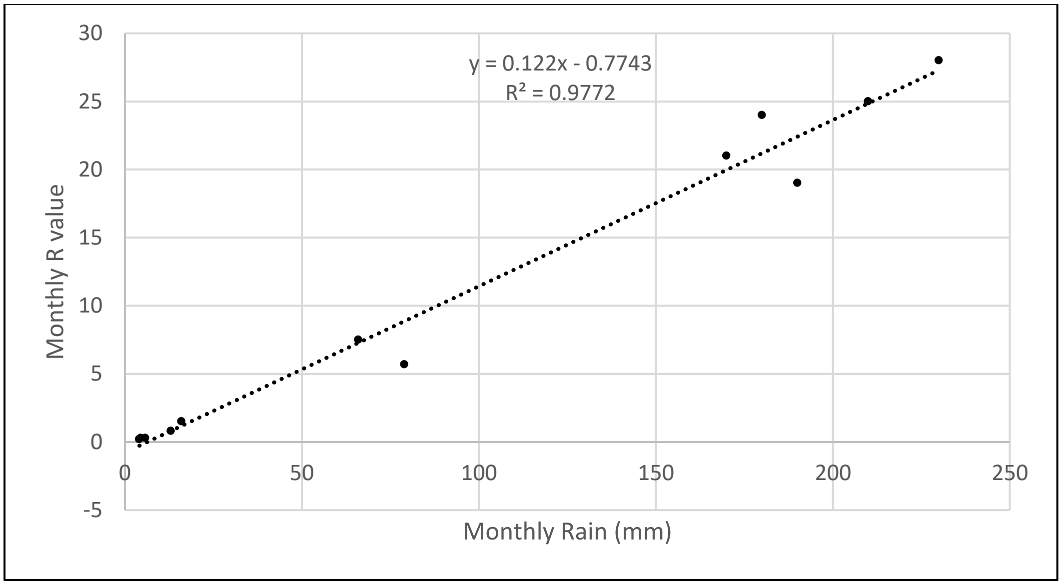


*Figure 11. Relationship between long-term average monthly precipitation corresponding R values for total annual precipitation of 46 inches.*

Monthly R-factors used to reflect the precipitation that occurred during the duration of this study were identified from the relationship between long-term average monthly precipitation and corresponding monthly R-factors (Figure 11). The equation derived from this relationship was applied for the measured precipitation from tipping bucket rain gauges present at Swanton Pacific Ranch from October 2021 until March 2022. The identified monthly R-factors were summed for both long-term average and observed precipitation totals to identify the R-factor to represent precipitation across the entire study period.

*Table 3. Monthly R-factors and their total sum. Data obtained using RUSLE2 software and field rain gauges.*

| *Month* | *2021-2022* | *Long Term Average* |
|---|---|---|
| *OCT* | 21.7 | 7.5 |
| *NOV* | 8.7 | 21 |
| *DEC* | 49.7 | 24 |
| *JAN* | 4.1 | 28 |
| *FEB* | 0 | 25 |
| *MAR* | 1.6 | 19 |
| ***Total R*** | **85.9** | **124.5** |

#### 3.8.1.4 Vegetative Cover Factor (C)

The vegetative cover factors used to resemble post-fire conditions in scenarios 1 and 2 were unique for each plot and were derived from the percent of bare soil as shown in equation 3.

$$C = 1 - \text{Average Percent Soil Cover} \qquad (3)$$

A C-factor value of 0.01, a commonly used value for unburned forested areas, was used for scenarios 3 and 4.

#### 3.8.1.5 Erosion Control Practice Factor (P)

The erosion control practice factor is commonly used when accounting for soil protection measures or other disturbances including tilling, watercourses, or roadways (Devatha et al, 2015). P-factors can also be used to calibrate the USLE if the level of erosion is known as in the case of this study. P-factors for each plot were solved algebraically using equation 4.

$$P = A / (R * K * LS * C) \qquad (4)$$

### 3.8.2 Quantifying Sediment Delivery

Sediment delivery to streams in the Little Creek watershed was quantified using predicted erosion from the USLE spatial extrapolation. The sediment delivery ratio was determined from the delivery factor identified by Megahan et al., (1986) for estimating sediment delivery from unpaved roads based on proximity of the road to the stream (Table 4).

*Table 4. Road Sediment Delivery Factors derived from Megahan et al., (1986).*

| **Drainage From Road Segment Flows** | **Percent of Sediment Delivering** |
|---|---|
| Adjacent to stream | 100 |
| Within 100 feet of stream | 35 |
| Within 200 feet of stream | 10 |

The delivery ratios listed in Table (4) can be used to predict the sediment delivery ratio of a road segment at a chosen distance from a stream (Figure 12).

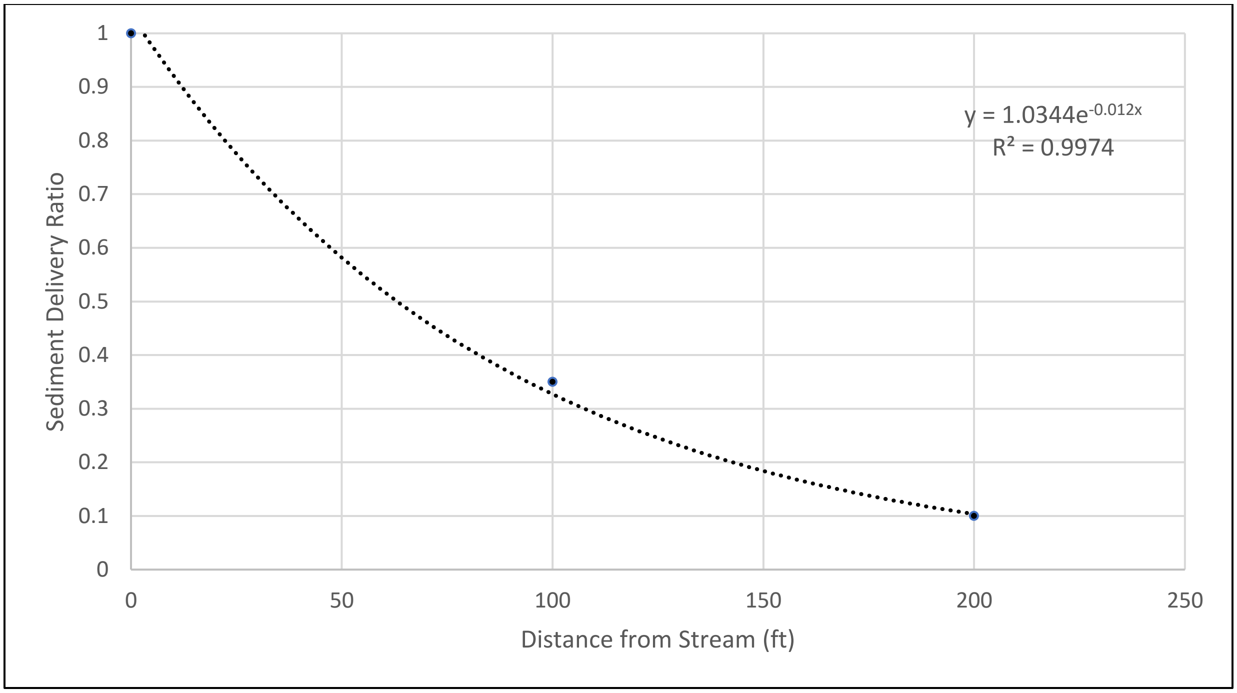


*Figure 12. Relationship between sediment delivery and distance from a stream derived from Megahan et al., (1986).*

This methodology allows for estimating sediment delivery from hillslope erosion from a contributing area of 200 feet from both sides of streams within the watershed (Figure 13).

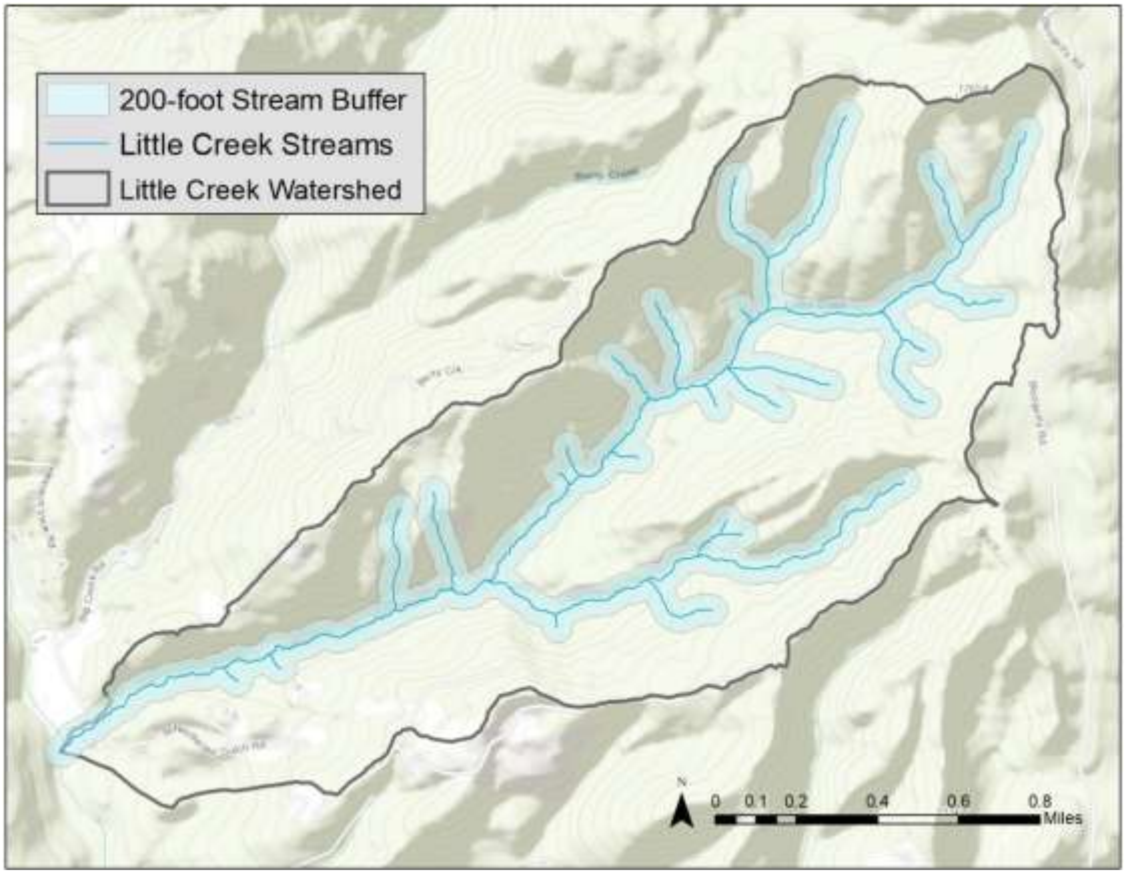


*Figure 13. 200-foot stream buffer area used to quantify sediment delivery to streams in the Little Creek watershed.*

Hillslope erosion was quantified for areas 50, 100, and 200 feet away from streams. This was done for each of the four scenarios to assess how fire and precipitation influence sediment delivery from contributing hillslopes. A sediment delivery ratio of 0.57 was determined for the 50 feet buffer distance (Figure 12), and sediment delivery ratios of 0.35 and 0.10 were used for distances of 100 and 200 feet respectively (Table 4). Sediment delivery ratios were multiplied by the total erosion estimates for each buffer distance. Estimated sediment delivery for the three distances were then averaged to determine sediment deposition to streams within 200 feet of watercourses within the Little creek watershed.

## Chapter 4

## RESULTS

### 4.1 Erosion Plot Characteristics

The results for measured covariates at each plot is summarized in Table 5. This includes slope, percent soil cover, percent canopy cover, burn severity, aspect, bulk density, and gravimetric water content.

*Table 5. Plot characteristics showing values for the seven covariates measured at each plot.*

| Plot | *Slope (%)* | *Percent soil Cover* | *Percent Canopy Cover* | *Burn Severity* | *Aspect (northness)* | *Bulk Density g/mL* | *Gravimetric Water Content* |
|---|---|---|---|---|---|---|---|
| *M2* | 25 | 65 | 60 | Moderate | -0.97 | 0.67 | 0.21 |
| *M3* | 25.5 | 87 | 45 | Moderate | -0.95 | 0.84 | 0.11 |
| *H3* | 31.5 | 46 | 81 | High | -0.98 | 0.74 | 0.12 |
| *H4* | 28 | 61.5 | 38.7 | High | -1.00 | 0.88 | 0.12 |
| *H5* | 15.5 | 59 | 77.5 | High | -0.99 | 0.70 | 0.14 |
| *H6* | 15.5 | 65 | 60 | High | -0.05 | 0.79 | 0.12 |
| *M7* | 16 | 82.5 | 65 | Moderate | 0.91 | 1.06 | 0.11 |
| *M8* | 24 | 66.5 | 65.3 | Moderate | -0.63 | 1.02 | 0.09 |
| *L9* | 21.5 | 66 | 2.6 | Low | 0.99 | 1.05 | .07 |
| *L10* | 24.5 | 78.5 | 49.7 | Low | -0.76 | 0.97 | .06 |

Low, moderate, and high burn severity was represented across the ten plots, with moderate and high severity representing four plots each, and low severity represented by two plots (Figure 10).

Slopes ranged from 15.5 to 31.5 percent across the ten erosion plots (Table 5). Given the topography of the study site, most erosion plots were south facing, with an average aspect of 196 degrees (Table 5).

Percent soil cover varied from 59 - 82.5% and changed considerably throughout the study period (Table 5). An average increase in soil cover of about 40% was observed from October 2nd until March 15th, the entire extent of the study period. Understory vegetation growth increased rapidly following substantial rain in late December. Plots M3 and M7 expressed complete soil cover on March 15th (Figure 14).

*Figure 14. Plot M2 completely overtaken by understory vegetation.*

Canopy coverage above the erosion plots was predominantly comprised of bare branches from scorched trees or dead leaves which had remained attached to branches (Figure 15). These values were highly variable and ranged from 2.6 - 77.5 % depending on the plot. Canopy coverage averaged 54% across the ten study plots (Table 5).  No changes in the type and degree of canopy cover occurred over the study period.

*Figure 15. Canopy coverage near plot L10 from scorched Coastal redwood and Tan oak.*

Soil bulk density fluctuated from 0.67 to 1.06 g/mL, which is considered low bulk density. However, how bulk density was impacted by wildfire is unknown due to the absence of pre-fire data. In situ gravimetric water content was less variable with values ranging from 6- 21 % percent (Table 5).

### 4.2 Eroded Soil Collected from Silt Fences

A summary of field measurements of eroded soil from each plot and the plot average is provided (Table 6). The data was compiled from two collection dates on October 2nd 2021 and March 15th 2022.

*Table 6. Total collected erosion from each plot over the study period and the plot average.*

| Plot | *Total Dry Weight Erosion (lbs)* | *Plot Area (acres)* | *Total Dry Weight Erosion (tons/acre)* |
|---|---|---|---|
| *M2* | 16.08 | .0069 | 1.17 |
| *M3* | 2.60 | .0071 | 0.18 |
| *H3* | 16.95 | .0076 | 1.11 |
| *H4* | 23.07 | .0070 | 1.64 |
| *H5* | 2.87 | .0072 | 0.200 |
| *H6* | 3.13 | .0080 | 0.20 |
| *M7* | 0.0 | .0074 | 0.0 |
| *M8* | 4.11 | .0072 | 0.29 |
| *L9* | 22.43 | .0073 | 1.54 |
| *L10* | 13.54 | .0075 | 0.90 |
| *Average* | - | - | 0.72 |

Total hillslope erosion compiled at the end of the study period was found to be 0.72 tons/acre on average across the ten plots. Erosion totals ranged from 0 –1.64 tons/acre (Table 6). Two storm events are estimated to have produced the greatest amount of hillslope erosion. An extreme storm on December 12th produced 6.4 inches of precipitation at the study site over a 24-hour period (Figure 16). A subsequent storm from December 21st-24th, produced 3.8 inches of total precipitation with peak rainfall intensity reaching 0.76 inches/hour (Figure 16). The December 12th storm event likely was the single most erosive event given the high rainfall intensity with peak intensity reaching 1.74 inches/hour. This event triggered mandatory evacuations for select areas with the CZU Lightning complex burn scar in response to heightened landslide and debris flow risk **(**Kathan, 2021) Erosion collected following these events was dominated by soil aggregates, with small portions of fine sediment. Aggregate detachment was only observed following these precipitation events. Prior to these storms, much less eroded soil had been observed in the silt fences. Total precipitation during this study equated to roughly 29 inches, 31% less than average precipitation for this same period at 46 inches. Following data collection on December 28th, 3.34 inches of precipitation occurred prior to the end of the study period on March 15th (Figure 16). No erosion was observed or collected from the silt fence traps during this period.

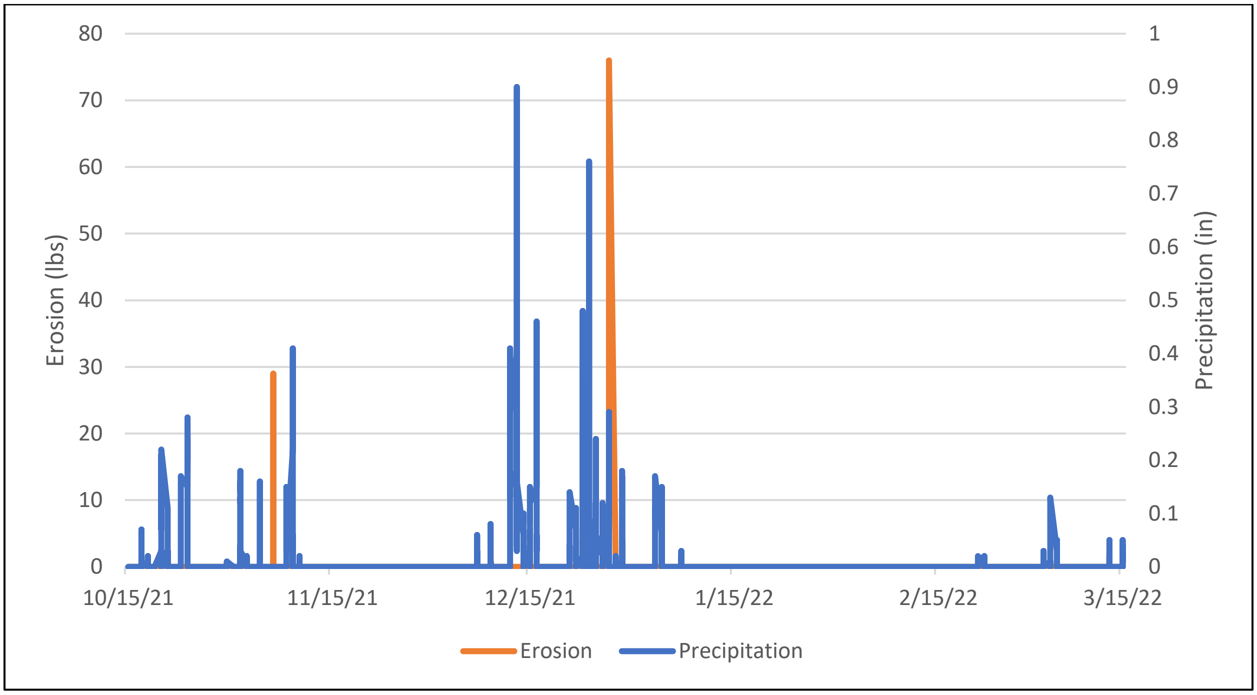


*Figure 16. Precipitation at study site from October 15th 2021 until March 15th 2022 and pounds of erosion collected during both data both collection dates. Data obtained from tipping bucket rain gauges.*

## 4.3 Statistical Analysis

### 4.3.1 Significant Univariate Correlations

Slope steepness was found to be the only statistically significant univariate correlation to hillslope erosion rates after testing each covariate (Table 7). Using slope alone as a predicting variable explains 45% of the variability in hillslope erosion across the ten plots (Table 7). The correlation between slope and annual hillslope erosion suggests a positive relationship as each percent increase in slope leads to a 0.04 ton increase in tons of erosion per acre (Figure 16).

Using p-values as a basis for significance, percent soil cover and percent canopy cover were the second and third strongest univariate predictors of erosion with p-values of 0.14 and 0.17 respectively (Table 7). Although both are not statistically significant, soil cover by itself explained 24% of hillslope erosion variability, while canopy cover explained 29%. Increases in soil and canopy cover indicate a reduction in hillslope erosion rates (Figure 17).

*Table 7. P-values and R-squared values derived from univariate correlations between hillslope erosion rates and the three most significant explanatory variables.*

| Explanatory Variable | P-value | R-squared |
|---|---|---|
| Slope (%) | 0.03 * | 0.45 |
| Percent Soil Cover | 0.14 | 0.24 |
| Percent Canopy Cover | 0.17 | 0.29 |

Note: P-value with * indicates a statistically significant correlation at P <. 05.

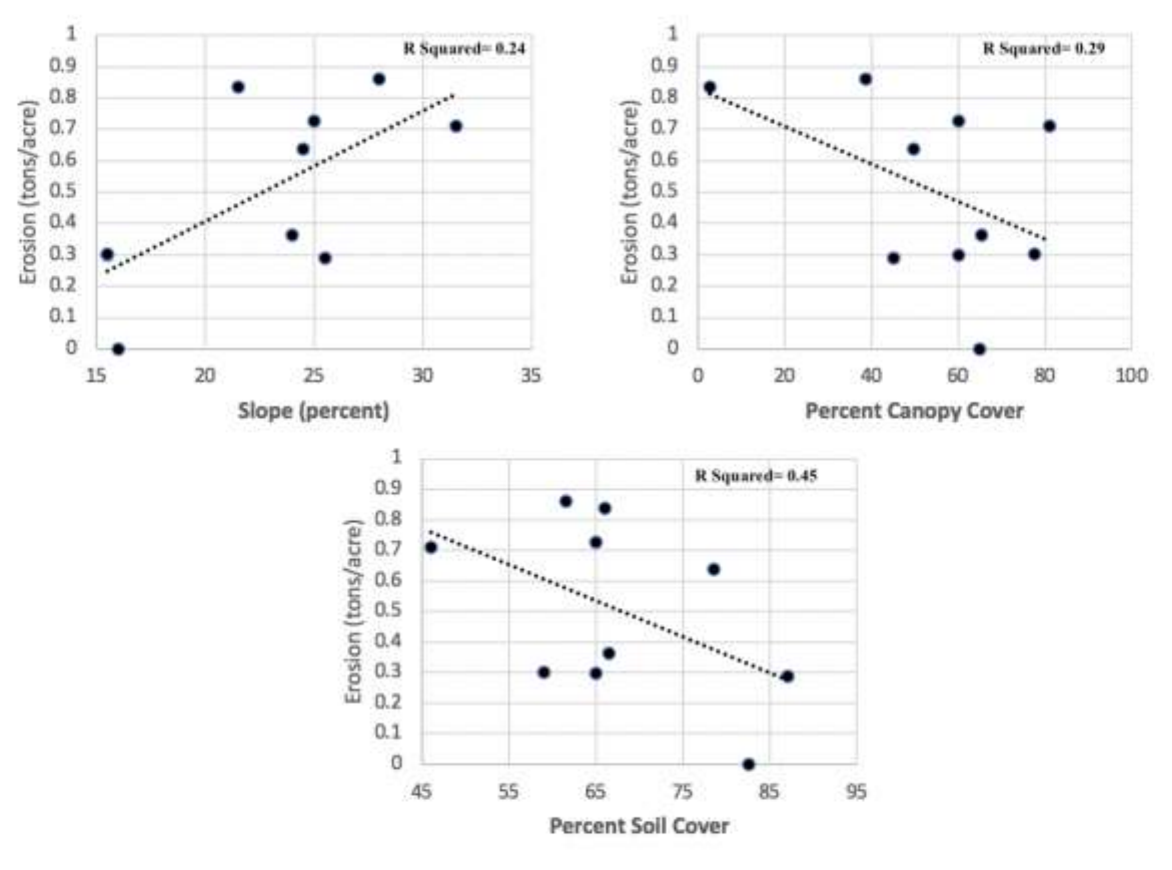


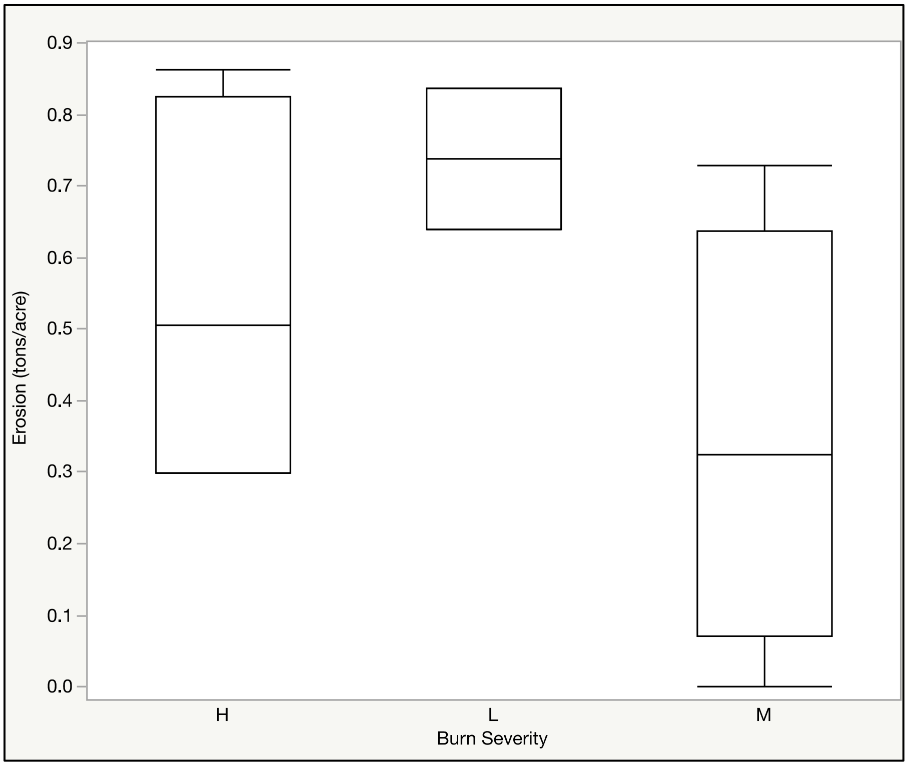
*Figure 17. a) Relationship between hillslope erosion and slope steepness. b) Relationship between hillslope erosion and percent canopy cover. c) Relationship between hillslope erosion and percent soil cover.*

#### 4.3.1.1 Effect of Burn Severity

The relationship between hillslope erosion and burn severity was not found to be statistically significant as proven from a p-value of 0.31 from ANOVA testing (Table 8). Mean erosion was highest for the low severity plots in the context of this study (Figure 18).

*Table 8. ANOVA table derived from relationship between burn severity and hillslope erosion rates.*

| Source | Degrees of Freedom | F-ratio | P-value |
|---|---|---|---|
| Burn Severity | 2 | 1.41 | 0.31 |
| Error | 7 | | |
| C. Total | 9 | | |



*Note: High and moderate burn severity were both represented in four plots, while low burn severity was represented in two.*

*Figure 18. Mean hillslope erosion rate for each degree of burn severity showing high and low values.*

### 4.3.2 Multivariate Model of Post-fire Hillslope Erosion

A preliminary model with three explanatory variables including slope, percent soil cover, and percent canopy cover, was chosen to predict post-fire hillslope erosion. However, the preliminary model presented problems due to lack of normality observed within the hillslope erosion rate data and associated residuals. A square root transformation was applied to erosion values to transform the values to a normal distribution and homoscedasticity of the residuals. Stepwise regression was then repeated following this transformation. Of the 200 model iterations, the best model shown in equation 5 included the same three explanatory variables as the preliminary model.

$$\text{Square Root of Predicted erosion (tons/acre/year)} = \\ 1.78 + .04\,(\text{Slope})\,^{*} - 0.02\,(\text{Percent Soil Cover})\,^{*} - 0.01\,(\text{Percent Canopy Cover}) \qquad (5)$$

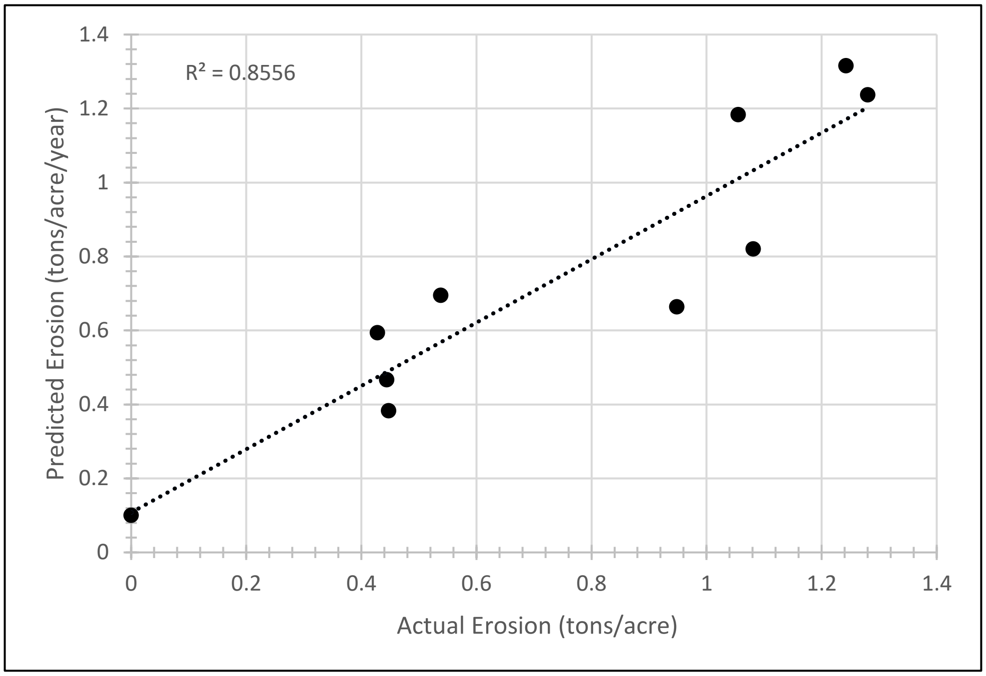


*Figure 19. Actual vs. predicted values for erosion based on the best produced model.*

These variables and the intercept of the model are all statistically significant at p <0. 05 (Table 9). This model was chosen because it expressed the lowest Akaike Information Criterion (AIC) value and maintained a high R-squared value in comparison to other models. The model explains a large proportion of the observed variability in erosion as seen through an R-squared value of 0.86 (Table 10) (Figure 19).  Root mean square error (RMSE), a measure how concentrated actual values are to the predicted regression line, is low at 0.13 tons/acre/year (Table 10).

*Table 9. Parameter estimates derived from the chosen multivariate model.*

| Term | Estimate | Std Error | t Ratio | P Value |
|---|---|---|---|---|
| Intercept | 1.78 | 0.65 | 2.73 | 0.03 |
| Slope (%) | 0.04 | 0.01 | 2.91 | 0.03 |
| Percent Soil Cover | -0.02 | .006 | -3.08 | 0.02 |
| Percent Canopy Cover | -0.01 | .003 | -3.59 | 0.01 |

*Table 10. Summary of fit for the chosen multivariate model. RMSE units are tons/acre/year.*

| R-Squared | 0.86 |
|---|---|
| Adjusted R-Squared | 0.78 |
| RMSE | 0.19 |

Parameter estimates obtained from the model quantify the effects of the explanatory variables towards influencing the rate of hillslope erosion. An increase in slope is found to be positively correlated to erosion, while increases in soil cover and ground cover lead to reductions in erosion (Table 10). These estimates inform a linear equation to predict post-fire hillslope erosion which can be used to plot the model predicted rates of hillslope erosion vs. actual observed values (Equation 5).

## 4.4 Results of Universal Soil Loss Equation (USLE) Spatial Extrapolation

### 4.4.1 Watershed Erosion Rate

Hillslope erosion estimates derived from USLE spatial extrapolation provide values for each scenario based on individual plot characteristics (Table 11). The average erosion estimates across all plots and scenarios provides an estimate for each scenario at the watershed scale. Across all plots, except for plot M7 which produced no erosion over the study period, erosion estimates were highest for Scenario 2 and lowest for Scenario 3 as expected given their respective values for precipitation and percent soil cover (Table 11). Pre-fire conditions based on the precipitation observed during the study period produced an annual average hillslope erosion rate at 0.08 tons/acre/year, with a 27% increase when using precipitation totals reflecting the long-term average (Table 11). Watershed average post-fire hillslope erosion over the course of the study period with the observed precipitation was estimated at 4.23 tons/acre/year. This value was found to increase by 32% when assuming long-term average precipitation levels (Table 11).

Post-fire erosion using precipitation values observed during the study period shows roughly a 53-fold increase compared to pre-fire conditions experiencing the same amount of precipitation (Table 11). This increase climbs to roughly 58-fold when comparing pre and post-fire hillslope erosion rates under long term average precipitation conditions (Table 11). Estimated post-fire hillslope as quantified in scenarios 1 and 2 exceeds the watershed average soil loss tolerance value of 2.4 tons/acre/year, while pre-fire erosion rates fall well beneath this value.

*Table 11. Predicted watershed hillslope erosion rates for each plot under four different scenarios.*

| *Plot* | *Scenario 1 Post-fire, 2021-2022 Precipitation (tons/acre/year)* | *Scenario 2 Post-fire, Long-term Average Precipitation (tons/acre/year)* | *Scenario 3 Post-fire, 2021-2022 Precipitation (tons/acre/year)* | *Scenario 4 Post-fire, Long-term Average Precipitation (tons/acre/year)* |
|---|---|---|---|---|
| *M2* | 6.33 | 9.16 | 0.12 | 0.18 |
| *M3* | 1.02 | 1.49 | 0.04 | 0.06 |
| *H3* | 4.74 | 6.87 | 0.08 | 0.11 |
| *H4* | 8.76 | 12.50 | 0.12 | 0.18 |
| *H5* | 2.08 | 3.28 | 0.03 | 0.05 |
| *H6* | 2.06 | 2.99 | 0.03 | 0.05 |
| *M7* | 0 | 0 | 0 | 0 |
| *M8* | 2.06 | 2.99 | 0.03 | 0.05 |
| *L9* | 10.60 | 15.34 | 0.19 | 0.27 |
| *L10* | 4.98 | 7.38 | 0.13 | 0.18 |
| ***Average*** | **4.23** | **6.20** | **0.08** | **0.11** |

Using average values, spatial extrapolation for scenario 1 showed average post-fire hillslope erosion rates to be highest on hillslopes with steep slopes and long slope lengths (Figure 19). Hillslopes producing high erosion rates scenario occurred throughout the watershed for this scenario, yet generally on hillslopes in close proximity to watercourses (Figure 20). These hillslopes adjacent to watercourses often possess steep slopes with long and continuous hillslopes resulting in greater rates of erosion.

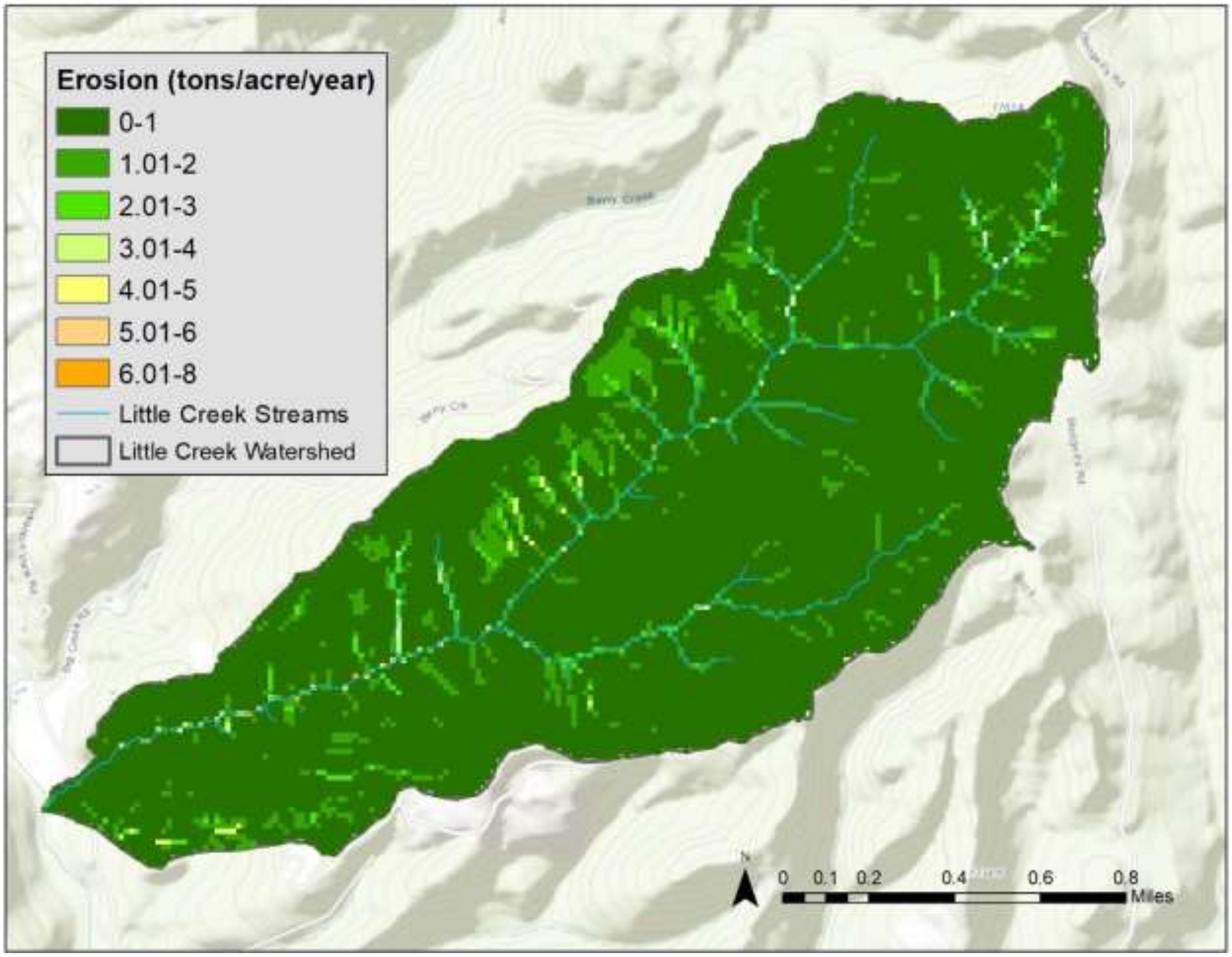


*Figure 20. Average annual post-fire hillslope erosion rates in the Little Creek watershed based on study period precipitation (Scenario 1).*

Average values for scenario 2 similarly showed areas of high erosion rates to occur on steep slopes with long slope lengths (Figure 20). Areas which experienced accelerated rates of erosion in scenario 1 also did so in scenario 2, yet a greater severity. Higher total precipitation in scenario 2 also resulted in areas of high hillslope erosion which were nor present in scenario 1 (Figure 20- 21).

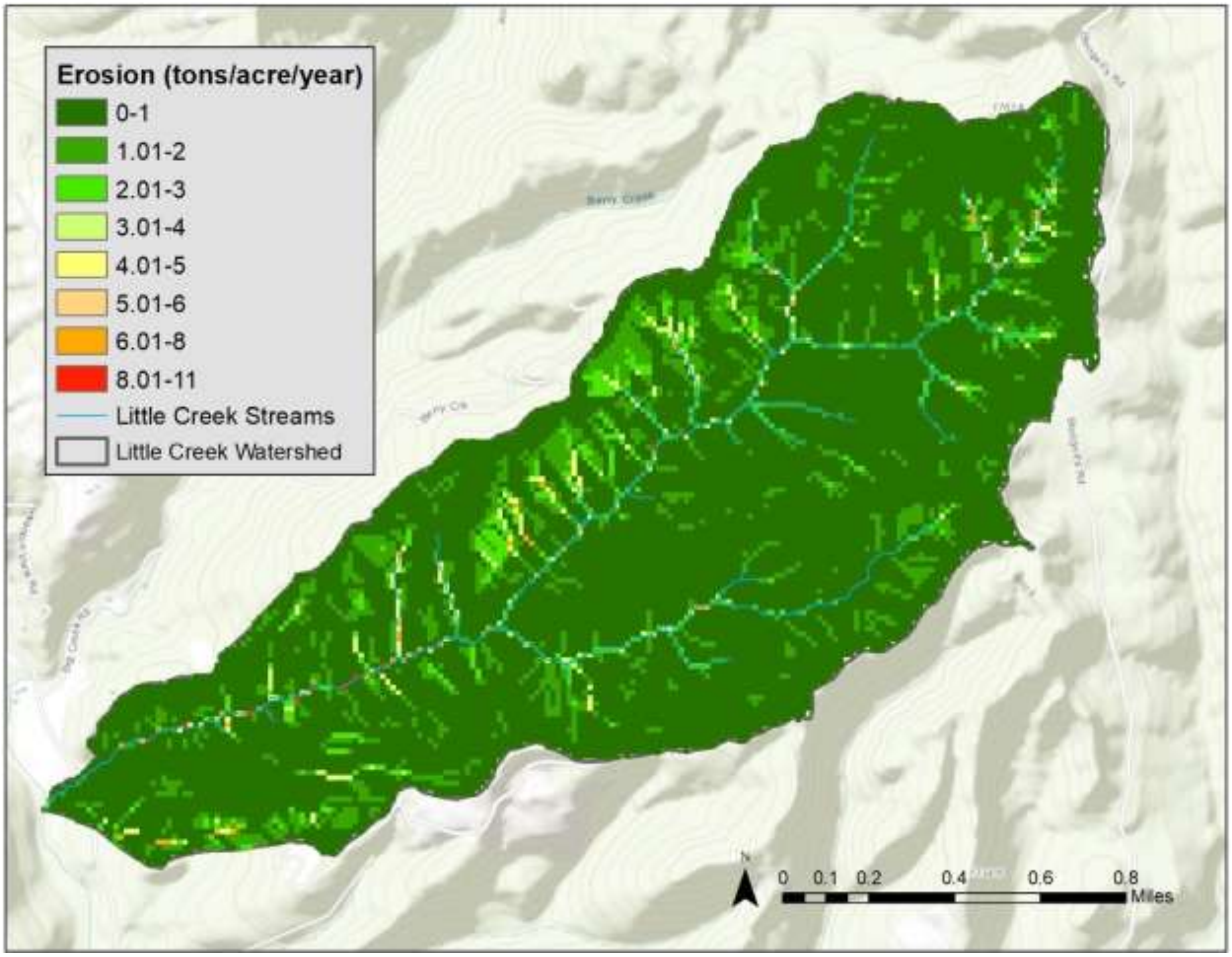


*Figure 21. Average annual post-fire hillslope erosion rates in the Little Creek watershed based on long-term average precipitation (Scenario 2).*

### 4.4.3 Sediment Delivery to Streams

Sediment delivery estimates follow a similar pattern to hillslope erosion with highest and lowest estimates for scenarios 2 and 3 respectively (Table 12). Pre-fire conditions based on the precipitation observed during the study period produced sediment delivery from hillslopes within 200 feet of watercourses within the watershed at 0.02 tons/acre/year (Table 12). A 33% increase in pre-fire sediment delivery was found when assuming long-term average precipitation values. Post-fire sediment delivery based on precipitation which occurred over the course of the study period was estimated at 1.16 tons/acre/year (Table 12). This value was found to increase by 37% when assuming long-term average precipitation levels (Table 12). Sediment delivery to streams using precipitation values observed during the study period produced roughly a 58-fold increase compared to pre-fire conditions experiencing similar precipitation. An estimated 62-fold increase was found when assuming long term average precipitation values (Table 12).

*Table 12. Predicted sediment delivery to streams in the watershed for each plot under four different scenarios.*

| *Plot* | *Scenario 1 Post-fire, 2021-2022 Precipitation (tons)* | *Scenario 2 Post-fire, Long-term Average Precipitation (tons)* | *Scenario 3 Post-fire, 2021-2022 Precipitation (tons)* | *Scenario 4 Post-fire, Long-term Average Precipitation (tons)* |
|---|---|---|---|---|
| *M2* | 667.94 | 966.56 | 12.66 | 18.99 |
| *M3* | 107.63 | 157.23 | 4.22 | 6.44 |
| *H3* | 500.16 | 724.92 | 8.44 | 11.61 |
| *H4* | 892.70 | 1318.47 | 12.66 | 18.99 |
| *H5* | 219.48 | 346.11 | 3.17 | 5.28 |
| *H6* | 217.59 | 315.51 | 3.17 | 5.28 |
| *M7* | 0 | 0 | 0 | 0 |
| *M8* | 217.37 | 315.50 | 3.17 | 5.28 |
| *L9* | 1119.33 | 1618.677 | 20.05 | 28.49 |
| *L10* | 525.51 | 778.68 | 13.72 | 18.99 |
| **Average (tons/year)** | 446.70 | 654.17 | 8.13 | 11.93 |
| **Average (tons/acre/year)** | **1.16** | **1.85** | **0.02** | **0.03** |

Sediment delivery was greatest in highly erosive areas directly adjacent to streams due to a higher sediment delivery ratio compared to that of hillslopes further from streams (Figure 22; Figure 23).

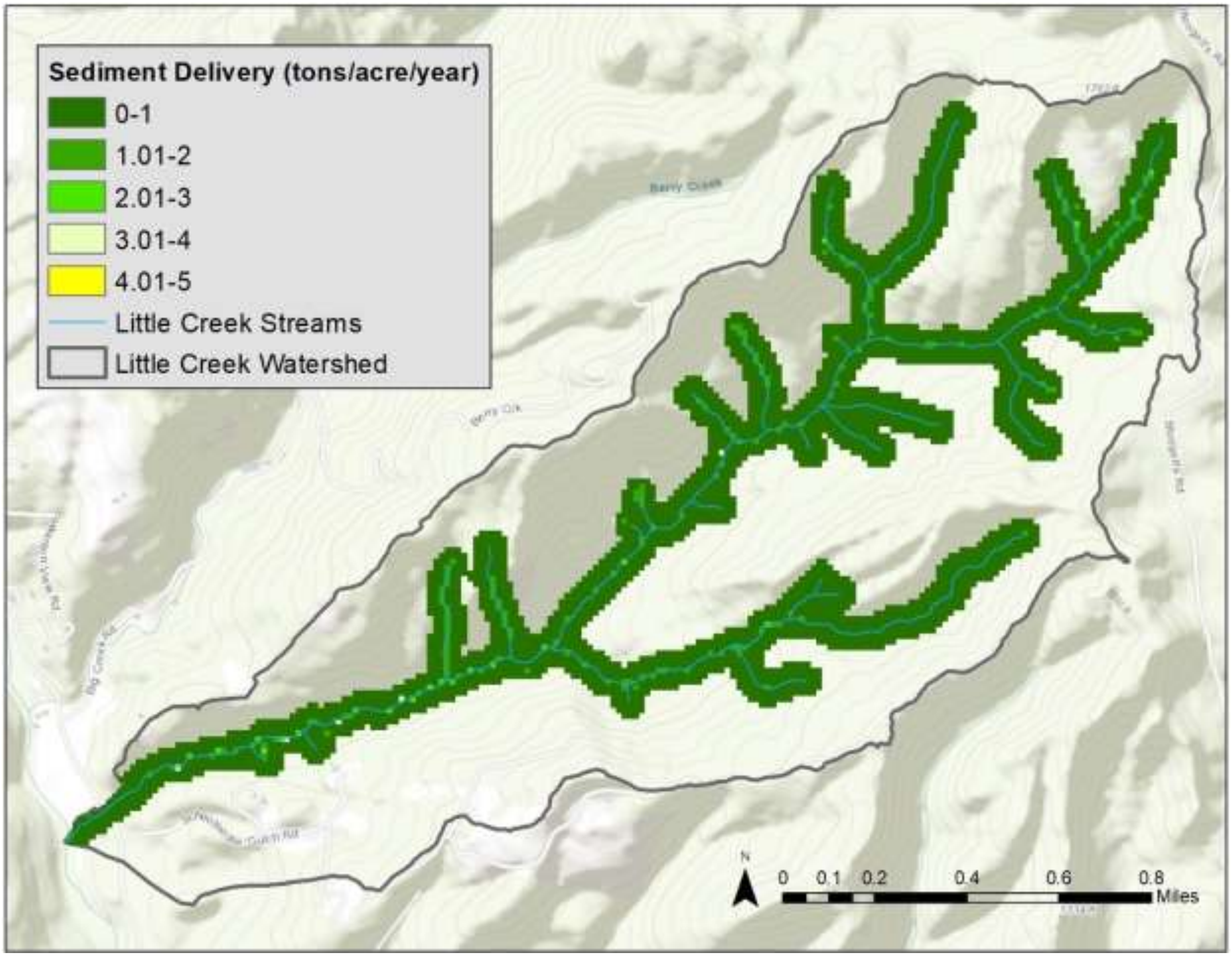


*Figure 22. Average annual sediment delivery in the Little Creek watershed based on post-fire conditions and study period precipitation (Scenario 1).*

Total sediment delivery to streams was greater in scenario 2 compared to scenario 1 due to higher erosion rates near streams (Figure 23).

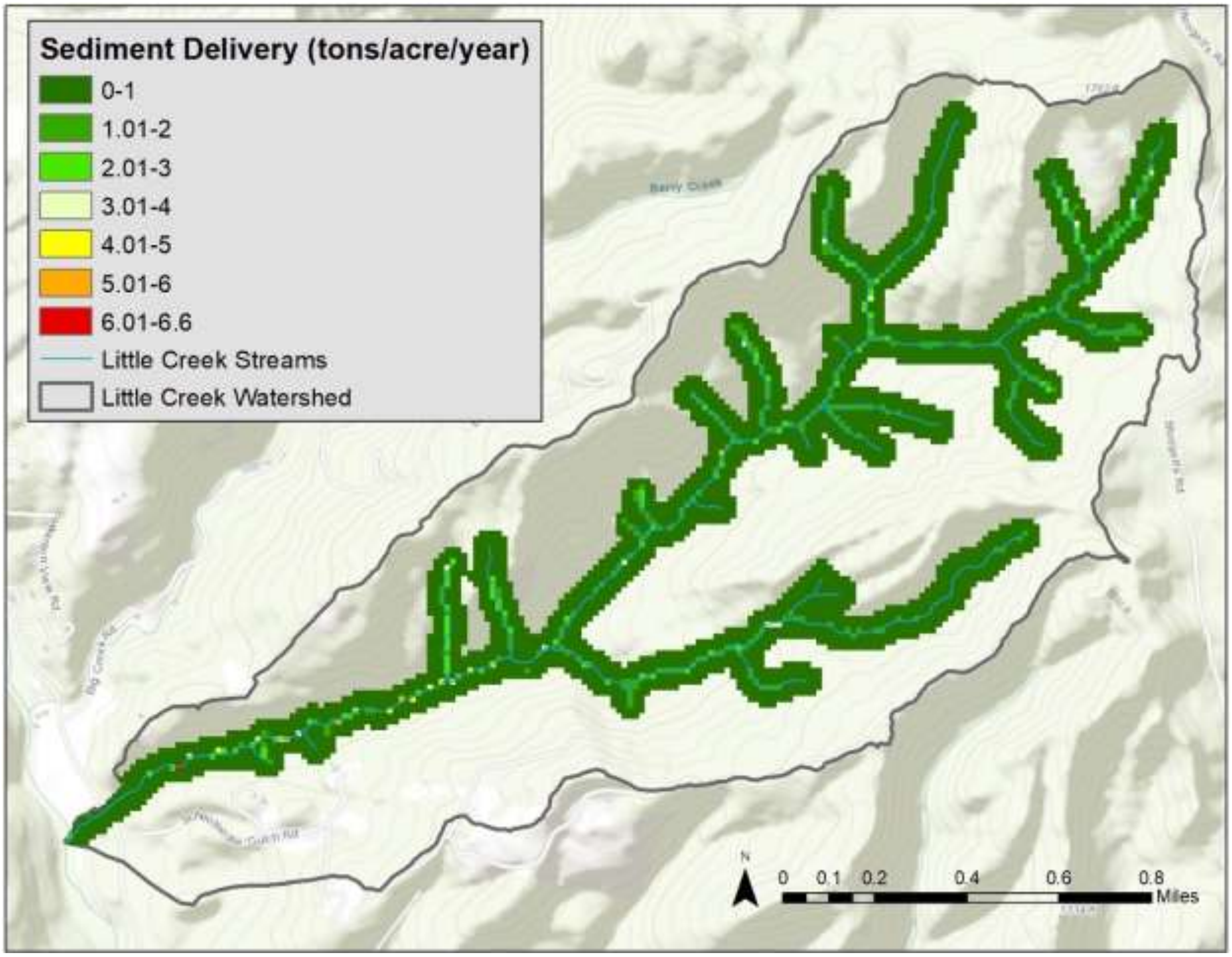


*Figure 23. Average annual sediment delivery in the Little Creek watershed based on post-fire conditions and long-term average precipitation (Scenario 2).*

## Chapter 5

## DISCUSSION

### 5.1 Drivers of Post-fire Hillslope Erosion

#### 5.1.1 Slope Steepness

Slope steepness was found to be the most influential factor influencing post-fire hillslope erosion, as steeper slopes were found to produce greater annual hillslope erosion rates. This was found true in both univariate and multivariate modelling. By itself, slope steepness was the only significant univariate predictor of the hillslope erosion rates and was able to explain 45% of the variability observed across the ten plots. Based on the coefficients in the multivariate model, slope steepness had twice the impact on the rate of hillslope erosion compared to percent soil cover, and four times greater impact than percent canopy coverage (Table 10).

Previous studies have also identified slope steepness to have the greatest influence on post-fire erosion (McCool et al 1987; Benavides-Solorio & MacDonald, 2001). Slope steepness produced the greatest post-fire hillslope erosion in a study conducted in the Lion's flat area of the Little Creek following the Lockheed fire **(**Loganbill, 2013**).**

While the literature suggests that a broad range of slopes is required to identify the impact of slope steepness towards hillslope erosion rates, we identified a significant relationship despite the narrow range of slopes represented across the ten plots (16-32 percent). In a study of post-fire hillslope erosion in the Colorado front range, Benavides-Solorio & MacDonald (2005) attributed slopes ranging from 25-45% to be too narrow of a range to avoid other controlling variables masking the influence of slope steepness. However, the results of this study indicate that hillslope erosion in the Little Creek watershed can be influenced by subtle changes in slope steepness. Further research may be needed to increase confidence in this claim due to the small sample size analyzed in this study. In addition, the study was dominated by a single soil type. Soil type often changes depending on slope steepness as factors including soil depth, infiltration rates, and drainage capacity are impacted. Future research should identify how slope steepness influences post-fire hillslope erosion rates across different soil types.

It should be noted that the study site was dominated by a single soil type. Soil type often changes depending on slope steepness as factors including soil depth, infiltration rates, and drainage capacity are impacted. Future research should identify how slope steepness influences post-fire hillslope erosion rates across different soil types.

### 5.1.2 Percent Soil Cover

Percent soil cover was not found to significantly influence post-fire hillslope erosion rates during univariate testing yet was significant when combined with slope steepness and percent canopy cover in the multivariate model. Percent soil cover is often attributed as the greatest predictor of post-fire erosion rates. While a relationship between percent soil cover and hillslope erosion rates was observed in the multivariate model, this relationship was not the most influential predictor, similar to other studies (Benavides-Solorio & MacDonald , 2005; Robuchaud et al, 2020) Soil coverage changed dramatically throughout the course of this study following significant rain in late December. Soil cover was found to increase by an average of 40% across the ten plots over the study period. The quality of soil cover also incurred substantial changes over time. Initial soil cover comprised of dead organic material and sparse live vegetation transitioned to dense live and leafy understory vegetation by the end of the study period. This emergence of high quality ground cover would have likely reduced hillslope erosion rates significantly (Pannkiuk & Robichaud, 2003). However, a significant absence of rainfall following the substantial revegetation in the study area limited our understanding of this relationship as no erosion occurred following the late December storms and subsequent revegetation. Previous studies suggest that at least 60% ground cover is needed to reduce post-fire hillslope erosion rates (Berg & Azuma, 2010; Pannkuk and Robichaud, 2003; Robichaud et al, 2020). Yet, our results suggest that ground cover values lower than 60% may be responsible for statistically significant reductions in hillslope erosion, given that all erosion occurred prior to the substantial increase in ground cover following the late December storms.  Therefore, ground cover values prior to the substantial regrowth in understory vegetation are more likely to represent soil cover values (31-74%) from the initial soil cover measurement at the beginning of the study period as opposed to cover values (52-100%) measured at the end of the study period.

This is highlighted when creating a multivariate model based on initial soil cover values instead of average values. When combined with slope steepness and canopy cover, initial percent soil cover values, the majority of which are less than 60%, remain significant predictors of hillslope erosion (Table 13).

*Table 13. Parameter estimates derived from the best multivariate model when assuming initial percent ground cover values.*

| Term | Estimate | Std Error | T-Ratio | P-Value |
|---|---|---|---|---|
| Intercept | 0.53 | 0.30 | 1.80 | 0.05 |
| Slope | 0.03 | 0.01 | 3.85 | 0.01 |
| Percent Soil Cover | -0.01 | .002 | -2.81 | 0.03 |
| Percent Canopy Cover | -0.01 | .002 | -2.90 | 0.03 |

These findings suggest that low soil cover, below 60%, significantly reduced the rate of post-fire hillslope erosion in this study.

As the timing of substantial revegetation of the understory appeared to be important in reducing erosion from hillslopes, accurate estimates regarding the timing of this occurrence would be beneficial for predicting the point after wildfire in which hillslope erosion rates are naturally mitigated by understory vegetation. This suggests that mitigation efforts are unlikely to be needed following the reestablishment of understory soil cover

### 5.1.3 Canopy Cover

Canopy coverage was found to be a statistically significant predictor of post-fire hillslope erosion rates when controlling for slope steepness and percent soil cover. Canopy cover was predominantly represented by scorched woody material and dead leaves. Live canopy cover in the study site was uncommon, burned trees maintained an average value of 49% cover across the ten plots. Although greater levels of canopy coverage were found to decrease rates of hillslope erosion, the opposite effect is commonly supported in previous studies (Rengers et al., 2016; Dunkerly, 2020; Cole et al., 2020). A greater presence of defoliated branches has been found to increase the size and kinetic energy of water droplets as interception occurs on defoliated branches leading to the coalescing of drops within the burned canopy. The relationship between canopy coverage and rate of hillslope erosion identified in the multivariate model suggests that the impact of droplet interception from defoliated branches may outweigh the impacts of increased droplet size.

### 5.1.4 Burn Severity

Burn severity was not found to be a significant predictor influencing rate of post-fire erosion from hillslopes during univariate and multivariate testing (Table 8). Previous studies attribute high soil burn severity with greater rates of hillslope erosion due to reductions in ground cover, the combustion and removal of canopy cover, and physical changes to the soil itself including the creation of a hydrophobic soil layer (De Bano et al., 1998; Shakesby and Doerr, 2006; Keesstra et al., 2014; Tessler et al., 2016). The literature also suggests that seed bank combustion can occur during severe fire, limiting the ability for recolonization of fire-adapted species (Kilgore and Biswell 1971, Weatherspoon,  1988, Moreno et al, 1991; Huffman et al, 2004; Knapp *et al.* 2007).

The normalized burn severity assessment method used is this study and commonly used among large land management agencies quantifies the degree of which a site has been altered by wildfire. These alterations include changes in the amount of living chlorophyl, reduced water content of soil and vegetation, and the increased presence of ash (Key, 2006; Kokaly et al., 2007). The amount of canopy combustion has been commonly identified as the strongest predictor of normalized burn severity, with the removal of canopy coverage resulting in greater burn severity designations (Miller et al, 2009; Harvey et al, 2009 ; Hoy et al, 2008; Wulder et al, 2009; Fassnacht et al, 2021).

While areas of high burn severity are likely to express little live canopy coverage, or results suggest that even defoliated branches are capable of reducing hillslope erosion rates. Canopy coverage in plots designated as high burn severity was higher than that of low and moderate severity plots, with low severity plots expressing the lowest canopy cover on average. Although high severity plots may have in fact experienced greater burn intensity, the abundance of retained canopy branches over these plots may have mitigated the severity of hillslope erosion.

Burn severity was found to influence changes in ground cover, with lowest soil cover observed in high burn severity plots on average at the beginning of the study period. These findings suggest that the normalized burn severity approach may effectively represent the degree of understory fuel combustion. Therefore, the level of remaining ground cover following a wildfire may be a better indication of burn severity, as these values are continuous rather than categorical classifications.

The timing of vegetative recolonization post-fire is also not predicted from the normalized burn severity approach, as this methodology is incapable of measuring impacts to soil seed banks (Lentile et al, 2007). A widespread revegetation of the study area, predominantly by *Cenaothus sp.*, was observed, with no indication of differences across different burn severities in the study area. While the dNBR approach may sufficiently quantify impacts to soil ground cover during the initial post-fire period, observations from this study imply that that burn severity classifications may be ineffective in predicting understory vegetative recolonization following the first year after wildfire. Therefore, the effects of burn severity towards influencing hillslope erosion rates may be masked by spatial variations in soil seed banks and the species which are present.

Small sample sizes for each burn severity classification in this study should be highlighted. This may have increased the likelihood of a Type 2 error, meaning that a true relationship between burn severity and hillslope erosion was masked by a small sample size. Future research would be improved by studying larger sample of hillslope erosion rates for each burn severity designation to reduce the chances of a Type 2 error.

### 5.2 Pre-fire vs Post-Fire Hillslope Erosion Rates

Results from the USLE spatial extrapolation identified an increase in hillslope erosion within the Little Creek watershed under post-fire conditions. Annual hillslope erosion rates were quantified to be 4.23 tons/acre on average throughout the watershed area using the measured winter precipitation values from the 2021-2022 in the model. Using the same monthly precipitation values,  the pre-fire annual average erosion rate for the watershed was found to be 0.08 tons/acre.  When integrating long-term average monthly precipitation totals into the USLE, average annual hillslope erosion jumped to 6.20 tons/acre/year post-fire, and 0.11 tons/acre/year under pre-fire conditions. Drastic differences in hillslope erosion rates between pre-fire and post-fire scenarios highlight the strong influence of percent soil cover for determining model outputs.

Post-fire conditions resulted in watershed average hillslope soil loss greater than the watershed average annual soil loss tolerance factor of 2.4 tons/acre. This causes reason to believe that soil health might have degraded in the Little Creek watershed during the second year following CZU Lightning Complex fire. First year post-fire hillslope erosion estimates are supplied from the WERT evaluation of the CZU Lightning Complex.  Using the Erosion Risk Management Tool (ERMiT), they predicted a hillslope erosion rate 5-10 tons/acre for the Little Creek watershed following a 50% (2-year) storm event (WERT, 2020).  While the annual rate of hillslope erosion during the first-year post-fire is unclear from their analysis, it is evident that this value is much higher than our estimates from the second-year post-fire (WERT, 2020). A previous hillslope erosion study using silt fence traps and conducted in the Little Creek watershed in the first year following the Lockheed fire in 2009 quantified annual hillslope erosion rates according to different slope classes, with an average rate of 2.83 tons/acre/year (Table 14) (Loganbill, 2013).

*Table 14. Results from a post-fire erosion study following the 2009 Lockheed fire at Swanton Pacific Ranch (Loganbill, 2013).*

| Slope Class (%) | Annual Hillslope Erosion Rate (tons/acre/year) |
|---|---|
| *0-54* | 2.64 |
| *55-74* | 1.42 |
| *75+* | 4.54 |
| ***Average*** | **2.83** |

While these values are confined to their study site and do not represent the overall watershed erosion rates, the results assist in comparing hillslope erosion rates between the first and second post-fire years. While this reason in addition to differences in precipitation, slope, and other factors including soil and canopy cover prevent a direct comparison of the two studies, it can be assumed that hillslope erosion rates remained substantial in the second year following the CZU Lightning complex.

While the USLE spatial extrapolation utilized slope steepness and percent soil cover, two factors we identified to be statistically significant towards hillslope erosion rates, it did not incorporate field measurements for percent canopy cover. Instead, the C-factor represented understory vegetation cover alone and not canopy coverage. Because canopy cover was found to be a significant predictor of hillslope erosion rates, it is important to note the absence of this predictor within the model and the potential resulting model inaccuracies.

### 5.3 Pre-fire and Post-Fire Sediment Delivery to Streams

Total annual post-fire sediment delivery to streams from soil erosion the 2$^{nd}$ year post-fire, in the Little Creek watershed, was found to be roughly 447 tons when using the measured 2021-2022 precipitation.  This equates to 1.16 tons/acre/year from the identified contributing area.  Pre-fire annual sediment delivery using the same precipitation values quantified sediment delivery at roughly 8 tons, or 0.02 tons/acre/year from hillslopes near streams.  Assessing the accuracy of these predictions proves difficult in result to a substantial lack of research in the watershed regarding sediment delivery from hillslopes and inconsistent methods for determining baseline and post-fire sediment delivery ratios. Long-term sediment measurements in the watershed exists, however these data represent only suspended sediment loads in streams following substantial precipitation events (Loganbill, 2013). In addition, the source of the sediment is not confined to hillslopes alone, but also includes sediment derived from rill and channel erosion. Regarding sediment delivery ratio uncertainties, the methods utilized in this study fail to account for changes in sediment delivery following a wildfire. The combustion of ground vegetation is likely to result in a greater watershed sediment delivery ratio during post-fire conditions (Goode and Luce, 2012). Therefore, it is possible that the predicted post-fire sediment delivery estimates are on the low-end.

While increases in sediment delivery are likely to alter aquatic habitats, further research is needed to determine the degree of increase sediment delivery necessary to degrade aquatic ecosystems.  In addition, a better understanding of pre-fire and post-fire sediment delivery ratios at the watershed scale are necessary to accurately quantify how increased erosion from hillslopes following wildfire influences the degree of sediment delivery to streams.

## Chapter 6

# CONCLUSION

Hillslope erosion was measured from 10 silt fence plots located within the Little Creek watershed in the Santa Cruz mountains of California, an area greatly impacted by the CZU Lightning complex of August 2020. Burn severity was not found to be a significant predictor of post-fire erosion from hillslopes.  Slope steepness was found to be the greatest predictor of hillslope erosion rate of the seven measured explanatory variables. Slope steepness by itself was found to explain roughly 45% of the total variability of hillslope erosion across the ten plots and was the only statistically significant stand-alone explanatory variable. When combined with slope in a multivariate statistical model, percent soil cover and percent canopy cover were found to be significant predictors of hillslope erosion rates. The multivariate model was able to explain roughly 86% of hillslope erosion variability across the ten plots. These results imply that post-fire hillslope erosion rates in the study area is influenced by multiple explanatory variables including slope steepness, percent soil cover, and percent canopy cover, with the relative influence towards influencing hillslope erosion in that order.

Field-data measured from the silt fence plots was used to calibrate the Universal Soil Loss Equation (USLE) to spatially extrapolate hillslope erosion for the entire larger area of the Little Creek watershed. Results from the spatial extrapolation inform our understanding of how wildfire and differences in monthly precipitation totals influence the rate of hillslope erosion at the watershed scale. Post-fire erosion using monthly precipitation values which occurred during the study period found average annual watershed erosion rates form hillslopes to be 4.23 tons/acre. This value climbed to 6.20 tons/acre when assuming long term average monthly precipitation values.  Post-fire erosion rates were found to be 53 and 58 times greater than pre-fire rates when utilizing observed and long-term precipitation values respectively. Post-fire sediment delivery from hillslopes to streams under average precipitation conditions was predicted to be roughly 62 times greater than pre-fire rates. However, there are uncertainties regarding pre- and post-fire sediment delivery ratios.

Hillslope erosion in the second year following the CZU Lightning Complex fire remained substantial in the Little creek watershed prior to substantial revegetation of understory species following substantial rain events in late December. Prior to this, average erosion rates exceeded the watershed average soil loss tolerance factor. Post-fire erosion was found to be most significant in areas where steep slopes were present, and soil and canopy cover were minimal. These three factors combined to significantly explain the observed variability in post-fire hillslope erosion.

While burn severity is often considered an accurate predictor of the severity of post-fire erosion, our findings suggested that the normalized burn ratio (dNBR) approach for quantifying soil burn severity may lead to inaccurate erosion estimates. The timing and degree of understory vegetation reestablishment was not observed to be influenced by different burn severity classifications, as the dNBR approach is incapable of considering spatial variability in soil seed banks and the presence of different species and their corresponding post-fire dynamics. While initial dNBR assumptions of soil cover in the short period following a wildfire may improve the relationship between soil burn severity and hillslope erosion in the first-year post-fire, results from this study imply that this relationship is weakened as the time since wildfire increases.

While some studies imply that a broad range of slopes is needed to lead to differing rates of hillslope erosion, our findings suggest that a narrow range of slopes can significantly influence post-erosion in the Little Creek watershed. In additions, the commonly held belief that 60% soil cover is needed to reduce hillslope erosion was not found to be true in the study area, as low-quality soil cover below 60% was found to significantly influence hillslope erosion when controlling for slope and percent canopy cover. In addition, while retained scorched canopy cover has been attributed to increased rates of post-fire erosion due to the potential for greater soil particle detachment from increased droplet size, our findings suggest that rainfall interception derived from defoliated branches reduced hillslope erosion and masked the effects of increase droplet size.

The results of this study provide pertinent information to land managers and policy-makers in their understanding of how wildfire impacts hillslope erosion rates in the Santa Cruz region. By identifying the significant drivers of accelerated erosion, interested groups can better predict where severe hillslope erosion is likely to occur. In addition, the degree of difference between pre-fire and post-fire erosion rates identified in this study provides these groups with context regarding the severity of post-fire erosion. Further, our findings provide a basis to explore the resulting ecological impacts of these erosion estimates, strengthening the reasoning and effectiveness of post-fire management decisions.

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## Chapter 7

# OVERVIEW OF POST-FIRE EROSION POLICY AND RECOMMENDED POLICY CHANGES

The increase in size and severity of wildfires in recent decades in California has drawn greater attention to post-fire response and the mitigation of secondary disasters and their resulting environmental impacts. Post-fire response is largely centered around assessing the risks to human life and property from hazardous events such as debris flows, flooding, or other soil mass movements. In response, land managers and erosion emergency response teams may conduct or recommend a range of mitigation practices aimed at reducing post-fire soil impacts. In addition, land managers may conduct different types of forest management depending on the management goals in a post-fire context. We provide an overview of the goals and functions of erosion emergency response agencies, highlight common erosion mitigation strategies, and describe common post-fire forest treatments which can influence erosion rates. Based on stakeholder interviews, literature review, and the findings from our post-fire hillslope erosion study, we identify the current problems limiting the effectiveness of post-fire erosion control and provide recommendations for future policy changes and best management practices aimed at reducing post-fire erosion.

## 7.1 Post-fire Erosion Emergency Response Teams

A review of post-fire response policy in California highlights two major working groups driving post-fire erosion policy and management; the Burned Area Emergency Response (BAER) and Watershed Emergency Response Team (WERT).

### 7.1.2 Burned Area Emergency Response Team

The Burned Area Emergency Response (BAER) is a sector within the USFS comprised of fire and resource specialists including hydrologists, foresters, engineers, and archaeologists (Napper, 2006). The objective statement of BAER states: *"To identify imminent post-wildfire threats to human life and safety, property, and critical natural or cultural resources on National Forest System lands and take immediate actions, as appropriate, to manage unacceptable risks."* BAER provides an assessment within seven days of full containment of wildfires larger than 500 acres on National Forestlands, or for smaller fires if threats from soil movement or debris flows exist. This assessment involves the creation of debris flow risk maps which highlight areas of concern (Napper, 2006). These maps are typically created by the U.S Geological Survey and use the proximity of high burn severity areas to steep slopes to model the likelihood of debris flows in burned areas receiving peak rainfall of 0.25 inches in 15 minutes (Foltz et al, 2009). BAER may choose to undergo mitigation and response measures only when such actions are likely to significantly reduce post-fire risks in the following year. In addition, the response measures must comply with local land and resource management plans. In the three years following BAER response, hazard reduction monitoring and repairs occur. BAER response measures are carried out and managed by regional foresters (Parsons, 2003).

### 7.1.3 Watershed Emergency Response Team

Post-fire response in California is also conducted by the Watershed Emergency Response Team (WERT), a collaborative agency group involving CAL Fire, the California Geological Society, and the Department of Water Resources (Cafferata et al., 2021). The main goals of WERT are to provide rapid assessment of values at risk (VARs), particularly those which threaten human safety or property including debris flows, flooding, and rock falls. Registered professional foresters and environmental scientist operate on state responsibility areas (SRA) to develop soil burn severity maps, model debris flow risk through the use of the USGS Post-Fire Debris Flow model, assess post-fire hillslope sediment production using the Erosion Risk Managemnt Tool (ERMit), provide recommendations to mitigate hazards, and communicate these risks and mitigations to affected and/or responsible stakeholders (Silver Jackets, 2020). While WERT recommends protection measures to groups at risk, a lack of a direct funding mechanism limits the enforcement of recommended measures. Therefore, responsibility lies on the landowner to carry out post-fire erosion mitigation. Further, WERT assigns less emphasis on protecting cultural and natural resources from post-fire hazards as compared to BAER which embodies a more holistic view of values at risk.

## 7.2 Overview of Common Post-fire Erosion Mitigation Practices

Post-fire erosion mitigation measures carried out or recommended by BAER and WERT often involve four management practices including mulching, seeding, erosion barriers, and maintenance of forest road infrastructure. We provide a description of each of these management practices.

### 7.2.1 Mulching

In some cases, mulch is spread over the soil surface in burned areas (Bautista et al, 2009; Prats et al, 2019; Robichaud et al., 2013; Bautista et al, 1996). The materials used for mulch vary, and include paper, woodchips, wheat, strap, jute, or natural synthetic fabrics (Robichaud et al., 2013). Some mulches may also have seeds mixed in to facilitate plant growth alongside soil coverage.  A relatively new form of post-fire mulch, hydro-mulch, combines a mixture of fiber, seeds and tackifier that forms a protective soil barrier when mixed with water (Vieira et al., 2018). Mulching is generally confined to target areas where erosion risk is substantial. Cover to the soil surface is provided, reducing the risk of particle detachment and slowing the rate of overland flow (Prats et al., 2019). In their study testing the effectiveness of mulch in reducing hillslope erosion rates, Robichaud et al., (2013) analyzed the performance of wood strand mulch, wheat straw mulch, and hydro-mulch. Wood stand mulch was effective in reducing hillslope erosion across all areas it was tested, whereas straw mulch reduced erosion in half of the treatments. Hydro-mulch was not found to reduce hillslope erosion post-fire (Robichaud et al., 2013). In part two of this study, the effectiveness of wheat straw mulch and hydro-mulch were compared. Wheat straw mulch was found to significantly reduce erosion yields, while hydro-mulch proved ineffective due to dramatic declines in ground coverage shortly after application (Robichaud et al., 2013). This highlights the importance of maintaining ground cover when selecting the mulch type for use in post-fire mulching treatments.

### 7.2.2 Post-fire Seeding

Post-fire seeding of grasses is a common post-fire mitigation approach (Fernandez et al, 2012; Kruse et al, 2004; Eiswerth et al., 2009; Diaz-Ravina et al., 2012. Historically, seeding was conducted from the air (Loftin, 2004). It aims to increase soil coverage by facilitating plant growth in freshly burned soils. In addition, it was intended to reduce invasive species colonization following wildfires (Eiswerth et al., 2009). While the most common mitigation practice historically, post-fire seeding rarely occurs today. Wagenbrenner and MacDonald (2006) found no increase in ground cover from seeding in 22 treated plots. However, seeding has been proven effective in other studies (eg., Fernandez et al., 2012; Diaz-Ravina et al., 2012). Like mulch, the effectiveness of post-fire seeding is largely tied to its effectiveness in increasing ground coverage.

While seeding may be effective in providing adequate soil cover, many argue that this practice limits the capacity for natural germination of post-fire species, while also introducing invasive species into the ecosystem (Beyers, 2004).

### 7.2.3 Erosion barriers

Erosion barriers are intended to reduce the velocity of overland flow, increase water infiltration, and obstruct the downhill travel of sediment.  Common erosion barriers include straw bales, straw wattles, contour-felled logs, and hillslope trenching. Erosion barriers are often utilized on steep slopes where significant soil erosion is likely, or alongside streams to prevent sedimentation (Fernandez et al., 2019; Robichaud et al., 2008; Fernandez et al., 2011). Wagenbrenner and MacDonald (2006) found strong variability in the effectiveness of contour-felled logs towards reducing hillside sediment loads. They found contour-felled logs effective in intercepting sediment generated in an average year, however, their effectiveness was limited during large storms. Fernandez et al. (2009) found no changes in hillslope erosion when comparing plots treated with erosion barriers. Highly high annual precipitation following the during the first year after wildfire in this study may further highlight the limitations of erosion barriers in relation to high precipitation.

### 7.2.4 Maintenance of Forest Road Infrastructure

Forest road infrastructure can create significant erosion concerns following a wildfire. Forests roads, particularly those that are unpaved, are designed to divert water away from the road surface towards a desired location. A sufficient diversion of water during storm events prevents washouts which can deliver substantial amounts of soil to nearby watercourses. While forest roads are often designed to accommodate peak flows in pre-fire conditions, these peak flows can be exceeded in post-fire conditions leaving roads susceptible to failure (Foltz et al.

2009). In post-fire conditions, culvert sizes may be upgraded to sufficiently pass higher flow rates. In extreme cases and often in fish-bearing streams, culverts may be completely removed to prevent road failure (Foltz et al, 2009). Other practices include increasing the frequency of rolling dips and water bars to allow for greater water diversion from the road surface in post-fire conditions (Foltz et al, 2009). Drainage crossings may also be armored with rock to prevent channel excision during peak flow events (Neary et al, 2011). Further, roadside ditches may need to be repetitively cleared to accommodate greater accumulations of forest debris (Foltz et al, 2009).

## 7.3 Post-fire Forest Treatments

Post-fire forest treatments are often conducted in burned forests to achieve various management goals. Forest treatments following a wildfire generally involve two main practices: salvage timber harvesting and fuels reduction treatments.

### 7.3.1 Salvage Timber Harvesting

Salvage timber harvesting generally occurs on private timberlands to obtain remaining value from burned merchantable timber. Big Creek Lumber company, owners of private timberlands in the Santa Cruz, San Mateo, and Santa Clara counties, conducted substantial salvage operations following the CZU Lightning complex fire after a considerable portion of their timberlands were burned. Salvage logging often qualifies under emergency exemptions described in the California practice rules. Timberland owners can bypass submitting a complete Timber Harvest Plan (THP) under emergency exemptions, while still required to follow the forest practice requirements described in the California forest practice rules. Following the submission of an emergency exemption to the Department of Forestry and Fire Protection, the local Regional Water Quality Control Board (RWQCB) is involved and may require further water quality monitoring and erosion control measures beyond those stated in the forest practice rules (California Department of Forestry and Fire Protection, 2020).

### 7.3.2 Fuels Reduction Forest Treatments

Fuels reduction treatments following wildfire are carried out when the management goal is centered around reducing fire hazard and improving forest health. Dead trees retained on the landscape increase fire risk given the increased presence of dead and dry fuels (Jenkins et al, 2008). CAL Fire’s Forest Health Grant program provides funds to owners of state land to conduct forest treatments that reduce fuels, reintroduce beneficial fire, and management of forest pests and diseases (Schwartz & Marte, 2019). Swanton Pacific Ranch was provided funding under this grant program to conduct post-fire forest treatments on 146 acres including log removal, lop and scatter treatments, piling and burning, and hazard tree removal. Projects such as this are required to comply with the California Forest Practice Rules and local Non-Industrial Timber management Plans (NTMP) in regard to forest practices and erosion control measures (California Department of Forestry and Fire Protection, 2020).

## 7.4 Current Problems Related to Post-fire Erosion Control and Policy Recommendations

Interviews with stakeholders, a review of the scientific literature pertaining to post-fire response, and the results of our hillslope erosion study identified specific problems limiting the effectiveness of post-fire erosion control as well of future policy and management steps in response.

### 7.4.1 Stakeholder Interviews

Interviews with four registered professional foresters were conducted in January and August 2022. Two individuals actively practice in the Santa Cruz region and directly experienced the CZU Lightning Complex fire. Their high level of knowledge pertaining to local ecology, regional forest management, and direct experience working in a post-fire context made them excellent interview candidates.  The third individual interviewed has considerable experience working in a post-fire forest management and has been actively involved with post-fire forest management following the Caldor fire near Pollock Pines, CA. The final interviewee is a previous Executive Officer of the California Board of Forestry and Fire Protection and possesses a robust understanding of the California Forest Practice Rules. The goal of these interviews was to understand professional opinions regarding the status of post-fire erosion control. Each individual was asked to provide recommendations for improving post-fire erosion control in the region. We provide a summary of these interviews and describe recommendations for improving post-fire erosion control.

1) Large blanket erosion control practices such as mulching and seeding are unlikely to be feasible or appropriate due to difficulties in implementing these practices and their negative impacts to natural ecological processes
    a. Many landowners lack incentives to manage post-fire erosion if threats to human life and property are unlikely.
    b. Erosion control practices that cover the soil prevent natural regeneration of fire adapted species. Further, post-fire seeding often introduces invasive species into the ecosystem which can present long term impacts. One forester noted that rare species that had not been observed in over 80 years were found present in the post-fire landscape following the CZU Lightning Complex fire.
2) Post-fire erosion control is costly and burdensome to landowners. WERT cannot enforce management and can only recommend protection measures for values at risk to landowners and local governments due to a lack of direct funding. Direct funding paths

from state and local government should be created to relieve these burdens and increase the capacity for erosion control for smaller landowners.

3) Priority should be given to maintaining forest road infrastructure given its capacity to contribute large sediment loads. Large washouts of forest roads were observed following the CZU Lightning Complex fire and Caldor fire due to clogged culverts and deep gullying of road surfaces.
    a. Decreasing the spacing of water bars on forest roads should be considered to reduce sediment delivery from road surfaces, especially when roads exist adjacent to watercourses.
    b. Forest stream crossings be frequently checked to prevent the clogging of culverts
    c. Landowners should create an inventory of water crossing locations to improve the efficiency of post-fire response
4) The effectiveness of the minimum requirements for erosion control as described in the California forest Practice Rules should be re-evaluated in a post-fire context.
    a. Current requirements may be inadequate towards controlling erosion during post-fire forest treatments given accelerated rates of erosion after wildfire.
    b. Current erosion hazard ratings for water bar spacing requirements are likely to underrepresent the erosion hazard in a post-fire context.
5) Soil burn severity is often misrepresented by the dNBR approach, as low severity fire may persist longer on the soil surface and result in greater losses of soil ground cover and destruction of the seed banks of understory species.
6) Post-fire forest activities should utilize existing or historic skid trails to reduce soil impacts. LiDAR imagery is an effective tool for identifying previously used skid trails.

7) Tolerable levels of sediment delivery to streams in a post-fire context is understudied. Further research is needed to identify this threshold to best protect the health of aquatic habitats.

### 7.4.2 Literature Review

A literature review was conducted to identify current issues related to post-fire erosion control. We summarize these problems and provide recommendations to mitigate them.

1) A gap between researchers and land managers currently exists, resulting in un-guided post-fire policy and mitigation (Chen et al., 2013). This gap is largely driven by a lack of synthesis in the scientific data, and attributes of land management agencies including their relationship to public opinion or political influence (Olsen and Shindler, 2010; Daley, 2009).
2) Erosion risk assessment methods are highly variable and use different methods and model inputs (Lopes et al, 2021).
3) Erosion risk assessment prioritize risks to human life and property and do not consider risks to soil health (WERT, 2020).
4) Many erosion risk assessment methods do not consider hillslope erosion, only debris flow risk (Foltz et al, 2009).
5) ERMit is difficult to apply at a watershed scale. This method assumes rectangular hillslopes which limits prediction accuracy at the watershed scale (Foltz et al, 2009).
6) The USGS debris flow model requires identification of the degree of increase of runoff rates in moderate and moderate and high burn severity which is difficult to determine across spatial variability (Foltz et al, 2009).

7) The USGS debris flow model lacks substantial validation outside of Southern California, Intermountain west, Southwest, and Colorado front range (WERT, 2020).
8) Predictive models used for post-fire risk evaluation are often not backed by field verification, or models lack calibration necessary to account for environmental conditions unique to the region. (Lopes et al., 2021).
9) Post-fire changes in watershed sediment delivery ratios are understudied preventing our understanding of how accelerated hillslope erosion impacts sediment delivery to streams (Walling, 1983).
10) Slash should be added to water bar outlets. This was found to result in greater reductions in sediment delivery when compared to applying slash only to skid trail surface (Wagenbrenner et al, 2020).

### 7.4.3 Recommendations as a Result of Hillslope Erosion Study

The results of our post-fire hillslope erosion study indicate that slope steepness, percent soil cover, and percent canopy cover are significant drivers of hillslope erosion rates in the Little Creek watershed. Accelerated erosion on steep slopes is likely due to greater speeds of overland flow and increase soil instability. Greater soil coverage is believed to shield the soil surface from detachment while also decreasing the speed of overland flow. Increased canopy cover provides rain interception resulting in decreased rates of soil detachment. These factors assist in determining areas where accelerated hillslope erosion is likely to occur and should be considered when conducting post-fire response activities.

1) Prioritized post-fire erosion control in the Santa Cruz region should be implemented on steep slopes where vegetation cover and canopy cover are minimal.

2) Post-fire erosion control in the Santa Cruz region, if implemented, is unlikely to be needed following substantial rain during the second year following wildfire as considerable reestablishment of understory vegetation provides natural erosion control.
3) Skid trails and temporary seasonal roads should be covered with slash, especially on steep slopes, to enhance soil cover and reduce soil detachment.
4) In addition to threats to human life and property, agency risk assessments should consider soil health and tolerable soil loss when recommending and implementing erosion management.
5) Post-fire treatments should consider retaining dead non-merchantable trees if they express significant amounts of canopy coverage.

## 7.5 Summary of Recommendations

We present the main problems and subsequent recommended policy changes to improve post-fire erosion hazard assessments, erosion mitigation activities, and post-fire forest management.

### 7.5.1 Improving Erosion Risk Assessment

***Problem #1*** *Current erosion risk assessments are highly variable across agencies and spatial scales.*

**Solution** Erosion risk assessments methods should be standardized across agencies and spatial scales to maintain similar model inputs to decrease variability of model outputs and improve stakeholder understanding.

***Problem #2*** *Current erosion risk assessments rarely consider impacts to soil health.*

**Solution** Incorporate an analysis of impacts to soil health into the current erosion risk assessment framework. Consider comparing hillslope erosion losses to the soil loss tolerance factor to identify areas where severe soil degradation is likely to occur in order to mitigate these impacts accordingly.

***Problem #3*** *Current erosion risk assessment methods lack field validation across spatial scales and often require specific inputs for the watershed being analyzed.*

**Solution** Prioritize field studies of post-fire erosion in understudied areas and in regions where predictive models lack field verification. Synthesize findings to provide model inputs and calibrations to agencies and land managers conducting erosion risk assessment across regional variability.

***Problem #4*** *Current erosion risk assessments often rely on soil burn severity from remote sensing sources to predict erosion hazards. However, current burn severity assessment methods may misrepresent changes in post-fire hillslope erosion as observed in our hillslope post-fire erosion.*

***Solution*** Consider using percent soil cover instead of burn severity to predict post-fire erosion rates. Utilizing this variable accounts for spatial variability in vegetation response, something not accounted for in common soil burn severity designations.

***Problem #5*** *A standardized approach for predicting post-fire sediment delivery is lacking and current methods commonly rely on a "black box" approach.*

**Solution** Prioritize further research regarding fire's effect on changes in watershed sediment delivery ratios. Develop and database of pre- and post-fire sediment delivery ratios in specific watersheds to identify patterns and significant drivers of accelerated sediment delivery ratios to apply in watersheds across regional variability.

### 7.5.2 Improving Post-fire Hillslope Erosion Mitigation

***Problem #1*** *The feasibility of implementing common hillslope erosion control measures is limited due to financial burdens placed on landowners.*

**Solution** Develop direct funding paths through state or local governments for landowners interested in conducting post-fire erosion control measures.

***Problem #2*** *Post-fire seeding is likely to result in adverse environmental impacts which limits natural ecological post-fire processes.*

**Solution** Consider implementing hillslope erosion control practices in strategic areas with methods that allow for natural ecological recovery such as erosion barriers.

***Problem #3*** *A gap between researchers and land managers limits the capacity for scientifically driven post-fire erosion management*

**Solution** Our findings suggest that post-fire erosion mitigation, if implemented, should be prioritized in areas with steep slopes and minimal soil and canopy coverage. Mitigation efforts are likely to be no longer necessary following substantial rains during the second-year post-fire as understory revegetation provides adequate soil protection.

### 7.5.3 Improving Post-fire Forest Practices

***Problem #1*** *Requirements for erosion control during post-fire operations are based on pre-fire assessments of erosion hazard which are likely to become elevated following wildfire.*

**Solution** Classify erosion hazard ratings specific to post-fire conditions in the California Forest Practice rules to manage for increased erosion rates following wildfire.

***Problem #2*** *Forest road infrastructure contributes to large erosion inputs following a wildfire.*

**Solution** Best management practices to reduce soil erosion from forest roads include:

1) Increase the frequency of water bars on forest roads and skid trails.
2) Pack slash into water bar outlets to provide soil coverage and decrease erosion.
3) Pack slash onto the downslope edge of the roads in close proximity to watercourses to minimize sediment delivery from roads.
4) Consider removing unnecessary water crossings to reduce the likelihood of road collapse due to culvert failure.
5) Landowners and managers should develop a geodatabase of road infrastructure (ex. culverts, stream crossings, bridges) to increase the efficiency of post-fire road monitoring and restoration.

***Problem #3*** *The California Forest Practice Rules provide minimum requirements for erosion control which may not be sufficient during post-fire operations.*

**Solution** The Board of Forestry and Fire Protection should create a Best Management Practice manual to educate licensed timber officers operating in a post-fire environment with the following recommendations, among others.

1) Utilize LiDAR imagery to identify previously utilized skid trails to minimize additional soil disturbance.
2) Choose skid trail palls that follow the contours of the hillslope and avoid skidding patterns which route sediment to watercourses.
3) Retain non-merchantable material during salvage operations to retain canopy coverage.
4) Consider contour ripping hillslopes to increase soil water infiltration capacity and to orient woody material perpendicular to the hillslope to create erosion barriers.
5) Pack slash onto skid trails to provide soil coverage and reduce soil impacts from heavy equipment.
6) Frequently monitor treated areas to identify erosion hotspots, especially after large rain events, to mitigate accordingly.

### 7.6 Conclusion

Some argue that post-fire response for mitigating accelerated erosion is lacking in its effectiveness for reducing threats to the environment and human life and safety (Chen et al., 2013). Predictions for the continued occurrence of severe wildfires in California give reason for emphasizing the improvement of post-fire erosion control. The current issues and recommended changes we have identified are beneficial to the agencies, landowners, and other interested parties seeking to better mitigate impacts from accelerated rates of erosion following wildfire. An implementation of these recommendations requires effective collaboration between researchers, policy and regulatory groups, and land managers. These groups should be accepting of an adaptive management approach which considers altering management strategies according to newly discovered information.

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