Spring 5-18-2018

Causal Fire Relationships in Sonoma County & Identification of Suitable Fire Management Strategies

Allison Howlett
amhowlett@dons.usfca.edu

This Master's Project

Causal Fire Relationships in Sonoma County & Identification of Suitable Fire Management Strategies

by

Allison Howlett

is submitted in partial fulfillment of the requirements

for the degree of:

Master of Science

in

Environmental Management

at the

University of San Francisco

Submitted:	Received:
________________________________	________________________________
Allison Howlett Date	Amalia Kokkinaki, Ph. D. Date

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Acknowledging recent wildfires that have set historic fire size records in both Northern and Southern California, it is important to understand what impacts can be expected and how variations in regional characteristics can influence fire severity. Combining a long history of droughts alongside periodic rain events this paper considers the causal fire relationships and fire management strategies necessary for implementation for future fire size and fire severity reduction in Sonoma County. Throughout this paper a subset of questions are answered regarding fire severity, precipitation, erosion and sediment response. Methods include the examination of peer-reviewed articles and grey sources to identify fire characteristics in relation to severity and region, habitat resilience and ability for self-restoration, and impacts that have been seen in areas following a fire. A comparative analysis was then made to assess the correlation between topography, soil burn severity, precipitation, vegetative cover, and acreage burned in order to determine the most suitable fire management practices to reduce severity and future fire occurrence. Data collected has been synthesized and presented throughout the paper in synthesis tables for additional examination and understanding. Further research included within this paper is an examination of various post-fire management measures and strategies to identify those most suitable for Sonoma County. In Sonoma County regional characteristics influence post-fire management practices, while the relationships between fire severity, soil composition, habitat and precipitation shape impacts. Analysis of average annual rainfall, average elevation, average elevation change, vegetative cover and soil burn severity were completed for seven fires. No correlation was identified between average annual rainfall and acreage burned. For both average elevation and average elevation change, acreage burned increased with increasing elevation and elevational change. All fires evaluated were in chaparral regions. Soil burn severity analysis found that severity tends to be distributed similarly among fires, with the greatest percentage of land having unburned or low severity, followed by moderate and high burn severity. Recommendations include the utilization of community education and awareness programs, wildland fire use and prescribed fire as fire management strategies to protect and prevent against large, severe and economically burdening fires.

1. INTRODUCTION

Ecosystems involve a complex interrelationship of many interacting factors, including the relationship of forests and wildfires. Forests contribute invaluable support to ecosystems throughout the world, providing ecosystem services and supporting both flora and fauna. Forests provide critical services to humanity. Oftentimes these values are difficult to accurately monetize, as the values assigned may not fully capture the economic benefit observed indirectly from forested ecosystems. An ecosystem service is a measurable benefit obtained from an ecosystem. A healthy forest is defined by its ability to provide a functional equilibrium between supply and demand of natural resources; diversity in cover types, stand structures and seral stages; its physical environment, resources and trophic networks; and its ability to resist large changes in populations of organisms that serve important roles within the ecosystem (Kolb et al., 1995). Unfortunately, unregulated threats from wildfires can negatively influence both forest ecosystem services and forest health when left unmanaged. Through the course of this paper, these threats will be addressed and discussed.

Wildfires can be seen as catastrophic events; however, wildfires are naturally occurring processes and are vital to the balancing of ecosystems. Wildfires provide a cleaning of the forest floor in which they remove underbrush, open up the forest to sunlight and nourish the soil through the redistribution of nutrients from plant material into the soil. Clearing brush with low intensity flames has been found to help prevent larger, damaging wildfires that are uncontrollable and destructive (California Department of Forestry and Fire Protection, n.d.). Additionally, wildfires provide habitat regrowth for new grasses, herbs and shrubs that provide food and shelter to many wildlife species. Wildfires have the capability of killing diseases and insects while providing nutrients that help enrich soils. Wildfires provide a source of change within forest ecosystems. There are species of trees and plants that depend of fire, requiring a fire frequency spanning from 3 to 25 years for regeneration (California Department of Forestry and Fire Protection, n.d.). California chaparral plants can benefit from fire, with plants including manzanita, chamise and scrub oak that require heat from fire for seed generation. These plants adapt naturally and without fire would eventually die and prevent the formation of new plant generations to replace them (California Department of Forestry and Fire Protection, n.d.). Wildfires are extremely important in the maintenance of healthy forests and reduction of large, damaging fire events. However, fire suppression has led to increased forest growth, regarding underbrush and tree density, and has greatly reduced diversity. With increased biomass availability in combination with fire suppression, large, more severe fires can result.

While wildfires are a part of nature and play a key role in shaping ecosystems, fire can be deadly. Fires can destroy homes, habitats and cause air pollution and water contamination that is harmful to human health (USFS, 2015). The impacts of fire can be long lasting, influenced by forest conditions before the fire and the management after the fire. To scientists, concerns of wildfires relate to ecological impacts. These impacts can include vegetation consumption, organic and mineral soil changes, and length of time for recovery (Doerr & Santin, 2016). To natural resource managers, policy makers, and the public, concerns of wildfires are directly related to their impact on people and society. This impact includes lives lost, damage to homes and infrastructure (Doerr & Santin, 2016). These impacts stress the importance of fire management and the necessity for fire occurrence to reduce the severity of fires.

As fires grow in both scale and duration, there are an increased number of communities impacted, physically, socially and economically. Diaz (2012) quantified losses for Florida and California, estimating $1,900 and $6,516 per acre, respectively, in losses due to fire. These costs are associated with disaster relief, fire suppression, tourism losses, hazard mitigation, insurance, among others. The idea is that these unexpected costs due to fires cause be replaced with costs of fuel treatments and other hazard mitigation activities that are utilized in order to reduce fire spread and effects. The economic impact borne by fires fall heavily on the community and business, while impacting natural areas, infrastructure and state with less significance (Diaz, 2012). While impacts of severe fires regionally, the impacts are borne on the community and can negatively effective the population.

Regional variations can largely impact fire susceptibility. California chaparral, the predominant ecosystem in California, is an environment that experiences frequent periods of drought, bringing increased probability of fire and other associated environmental impacts to a region (Quinn & Keeley, 2006). Seasonal fluctuations and precipitation related cycles can result in great fire diversity and increased fire frequency. Forest structure and composition can widely vary, causing considerable variation in the accumulation of fuel, biomass availability, fire severity and frequency, and the overall effects of fire. The combination of these factors can greatly influence probability, severity, and destruction caused by wildfires. Fire severity can impact soils variably, ranging from light scorching to the total destruction (Quinn & Keeley, 2006). Taking into consideration recent wildfire events in Sonoma County, it is important to understand the causes of these wildfires and to identify fire management strategies for future implementation that can reduce frequency and severity of wildfire.

The purpose of this paper is to identify the causes and fire management strategies necessary to protect and prevent future devastating fires in Sonoma County. The aim of this paper is to answer how factors causing wildfires are interconnected and, through the understanding of their interconnectedness, how fire management strategies can be implemented in order to reduce both fire severity and fire frequency. This paper will begin by identifying indicators and environmental conditions that increase fire susceptibility, followed by an in-depth analysis of the interconnectedness of these factors. Next, fire management strategies will be evaluated and presented by effectiveness. Finally, the information gathered will be synthesized to determine the most suitable management strategies for Sonoma County in relation to historical environmental conditions and observed effective management strategies for varying regions.

2. BACKGROUND

2.1. FACTORS CONTRIBUTING TO THE OCCURRENCE OF WILDFIRES

Fire occurrence can be defined by a number of factors that can influence the state of the ecosystem. The ecosystem can be in one of three stages: Pre-Fire, Fire, and Post-Fire. Figure 1 depicts the pre-fire, fire and post-fire environments in relation to the physical, chemical and biological response of soils (Jain, et al., 2008). Beginning with the pre-fire environment, climate, drought, disturbance legacy, pre-fire weather and fuel characteristics define the transition from pre-fire to fire environment. Fuel characteristics can be defined as the types of vegetation (shrubs, trees, grasses, etc.) in an area and the associated flammability and susceptibility to set fire. Significant influences in the transitional stages are land cover, physical settings and soil composition. This stage can last from years to hours. Once conditions are ideal for fire, a system can enter the fire environment. This stage is when a fire is actively burning and in which both fire weather and fire suppression influence fire severity and fire intensity. This stage can last from seconds to days to weeks. Post-fire environment transitions with post fire weather and secondary disturbances, influence the environments short and long-term response in addition to burn severity. This stage can last from hours to centuries. Exiting the post-fire environment, the pre-fire environment begins, and the cycle continues (Jain, et al., 2008). These factors can act alone in determining the environmental stage or can be analyzed individually. Below, each factor is considered individually in regard to its impact on fire occurrence.

2.1.1. LAND COVER AND FIRE WEATHER

Fire weather is not a singular control that can determine fire spread and size. Topography and land cover are important in the formation of a pre-fire environment. Fires tend to burn certain fuel types and avoid others, preferentially burning different regions (Jain, et al., 2008). Fuel sources for fires include vegetation, underbrush and other flammable naturally occurring and anthropogenic sources. In analysis conducted by Marchal et al (2017), it was determined that land cover typically has the greatest effect on fire size rather than fire weather. However, under specific extreme fire weather conditions, high intensity fires can be observed, with little effect due to land cover. Varying fuel types can lead to different fire behaviors due to changes in fuel load and drying rates. Based on land cover classes and fire association, Vollmar (2014) determined that regions with evergreen and shrub coverage contained the largest percentage of fire occurrence, followed by grassland, wetland, deciduous, and other, respectively. As a result, land cover can greatly influence fire spread and occurrence. (Vollmar, 2014)

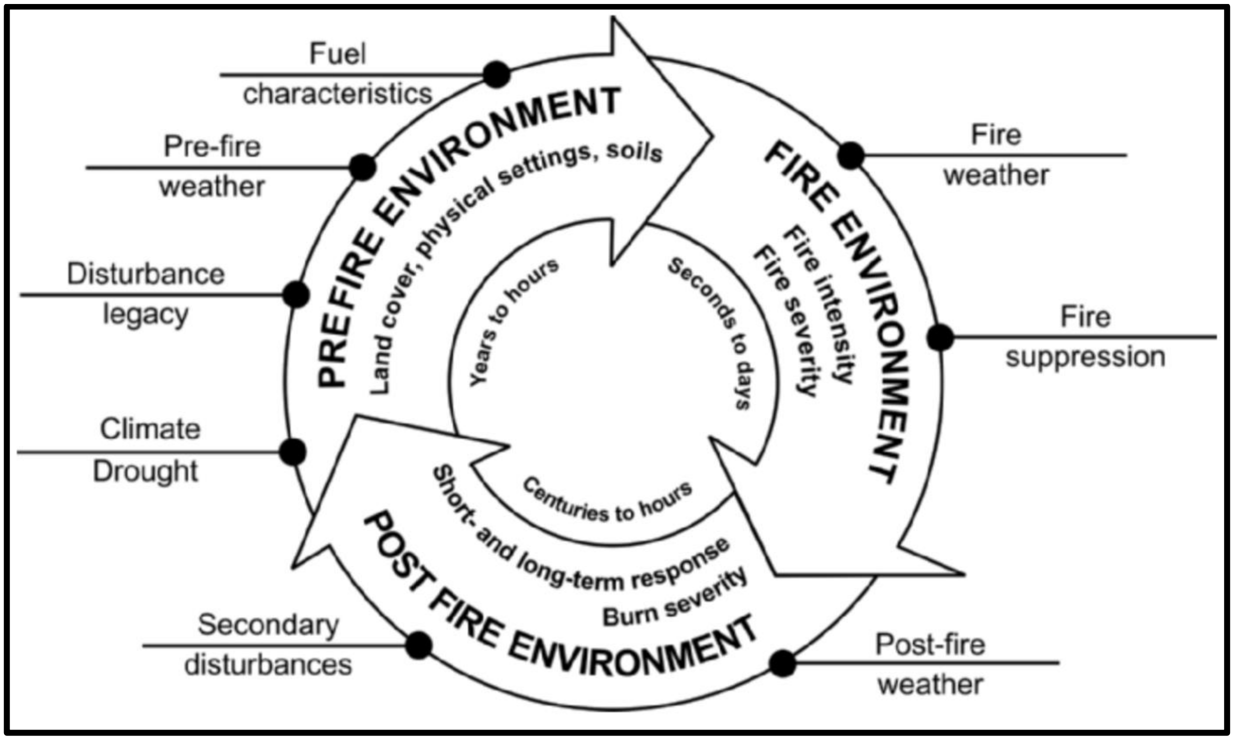

Figure 1: Fire Disturbance Cycle (Jain, et al. 2008).

2.1.2. PHYSICAL SETTING AND SOIL

In addition to land cover, there is the combination of physical settings and soils that can impact fire occurrence. physical setting can be defined by the location and topography. This can take into account the slope, angle, and aspect of an area (Jain, et al., 2008). The physical setting on an area can be defined by hillsides, mountains, plains, and other geographic features. These features can influence wind patterns, precipitation patterns and vegetation growth. As a result of these influences, the physical setting can influence fire susceptibility and likelihood in a region, as well as burn patterns.

Fire, itself, can be a driver in landscape changes, through land use regulations and fire management. Changes in land use can lead to changes in fire frequency, fuel loading and fire regimes (Butsic et al., 2015). Fire regimes are typically quantified at a regional scale by size, frequency, intensity and seasonality. Different scales can be used to describe and drive land use changes: global, national and regional. Economic drivers tend to be key in influencing land use change. Globally, land use change contributes to climate change and can impact fire regimes. Locally, land use changes impact primary regulators of local fire conditions: fuel loading and ignitions. As a result, land use change can largely impact the physical setting and be a leading driver of fire in a region. The interaction of vegetation management, landscape planning, fuel loading, ignition sources, and land use change influence landscape outcomes and the resulting fire risk (Butsic et al., 2015). An analysis of the physical setting can directly relate to the soil and the resulting soil-fire response.

There is a distinct relationship between soil and fires. Soil burn severity can be measured and related to general wildfire conditions. Variations in the soil burn severity can reflect fire duration, fuel moistures, heat production, physical setting and geographic location (Jain et al., 2006). Soils naturally provide a microclimate in combination with the forest cover from which a variety of microorganisms are associated, resulting in nutrient recycling. These natural processes can be disrupted and greatly altered following a wildfire, removing its litter layer, depositing fine ash and forming water repellent soils (Ice, 2004). These changes can influence the flow of sedimentation with precipitation and lead to water pollution. These changes can largely impact the post-fire environment and the recovery period for an environment.

2.1.3. FIRE INTENSITY AND SEVERITY

Fire intensity and severity are the most concerning aspects of the fire disturbance cycle and play the largest role in ultimate environmental outcomes, response and necessary fire management practices. The terms fire intensity and severity are often used interchangeably; however, they are different. Intensity involves the rate at which fuel is consumed, heat is produced and spreading patterns while the severity is described by the fire intensity and ecosystem effects (Miller et al., 2012). Severity references the post-fire impacts of a burned area. Over the last several decades, wildfire size and severity has increased in the western United States. This means that frequency, size and severity have continued to increase, leading to larger and more destructive fires (Scasta et al., 2016). Frequency, size and severity are dependent on drought conditions, fuel availability, and ability to spread. These in turn translate to both fire intensity and severity. Fires can impact society through agricultural damage, loss of property and threat to lives. Fire severity can be measured variably, with regional differences in identified impacts and resulting damages. Monitoring of fire severity can vary dependent on agency identifying and monitoring fires. Three primary monitoring programs are: Burned Area Emergency Response (BAER), the Rapid Assessment of Vegetation Condition after Wildfire (RAVG), and Monitoring Trends in Burn Severity program (MTBS) (Whittier & Gray, 2015). These programs are utilized in analysis of fires and will be further discussed in this paper. Burn severity is often based on a multitude of characteristics because it is not defined by a single quantifiable measurement. These characteristics include post-fire vegetation, litter and soil.

2.2. ECOSYSTEM MANAGEMENT

Ecosystem management is a focus on natural resource management, to manage the forest in its entirety (Williams, 1995). The idea that is managing the forest as a whole leads to more sustainable future resource outputs. Often times, management of the whole system is not possible, however, it is important to identify those aspects more important in the management of an ecosystem. Fire is one of those aspects that must be managed. Fires have large biological influences on the composition, structure and function of forests. In the absence of low intensity fires that occur periodically, large changes in specie composition and structure can lead to insect and disease outbreak in addition to severe wildfire outbreaks. In support of ecosystem management, Williams (1995) made five recommendations as fire and aviation management goals. These goals include: communication of the role of fire in the ecosystem to both decision-makers and the public; communication and informing of long-term effects of prescribed wildfire and fire suppression regimes; management of prescribed fire risk; and the alignment of fire management programs (Williams, 1995).

2.3. IMPORTANCE OF FIRE MANAGEMENT

Wildfire management is of extreme importance in balancing the risks of wildfires on society and the ecological benefits that can be extracted from fire occurrence. Within the United Sates, national-scale models are utilized to inform fire management decisions due to fire policy, management directives and funding lying within the scope of the national government (Hawbaker, et al., 2013). Key to defining the balancing of ecological benefits versus societal risk, it should be acknowledged that fire suppression is important in limiting damage to property and threat to life while fire is important and necessary to maintain an ecosystem's balance in composition and structure. While balancing of these are important, consideration for the cost of wildfire fighting and damage caused are large. Because there is a great expense for fighting wildfires and great consequences of uncontrolled wildfires, it is necessary to better understand and predict fire occurrence.

Effective fire management depends on an understanding of both the human and natural resource. Land use can greatly impact fire characteristics and patterns in association with fire management strategies. California faces the challenge of maintenance of functional ecosystems while meeting fire protection demanded by the public in regard to life, property and natural resources. The U.S. Forest Service defines fire management as the planning, implementation, and monitoring of fire and protection from fire to achieve healthy ecosystems and fire safe communities (California Department of Forestry and Fire Protection, 1995). Fire management can be crucial to the development of fires, and certain management strategies can inadvertently cause increase in fire prevalence, rather than prevent against. Fire suppression has been found to shift fires from small, more frequent fires to larger, more severe fires. Fire suppression can lead to increased fuels, with denser stands of forest with greater flammability potential. When identifying effective management strategies, options and opportunities should be evaluated to prevent severe fires while reducing risk of the societal damages and destruction.

2.4. SONOMA COUNTY: ECOSYSTEM, POPULATION DEMOGRAPHICS AND DISTRIBUTION

Regional variations can largely impact fire susceptibility. For the United States there are 17 Omernik level II ecoregions, including what is defined as Mediterranean California (Figure 2), otherwise defined as California Chaparral (Hawbaker, et al., 2013). Ecoregions are ecosystems defined by distinctive geography, solar radiation and moisture. Each ecoregion is defined by a specific set of characteristics. California chaparral is defined by both the vegetation type and the community of plants and animals that are found in both the foothills and mountains of California (Quinn & Keeley, 2006). Vegetation in chaparral regions includes evergreen drought and fire-hardy shrubs. The shrubs are adapted to California's drought conditions and unpredictable rainfall characteristics. Chaparral regions naturally have existed with fire, with fire frequency dependent on vegetation conditions, ignition source, winds, season, topography and period of time since last fire. Chaparral covers nearly 7 million acres in California, ranging

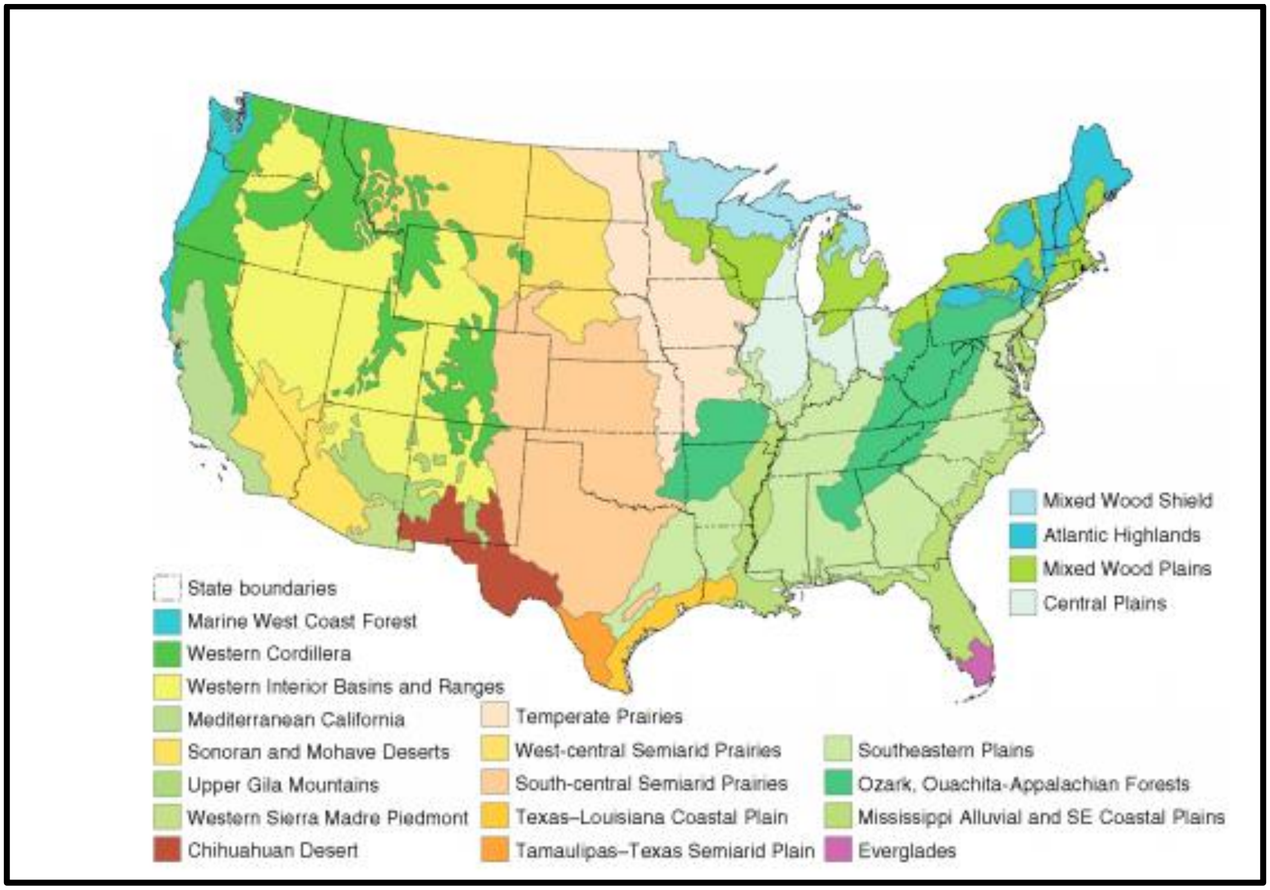

Figure 2: Omenrik Level II Ecoregions (Hawbaker et al. 2013).

from coastal and inland mountainous regions to deserts (Quinn & Keeley, 2006). Within the chaparral regions, vegetation types may be intermingled with pine and oak forests or grasslands, this causes local variation in plant species, dependent on local climate, soils and topography.

Sonoma County lies within the California Chaparral and occupies more than one million acres of land and water. Along with a large variety of land use, open space and agricultural land accounts for a majority of Sonoma County acreage, approximately 60 percent (County of Sonoma, 2018a). As of 2015, Sonoma County was occupied by nearly 500,000 residents, with a 10.7 percent growth in Santa Rosa over 10 years (County of Sonoma, 2018b). With a dense population compared to neighboring counties, the risk posed to Sonoma County in regard to society fire impacts is great. As a result, the interconnectedness of fire characteristics and fire management is key to protection and prevent of wildfires.

One must consider as life moves forward how all aspects of fire occurrence and recovery interact and shape the future ecological habitat. Interactions among the varying aspects can make a significant difference in the final outcome of a fire, whether that is defined by severity, economic losses, community impact or habitat loss. This paper will analyze important contributing factors to fire occurrence and resulting impacts. This paper will further discuss individual fire occurrence globally, nationally and regionally. Through this discussion, the goal is to identify key issues in current landscapes for fire causes, occurrence and management and similarly identify the most applicable, effective and useful management practices that should be implemented and monitored in Sonoma County.

3. METHODOLOGY

The research conducted for the purpose of this paper was compiled to regionally analyze the main research question:

> Based on the causal relationship of fire characteristics, what fire management strategies should be implemented in Sonoma County in order to reduce fire occurrence and severity?

For deriving an answer to the primary research question, methodology used included literature review and synthesis. For the purposes of this study, research focuses on the analysis of causal relationships of factors contributing to wildfires and identification of fire management practices that should be implemented in Sonoma County, California. The first goal of this research was to analyze fire setting characteristics and derive the key drivers in fire occurrence. The second goal was to analyze fire regimes and determine the most effective and applicable fire management strategies to be implemented in Sonoma County. Considering recent large wildfires taking place in late 2017, the answer to what effective management strategies to be implement is extremely important and relevant.

To properly examine both causal relationships and effective fire management strategies, an analysis of historical and regional wildfires and their associated impacts regarding vegetation, recovery time, fire severity and associated erosion and sedimentation will be considered. Peer-reviewed articles will be gathered from FUSION, SCOPUS and Environment Complete. The data obtained from these articles will be summarized and synthesized to compare and contrast fire impacts in regions where the vegetation is similar to Sonoma County. Synthesis tables will be used to compare regional and fire specific characteristics. Data will then be gathered in a series of synthesis tables to be further analyzed. Finally, fire management strategies will be comparatively analyzed and applied to the local conditions in Sonoma County in regard to soil burn severity, average annual precipitation, vegetative cover, topography, and historically utilized strategies for previous local fires. This paper will strictly focus on the analysis of fire management strategies for Sonoma County, but will reference to global, national and regional strategies that have been established or considered. Evidence supporting my conclusions and recommendations made in section 5.0 are explicated in section 4.0: Results.

Table 1 below identifies key sources utilized in the creation of this paper and indicates the category of usefulness based on topic. Table 2 looks specifically at sources topic distribution in relation to fire impacts.

Table 1: Topic distribution of key references utilized in this paper.

REFERENCES	Fire Severity Impacts	Erosion & Precipitation	Habitat Restoration	Wildfires in California Chaparral	Post Fire Land Management
(BUTSIC, KELLY, & MORITZ, 2015)	✓	✓			
(CALIFORNIA DEPARTMENT OF FORESTRY AND FIRE PROTECTION, 2017A)				✓	
(CALIFORNIA DEPARTMENT OF FORESTRY AND FIRE PROTECTION, 2017B)				✓	
(CALIFORNIA DEPARTMENT OF FORESTRY AND FIRE PROTECTION, 2017C)				✓	
(HAWBAKER, ET AL., 2013)	✓				
(ICE, 2004)		✓			
(JAIN, ET AL., 2008)		✓			
(MECHADO-VEZZANI, ET AL., 2018)			✓		
(QUINN & KEELEY, 2006)			✓	✓	
(RABOT, WIESMEIER, SCHLUTER, & VOGEL, 2018)		✓			
(TYLER, 1995)				✓	
(USFS, 2015)	✓				
(WILLIAMS, 1995)					✓
(WIRTH & PYKE, 2006)					✓

Table 2: Topic distribution of key references in Fire Impacts Analysis.

REFERENCES	Land Cover	Physical Setting	Soil	Fire Intensity & Severity	Ecosystem Management	Fire Management
(BUTSIC, KELLY, & MORITZ, 2015)		✓				
(CALIFORNIA DEPARTMENT OF FORESTRY AND FIRE PROTECTION, 1995)						✓
(HAWBAKER, ET AL., 2013)						✓
(ICE, 2004)			✓			
(JAIN, GRAHAM, & PILLIOD, 2006)			✓			
(JAIN, ET AL., 2008)			✓			
(JAIN, PILLIOD, GRAHAM, LENTILE, & SANDQUIST, 2012)			✓			
(MARCHAL, CUMMING, & MCINTIRE, 2017)	✓					
(SCASTA, WEIRD, & STAMBAUGH, 2016)				✓		
(VOLLMAR, 2014)	✓					
(WHITTIER & GRAY, 2015)				✓		
(WILLIAMS, 1995)					✓	

4. RESULTS

4.1. FACTORS AND IMPACTS RELATED TO FIRE OCCURRENCE

Climate, vegetation and land use are factors that can contribute to the occurrence of wildfires. The interactions between these factors are complex, with each contributing to fire occurrence individually. Climate is believed to be one of the natural factors that influence the distribution of vegetation and the resulting fire regime characteristics (Armenteras-Pascual, et al., 2011). Armenteras-Pascual et al (2011) found that differences in climate and fire seasonality in combination with regional variations largely influenced fire occurrence while changes in land use also influenced marked differences.

Fuel conditions largely influence both fire occurrence and behavior, shaping and characterizing fire risk. Fuel loading, or the presence of shrublands, agriculture and forests, greatly influence fire occurrence (Fischer, Di Bella, & Jobbagy, 2015). Fischer et al (2015) found that differences in burned and unburned regions could be attributed to fuel thickness, type and degradation state. Fire size was similarly impacted by vegetation conditions. Overall, vegetation conditions largely impact fire duration, fire size and fire occurrence (Fischer, Di Bella, & Jobbagy, 2015).

4.1.1. FIRE SEVERITY IMPACTS

The intensity of a fire along with its ecosystem effects define fire severity, that is a combination of the impacts of fires on watersheds, wildlife, soils, vegetation, habitat and forest products. Some definitions of fire severity are general statements regarding the broader impacts of fire, such as the degree of environmental change resulting from a fire. However, the definition of fire severity is complex. Fire, or burn, severity can result in two definitions: ecosystem response and societal impacts. The ecosystem response involves the relationship of erosion and vegetation recovery while the societal impacts involves the loss of life or property alongside suppression costs (Keeley, 2009).

Fire severity can be related to changes in aboveground vegetation and soil organic matter. Keeley (2009) presents descriptions for five classes of fire severity, solely dependent on aboveground vegetation and soil organic material. Table 3 differentiates between the five classes of fire severity (Keeley, 2009). These classes are: unburned, scorched, light, moderate/severe surface burn, and deep burning/crown fire. These classes are variable from each other due to vegetative state, heat impact, and soil burning. While Keeley (2009) defines fire severity based on these aspects, there are many other factors that influence fire severity. Miller et al (2012) found a correlation between fire severity and fire size. For individual fires in conifer vegetation types, the degree of severity was greater with larger fire size, in fires that occurred later in the year and in years when a smaller area had been burned in the region. It was similarly found that fire severity was inversely proportionate to spring precipitation, indicated that increased rainfall caused decreased fire severity (Miller et al., 2012).

Table 3: Fire Severity Classes (Keeley, 2009)

FIRE SEVERITY	DESCRIPTION
Unburned	Plants parts green and unaltered, no direct effect from heat
Scorched	Unburned but plants exhibit leaf loss from radiated heat
Light	Canopy trees with green needles although stems scorched; surface litter, mosses and herbs charred or consumed; soil organic layer largely intact and limited charring
Moderate or Severe Surface Burn	Trees with some canopy cover killed but needle not consumed; all understory plants are charred or consumed; fine dead twigs on soil surface consumed and logs charred; pre-fire soil organic layer largely consumed
Deep Burning or Crown Fire	Canopy trees killed and needles consumed; surface litter of all sizes and soil organic layer largely consumed; white ash deposition and charred organic matter to several cm depth

Key influences in defining fire severity for a particular fire event include topography, weather, and indirect and direct variables influencing fuels. Factors that define weather consist of temperature, relative humidity, temperature inversions, and solar radiation, at time of burning. Direct and indirect influences on fuel include vegetation type, number of previous fires and time since last fire (Estes et al., 2017). All of these factors work together in defining fire severity. In order to best understand fire severity for a region, both fire management and fire monitoring are extremely important.

4.1.2. EROSION AND PRECIPITATION

Wildfires have historically been a natural disturbance factor in forested ecosystems but have recently become an environmental problem with fire regimes that have been implemented resulting in changes in both land cover and use (Vieira et al., 2015). As a result of these changes, soil erosion and land degradation remain among the environmental impacts of wildfires. Erosion is one of the primary concerns following a wildfire. Runoff and erosion related to fire can cause alterations in soil properties, such as the removal of protective soil by vegetation and litter, aggregate stability and action as water repellent. To describe heat-induced changes in soil, the term soil burn severity is used (Vieira et al., 2015). Soil burn severity is often utilized as an indicator for hydrological and erosion response to recently burned areas (Vieira et al., 2015; Rabot et al., 2018; Mechado-Vezzani et al., 2018).

Burn severity measures the degree of change that is directly caused by a fire (Jain et al., 2012). Following a fire, the burn severity can be measured by the chemical, biological and physical responses of soil (Jain et al., 2012). To understand burn severity, it is important to understand the structure and function of soil. Soil function can largely define soil structure. Soil structure causes the regulation of water infiltration and retention, allows for the storage of soil organic matter (SOM) and nutrients, root penetration and the susceptibility of soil to erosion (Rabot et al., 2018). As plants are dependent on soil, soil is dependent on plants. Soil structure can develop and maintain soil structure, microbial communities and ecosystem function (Mechado-Vezzani, et al., 2018). Plants are the primary contributor of organic material and energy input for microbial communities and soil structure. Plants form biopores from root growth, stabilize soil aggregate and are important in the development of soil structure (Mechado-Vezzani, et al., 2018). Large, hot fires decrease soil organic matter (SOM), alter the hydrogeological properties of the area and break up soil aggregates (DeBano, 1990). The SOM contained nearly all nitrogen, sulfur and phosphorous within soil, in addition to ammonium, potassium and calcium

(DeBano, 1990). As a result, when fire burn large quantities of vegetation, this interaction of plants and soil is interrupted in which soil systems are altered.

Burn severity can be used as a baseline for the ecological response. Often times, soil conditions are either described as burned or unburned (Jain et al., 2012). This limited impact analysis can overlook the realities of fire impacts on the soil and what ecological responses should be anticipated. Instead, soils can be classified in a range of burned categories. Factors that can be utilized in the evaluation of soil and forest floor can include a large range of values including physical, chemical, and biological effects (Jain et al., 2012). Ice (2004) identified four soil burn severity classes: unburned, low, moderate and high (Table 4). These burn severity classifications are similarly defined, however there are some variations. While burn severity can be classified as unburned, low, moderate and high burn severity, most commonly these severity classes are intermixed in a recently burned area. This intermixing of severity classes can result in the formation of "mosaics" of soil burn severities in an area due to variable burn patterns (Vieira et al., 2015).

The disturbance of soils and removal of vegetative cover greatly influences erosion flows during precipitation events. Fire can cause loss in ground cover, reducing water infiltration and increasing overland flow and erosion. Increased erosion can cause changes to water quality, while filling reservoirs and damaging aquatic habitats (Schmeer et al., 2018). The measure of rainfall intensity is the greatest contributing factor to erosion on hillslopes following burning. Studies have found that increased rainfall intensity in combination with land cover increase the erosion and sedimentation of hillsides (Kampf et al., 2016; Schmeer et al., 2018; Vieira et al., 2015). A meta-analysis of field rainfall simulation by Vieira et al (2015) found that fire occurrence typically leads to the generation of overland flow and sediment losses. In Vieira et al.'s study, erosion rates were found to be increased more significantly when compared to runoff rates during a precipitation event. Dependent on vegetation recovery rate, post-fire weather conditions, availability of sediment, and morphology, among others, different fire severities develop into different recovery periods (Vieira et al., 2015). Vieira et al's (2015) meta-

Table 4: Soil Burn Severity Class Descriptions (Ice 2004).

SOIL BURN SEVERITY CLASS	SUBSTRATE – LITTER/DUFF	VEGETATION – UNDERSTORY/SHRUBS/HERBS
UNBURNED	Not burned	Not burned
LOW	Mineral soil unchanged; litter charred or partially consumed; upper duff layer charred; wood/lead/needle structures charred but recognizable	Foliage and smaller twigs (less than ¼ inch) scorched or partially consumed; grassed mostly consumed, black or gray ash; shrub stems intact, canopy scorched
MODERATE	Moderate soil heating, moderate ground char; soil structure intact; litter mostly charred but not ashed, however some areas of litter consumption may be found, leaving shallow ash; duff and wood partly consumed; wood/leaf structure may be recognizable; burned roots and rhizomes usually still present; reduced permeability may be present over some of the area.	Foliage, twigs and small stems ¼ to ¾ inch) consumed; shrub stems charred, root crowns intact, shrub canopy consumed
HIGH	High soil heating, deep ground char; litter and duff consumed leaving fine ash, often more than an inch or two deep and often gray or white; surface soil may be visibly altered, often blackened or reddish and usually lacking structure; all or most organic matter is removed; fine roots and rhizomes may be consumed; reduced permeability may be pronounced (strong and or thick water repellant layer) over much of the area; large fuels completely consumed or close to.	All plant parts consumed including fuels greater than ¾ inch, leaving some to no major stems/trunks of shrubs.

analysis of rainfall intensity found that intensities higher than 150 mm/h most noticeably increased erosion rates. Kampf et al (2016) found that large, less frequent precipitation events can lead to increased erosion rates, extremely flooding and road damages. Most geomporhic changes occurred with high intensity rainfall above a threshold specific to a region (Kampf et al., 2016). Schmeer et al. (2018) modeled sediment yields using ground cover, rainfall, topographic and sediment yield data and found that the percent of bare soil cover was the largest factor influencing sediment yield. These findings directly link erosion and sedimentation transport with vegetative cover or fire and soil burn severity.

4.2. HABITAT RESILIENCE AND RESTORATION

The U.S. Environmental Protection Agency (EPA) defines four level of ecoregions that can describe a region based upon the type, quality and quantity of environmental resources. Ecoregions identify areas of general similarity within ecosystems (Griffith, et al., 2016). Level 1 ecoregions define 15 regions within North America; level 2 ecoregions define 50 regions; level 3 ecoregions define 105 regions within the continental United States; and level 4 is further refinement of level 3 ecoregions (Griffith, et al., 2016). Within California, there are 13 level 3 ecoregions and 177 level 4 ecoregions. Table 5 provides a list of the two level 13 ecoregions located in Sonoma County, with brief descriptions. The ecoregions in Sonoma County are: Coast Range and Central California Foothills and Coastal Mountains. These ecoregions will be broken down into three sub regions for the purpose of this discussion: California Chaparral, Coastal Oak Woodlands, and Hardwood and Conifer Forests.

Table 5: California Level III Ecoregions (Adapted from Griffith, et al., 2016; U.S. EPA, 2016)

ECOREGION	CHARACTERISTICS
COAST RANGE	Covers coastal mountains of western Washington, western Oregon and northwestern California. Defined by highly productive, evergreen forests. In California, redwood forests are a dominant component along with some hardwoods, beach pine and bishop pine.
CENTRAL CALIFORNIA FOOTHILLS AND COASTAL MOUNTAINS	Mediterranean climate with mixed chaparral and oak woodland vegetative cover, some grasslands and pine can be found. Large areas of ranchland and agricultural centers.

4.2.1. CALIFORNIA CHAPARRAL

Fire plays an important role in plant communities, in particular grasslands, shrublands, savannas, woodlands and forests (Tyler, 1995). California chaparral is highly associated with fire and the resulting habitat disturbance (Zammit & Zedler, 1988). Typically, fires in chaparral regions burn as crown fires, which remove organic material above ground for most plants. Well adapted to regeneration, chaparral vegetation typically can regenerate through seed or basal sprouting (Barro & Conard, 1991). In chaparral systems, the most significant seedling establishment occurs following fire. Heating and burning has been found directly related to significant increase in seed release and germination (Tyler, 1995). Post fire, burned landscape is suitable for seedling recruitment due to the removal of more above ground biomass and altering the quantity of resources (Zammit & Zedler, 1988). Fire-adapted communities have seeds that require heating into order to germinate. The mechanisms that have been found to cause this establishment include the direct heating of both the soil and seed bank in addition to the reduction in competition and herbivory temporarily (Tyler, 1995). Tyler (1995) found that the burning and reduction in herbivory were most important in the resulting seedling establishment post fire. While this establishment varied among plant functional groups, herbivory reduction was determined to be most important. Reduced soil heating in burned areas resulted in overall increased seedling densities, cover and biomass (Tyler, 1995). Excessive heating has been found to adversely impact seedling establishment in comparison to reduced heating (Tyler, 1995). Specie composition plays a large role in a chaparral community's response to fire as both flora and fauna response greatly influence the initial response and overall recovery of the community post-fire.

Following fire disturbance, the first vegetation to establish are annuals. Shortly after, shrubs and new seedlings of shrubs and herbs become established (Zammit & Zedler, 1988). In an analysis of the time since fire, Zammit and Zedler (1988) found that the overall density of seeds in the soil increased. However, this seed accumulation was observed more so in one shrub type versus another, both of which are found in chaparral stands (Zammit & Zedler, 1988; Whittier & Gray, 2015).

The fire-prone nature of many chaparral species has been speculatively related necessary evolutionary response to nutrient limitation and drought-stress, causing adaptation through deep root systems, crown sprouting and sclerophyllous leaves (Barro & Conard, 1991). Up until the Euro-American settlement of the western United States, the distribution and structure of fire dependent ecosystems were sustained through fire (Stephens, et al., 2018). Frequent fire forests selected and protected a large majority of large, old trees through the limitations of biomass accumulation and through thinning of underbrush. Historically, these fires were highly variable, but with fire suppression regimes these forests began to experience large amounts of tree regeneration. For the purpose of harvesting, this growth was a positive impact, however with increased quantities of fuel, frequent fire forests have become increasingly susceptible to tree mortality and negative fire impacts (Stephens, et al., 2018).

4.2.2. CALIFORNIA COASTAL OAK WOODLAND

Coastal oak woodlands are among habitat types that are often interspersed among California chaparral. These woodlands can be highly variable, with an overstory consistent of deciduous and evergreen hardwoods and occasional conifers (Holland, 2005). The overstory can form dense canopies or open woodlands. The understory can be composed of shrubs from adjacent chaparral or coastal systems, scattered or closely packed. Where the overstory forms closely packed canopy, shade tolerant shrubs, ferns and herbs create a thick carpet of litter on the ground. The structure of coastal oak woodlands can vary based on slope, precipitation, moisture availability, temperature and soil (Holland, 2005). Structural variation in coastal oak woodlands can result from the relationships of slope, soil, precipitation, moisture availability and ambient temperature (Holland, 2005).

The composition of coastal oak woodland can vary, dependent on environmental diversity of the region. In the North Coast Range to Sonoma County, coast live oak is predominately present, this vegetation is considered Montane Hardwood, otherwise composed of white oak, California black oak, canyon live oak, madrone and interior live oak. South of Sonoma County, coast live oak is dominant with mixed evergreen forests such as California bay, madrone and canyon live oak (Holland, 2005).

Coastal oak woodlands can be found in Mediterranean climate types, with precipitation occurring in mild, winter months characterized by rainfall and warm to hot, dry summers (Holland, 2005). Precipitation typically varies from 15 to 40 inches annually, with minimum temperatures ranging from 29 to 44 degrees Fahrenheit and maximum temperatures ranging from 75 to 96 degrees Fahrenheit (Holland, 2005).

4.2.3. HARDWOOD & CONIFER FORESTS

Hardwood and conifer forests are often referred to as Montane Hardwood-Conifer (MHC) (Anderson, n.d.). To be considered a hardwood-conifer forest, at least one third of the forest must be conifer while another one third must be broad-leaved. Typically, there is little understory in MHC due to a dense and bi-layered canopy, however there can be considerable ground cover when the forest experiences disturbance, such as logging and fire. MHC forests are often associated with ponderosa pine, Douglas-fire, incense-cedar, California black oak, madrone, Oregon white oak and other species (Anderson, n.d.).

Following disturbance, MHC begins with dense shrubs, characterized primarily by taller, broad leaved species (Anderson, n.d.). Gradually, the stand increases height while developing the bi-layered canopy. Conifer tree types grow faster and above broad-leaved species in the second canopy layer. Secondary succession following disturbance occurs rapidly as trees and shrubs regenerate together. Over 30 to 50 years, conifer forests develop large, mature trees. The broad-leaved trees require between 60 and 90 years to develop large, mature trees (Anderson, n.d.).

These forests are typically found in regions with coarse, well drained soils in mountainous regions (Anderson, n.d.). Average rainfall for these regions include 25 to 65 inches annually, and minimum temperatures ranging from 29 to 30 degrees Fahrenheit and maximum temperatures ranging from 75 to 95 degrees Fahrenheit (Anderson, n.d.).

4.3. WILDFIRES IN CALIFORNIA

California's history is laden with fire. Perhaps an environment that creates the optimum conditions for fire, there have been record setting California wildfires within the last 10 years, in both size and destruction. Since 2008, there have been nine fires within California that are within the top 20 largest California fires since 1932. These fires include Thomas (2017) and Rim (2013) (California Department of Forestry and Fire Protection, 2018c). In this same time period there have also been nine different fires within the top 20 most destructive California wildfires, while not necessarily being among the largest in California's recent history (since 1932). These fires include Tubbs (2017), Nuns (2017), Thomas (2017), and Atlas (2017) (California Department of Forestry and Fire Protection, 2018d). This paper will particular focus on the Central Sonoma-Lake-Napa Unit (LNU) Complex Fires, a part of what has been referred to as the North Bay Fires. These, in addition to other notable fires will be evaluated to understand key relationships to local fire history in Sonoma County.

4.3.1. HANLEY-NUNS CANYON FIRE, 1964

Although not documented thoroughly, news sources indicate that the Hanley-Nuns Canyon Fire Complex provides valuable insight to the geography and fire-ecosystem relationship in Sonoma County. On September 19, 1964, two fires started in Sonoma County, soon to be known by Hanley and Nuns Canyon fires (LeBaron, 2014). Conditions leading to the fires included sparks that ignited brush that had been dried from months without rain, temperatures of 100 degrees, and strong down-sloping winds. The Nuns Canyon Fire burned 9,808 acres in Sonoma County (California Department of Forestry and Fire Protection, 2017b). The region burned in this fire can be compared to the Nuns Fire that occurred in 2017 (Figure 3). This relationship can be utilized to determine conditions under which fire more readily starts in the region and potential interconnected conditions pre-fire that cause fire. The physical settings and environmental conditions of the area will be further discussed under the Nuns Fire (2017).

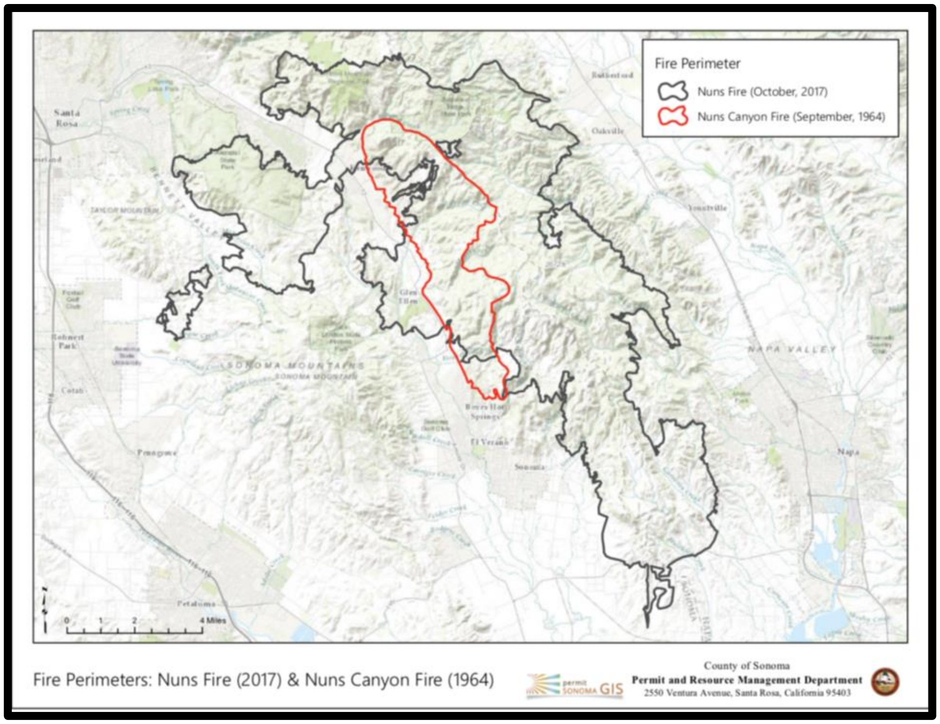

Figure 3: Fire Perimeters of Nuns Canyon Fire (1964) and Nuns Fire (2017) [County of Sonoma, 2017].

4.3.2. RIM FIRE, 2013

The Rim Fire began on August 17, 2013 in the Stanislaus National Forest within the steep and rugged canyons (Sierra Nevada Conservancy, 2014). To date, the Rim Fire is the largest fire in recorded history of the Sierra Nevada, burning 257,314 acres. In a period less than 3 weeks, the Rim Fire became the largest wildfire in Sierra Nevada written history and the third largest in the state of California. The large majority of the fire burned in forested vegetation types.

The burned area ranged from elevations of 869 feet (265 meters) to 7874 feet (2400 meters) above sea level (Staley, 2013). Along plateaus, topographical slopes were characterized by more gentle gradients while along canyon walls there were steeper slopes.

The burn severity for the region consisted of 56 percent low burn severity, 37 percent moderate burn severity and 7 percent high burn severity. Areas with steeper slopes and more dense vegetation were found to have a higher burn severity when compared to lesser slopes and vegetation cover (Staley, 2013). Approximate annual precipitation is 37.99 inches (Chester, Graham, Mazurkiewicz, & Tsang, 2016)

The extent of information available regarding the Rim Fire does not thoroughly cover the topographical, geologic and climatic characteristics but rather shows the importance of fire management and protection of healthy forests. This fire had the potential to impact vast numbers of people, and potentially the entire City of San Francisco due to threats posed to both water and power resources. Additionally, air quality for nearly a 100-mile radius was impacted. The outcome of this fire included the burning of 257,314 acres, over $127 million in suppression costs, nearly $9 million in emergency road, trail and watershed stabilization efforts, impacts to habitat for many species, losses to the ranching community and reduced tourism-drive income (Stanislaus National Forest U.S. Forest Service, 2013). This fire emphasized the unpredictability and great losses that can be experienced with a wildfire when proper fire management is not maintained.

4.3.3. THOMAS FIRE, 2017

On December 4, 2017, the Thomas Fire started along State Route 150 in Southern California (California Department of Forestry and Fire Protection, 2018e). The Thomas Fire burned west and north, burning a total of 281,893 acres. The Thomas Fire is the largest fire in California's written history.

The region in which Thomas Fire burned has had an active fire history. Within the fire perimeter for Thomas Fire, approximately 66 percent of the area has burned since 1983. Within the last 10 years, 10 major fires have occurred in the region, impacting debris flows and sediment transportation (California Department of Forestry and Fire Protection, 2018e).

The Thomas Fire covered a large range of geography, encompassing a variety of topographic, climatic and geographic areas (California Department of Forestry and Fire Protection, 2018e). The topographic elevation ranged anywhere from 10 feet above sea level to 6,383 feet above sea level, with an annual precipitation range just as wide from 3.99 inches to 72.39 inches. The climate can be generally described as Mediterranean, however there are a plethora of vegetation types within the burned area. The vegetation cover ranges from mixed chaparral to coastal shrub to coastal oak woodland and annual grassland. However, the soils throughout the burned area were predominantly shallow depth (California Department of Forestry and Fire

Protection, 2018e). Geologically set in the western portion of the Transverse Ranges Geomorphic Province to the north, the area can be characterized by potential landslides alluvial fan flooding and debris flow hazards (California Department of Forestry and Fire Protection, 2018e). The primary concerns following this fire are the potential for hillside and channel erosion, streamflow increases, debris flows, and debris flows as a result of erosion.

4.3.4. NORTH BAY WILDFIRES, OCTOBER 2017

In October of 2017 a series of wildfires, now referred to as the North Bay Wildfires, began in Sonoma, Napa, Lake, Solano and Mendocino counties and have become among the most deadly and costly wildfires in the history of California. Three wildfire complexes were defined: Southern LNU Complex, the Central LNU Complex and the Mendocino Lake Complex. Of these, the Central LNU Complex, made up of fires referred to as Nuns, Tubbs and Pocket, burned a total of 110,720 acres and resulted in 24 fatalities (California Department of Forestry and Fire Protection, 2017b). Figure 4 shows the locations of North Bay Wildfires and the area occupied by the Central LNU Complex and Southern LNU Complex. These fires burned primarily in Sonoma and Napa Counties but reached into Lake County. Many climatic, topographic and regional similarities are observed among the region. For the purpose of this section, the Central LNU and Southern LNU Complexes will be discussed however the Central LNU Complex will be focused on.

4.3.4.1. ATLAS FIRE, OCTOBER 2017

Starting on October 8, 2017, the Atlas Fire began in Napa County and burned a total of 51,624 acres (California Department of Forestry and Fire Protection, 2018a). Destroying 90 structures and damaging 481, the Atlas Fire formed the Southern LNU Complex of the North Bay Fires. The region has an active fire history, with approximately 58 percent of the area having been previously burned since 1980. In 1981, the Atlas Peak Fire burned approximately 23,000 acres within the northern portion of the 2017 Atlas Fire perimeter (California Department of Forestry and Fire Protection, 2018a).

The topography of the region ranges from 50 feet above sea level to 2663 feet above sea level with slopes varying from gently sloped volcanic tablelands to very steep and deeply dissected

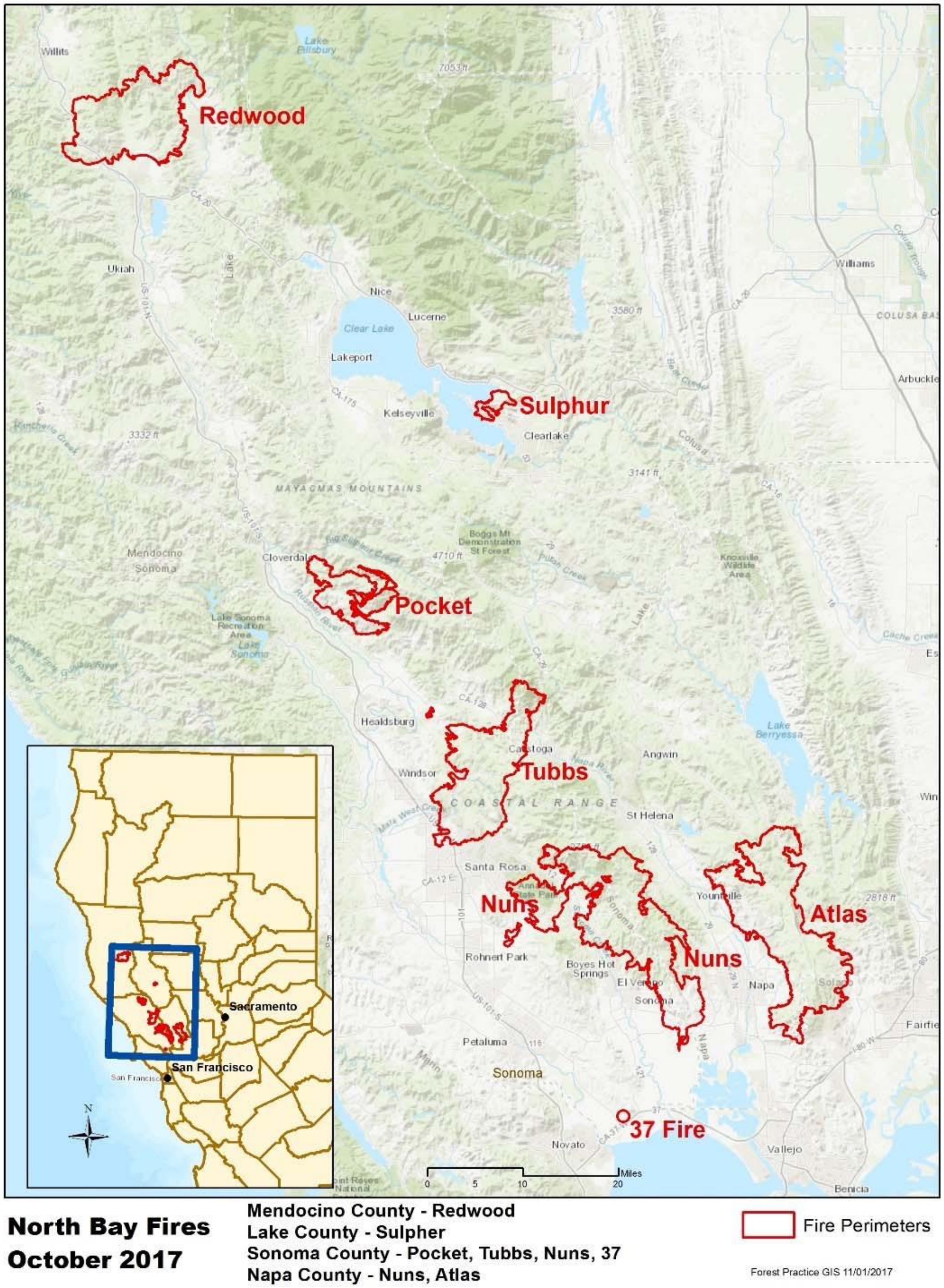

Figure 4: North Bay Wildfires Location Parameters, 2017 (California Department of Forestry and Fire Protection 2017).

slopes (California Department of Forestry and Fire Protection, 2018a). Annual precipitation for the area ranges from 18.9 to 77.3 inches.

The climate can be characterized as Mediterranean with predominant vegetation types of hardwood woodland and shrubland with grassland, agricultural land, and some areas of coniferous forests (California Department of Forestry and Fire Protection, 2018a). The soils range from shallow to thick, derived from eolian deposition and weathered bedrock. It was found that approximately 74% of the area had an unburned/low soil burn severity, 26% moderate soil burn severity, and less than 1 percent of high soil burn severity (California Department of Forestry and Fire Protection, 2018a).

4.3.4.2. NUNS FIRE, OCTOBER 2017

On October 8, 2017, the Nuns Fire began, burning a total of 56,556 acres in Napa and Sonoma counties (California Department of Forestry and Fire Protection, 2017b). The area burned was watershed area in Sonoma Creek (43%), Napa River (29%) and Laguna de Santa Rosa (16%). This burned area has a well-documented fire history. Approximately 27 percent of the burned area from the 2017 Nuns Fire had been previously burned in the time since 1951. The Nuns Canyon Fire of 1964 burned within 14 percent of the footprint of the Nuns Fire of 2017. Figure 3 shows the overlapping Nuns Canyon Fire, 1964, and Nuns Fire,2017, while figure 5 shows the area burned from 1951 to present.

The area can be described as follows. Within the burned area, topography of the area includes a range of elevational changes, from gentle (200 feet above sea level) to steep (2,730 feet above sea level) (California Department of Forestry and Fire Protection, 2017b). Average rainfall ranges from 23 to 50 inches. The climate can be described as Mediterranean, with warm dry summers and cool wet winters. The vegetative cover includes coastal oak woodlands, mixed chaparral and mixed hardwood and conifer forest.

The soils are generally shallow on slopes greater than 30 percent, with soil depth ranging from less than 10 to 35 inches (California Department of Forestry and Fire Protection, 2017b). The makeup includes several varieties of weathered bedrock, metavolcanics and sedimentary rocks, including sandstone, and shale. Within the region there are many different soil types, however the majority are derived from volcanic bedrock. The remaining soils tend to be composed of loam soils that are derived from sandstone, shale and serpentinite, with greatest susceptibility to erosion.

Soil burn severity and debris flow likelihood were measured through fire analysis by a variety of agencies, including Earthstar Geographics. Soil burn severity distribution for the Nuns fire can be approximated at 82% unburned/low burn severity, 16% moderate burn severity and 2% high burn severity (California Department of Forestry and Fire Protection, 2017b). Figure 6 shows the soil burn severity for the Nuns Fire and figure 7 shows the debris flow likelihood during a precipitation event of 6 mm within a 15-minute time period. Together, these figures can help demonstrate the impact in which soil burn severity has on erosion, or debris flow. Figure 6 shows that the majority of the area burned had a soil burn severity of either low or moderate. These same areas have a greater likelihood of rainfall related debris flow, as shown in figure 7. Analysis of this can lead to considerations of likely sediment transportation following a precipitation event due to relative soil burn severity. The northern most area of the Nuns Fire will likely experience the greatest debris and sediment transport while other portions will experience low to moderate levels of sedimentation. Areas of greater burn severity are linked to areas with the greatest erosion potential. Following the Nuns Fire, the greatest concerns are sedimentation flows and potential water contamination through increased sedimentation and alterations to aquatic habitat. The regional soil burn severity and debris flow likelihood can potentially be linked to elevational changes in the region, with areas of higher elevation having greater soil burn severity and debris flow risk.

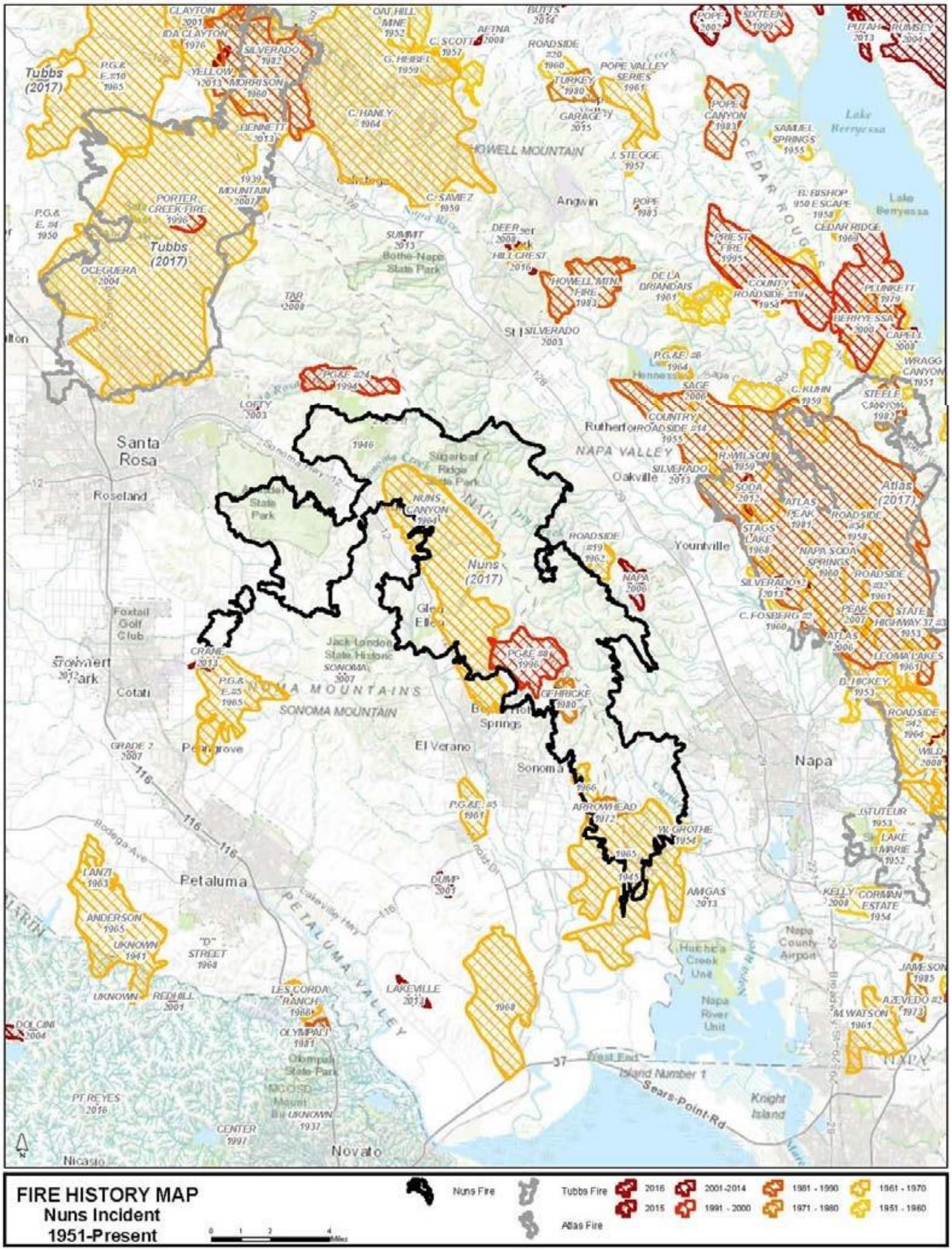

*Figure 5: Nuns Incident Fire History M*ap, 1951 To Present *(California Department of Forestry and Fire Protection, 2017)*

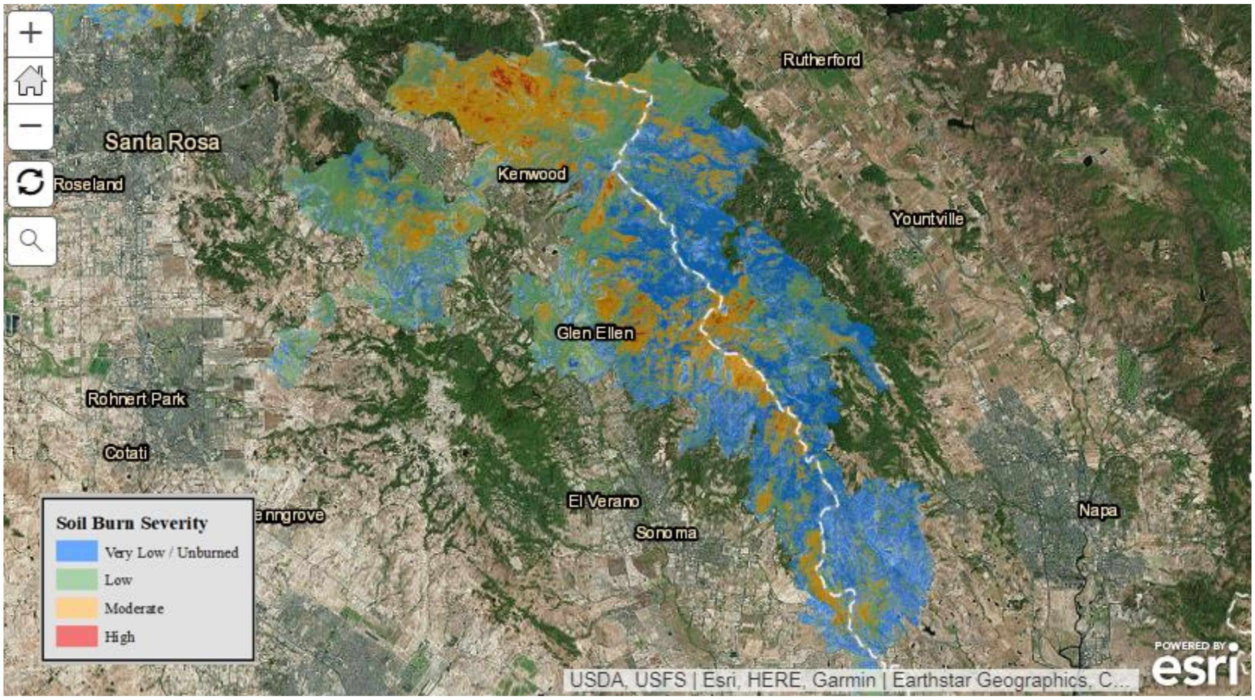

Figure 6: Soil Burn Severity of Nuns Fire, 2017 (Sonoma Open Space, 2017).

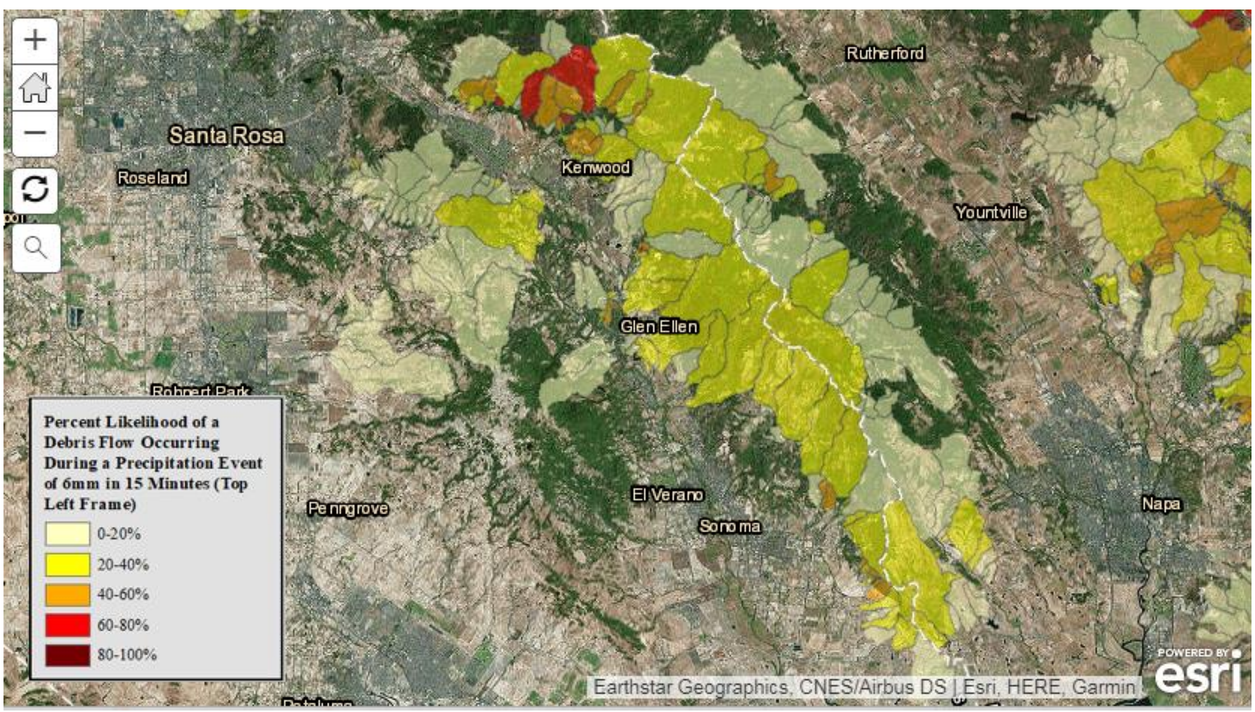

Figure 7: Debris Flow Likelihood Following Nuns Fire With 6 mm of Rainfall Within 15 Minutes (Sonoma Open Space, 2017).

4.3.4.3. TUBBS FIRE, OCTOBER 2017

Along with the Nuns Fire, the Tubbs Fire began on October 8, 2017 in Calistoga, California, burning 36,807 acres in Sonoma and Napa counties (California Department of Forestry and Fire Protection, 2017c). Part of the Central LNU Complex, the Tubbs fire began in the upper Napa River watershed and later impacted both the Russian River and Putah Creek watersheds. Figure 8 shows the fire history, since 1951, of the burned area. During the Hanley Fire in 1964, the large majority of the area burned in the Tubbs Fire was burned. Prior to the Tubbs Fire, the northern region had been burned in 1986, and a small fire burned in 1996 (California Department of Forestry and Fire Protection, 2017c). However, in the northern portion of the map, in Lake County, there was a significant area burned in 2015 and 2016, potentially outlining the regional conditions and susceptibility to fire.

The area burned ranged from steep mountains, gentle rolling hills and to flat valley bottoms. The elevational changes are from roughly 120 feet to 4,100 feet above sea level. This region has an average annual rainfall ranging from 31 to 45 inches. The climate is typically Mediterranean with warm, dry summers and cool, wet winters. The vegetative cover consists of oak woodland, chaparral, mixed hardwood and conifer forests, also covering urban environments. Soils range from shallow (less than 2 feet) to thick (greater than 5 feet). Geologically, the Tubbs fire burn area lies within the Mayacamas Mountains. This region is prone to landslides and erosion (California Department of Forestry and Fire Protection, 2017c).

Soil burn severity distribution for the Tubbs Fire varied slightly from the Nuns Fire. The Tubbs Fire had approximately 61% of the region with unburned or low burn severity, 38% with moderate burn severity and 2% with high burn severity. (California Department of Forestry and Fire Protection, 2017c). Figures 9 and 10 show the regional variations in both soil burn severity and debris flow likelihood with 6 mm of rainfall in 15 minutes. Analysis of these figures show that a large portion of the burned area had moderate soil burn severity and thus have a corresponding high possibility of sediment and debris flow following a precipitation event. Similar to the Nuns Fire, the Tubbs Fire has a large concern with sedimentation flow and deposition post-fire. Regions with a higher elevation have observably increased soil burn severities in comparison to regions with lower elevation. Compared to Nuns Fire, Tubbs fire has a greater proportion of moderate burn severity, leading to greater concern for sedimentation and water contamination.

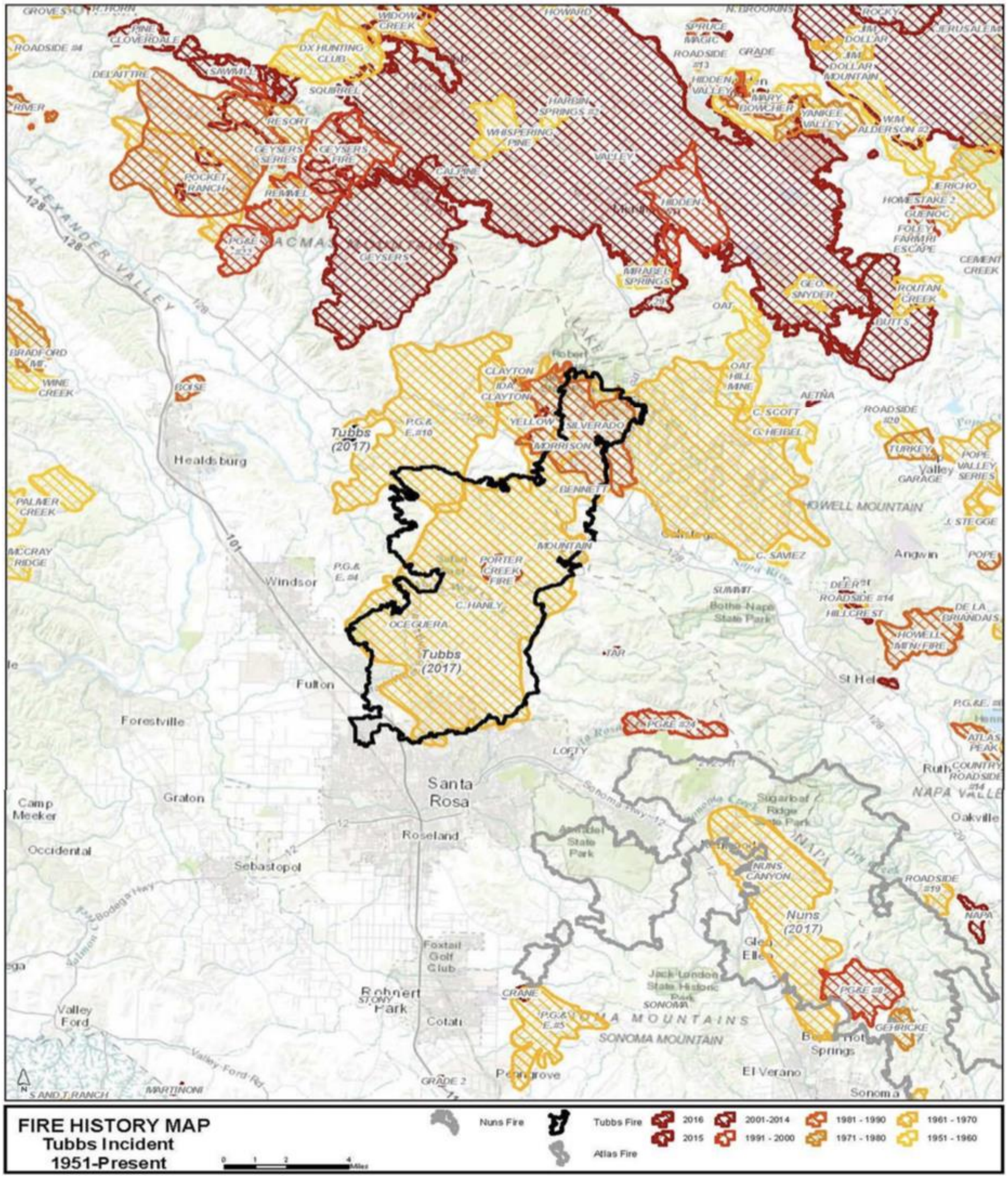

Figure 8: Tubbs Fire History Map From 1951 To 2017 (California Department of Forestry and Fire Protection, 2017c)

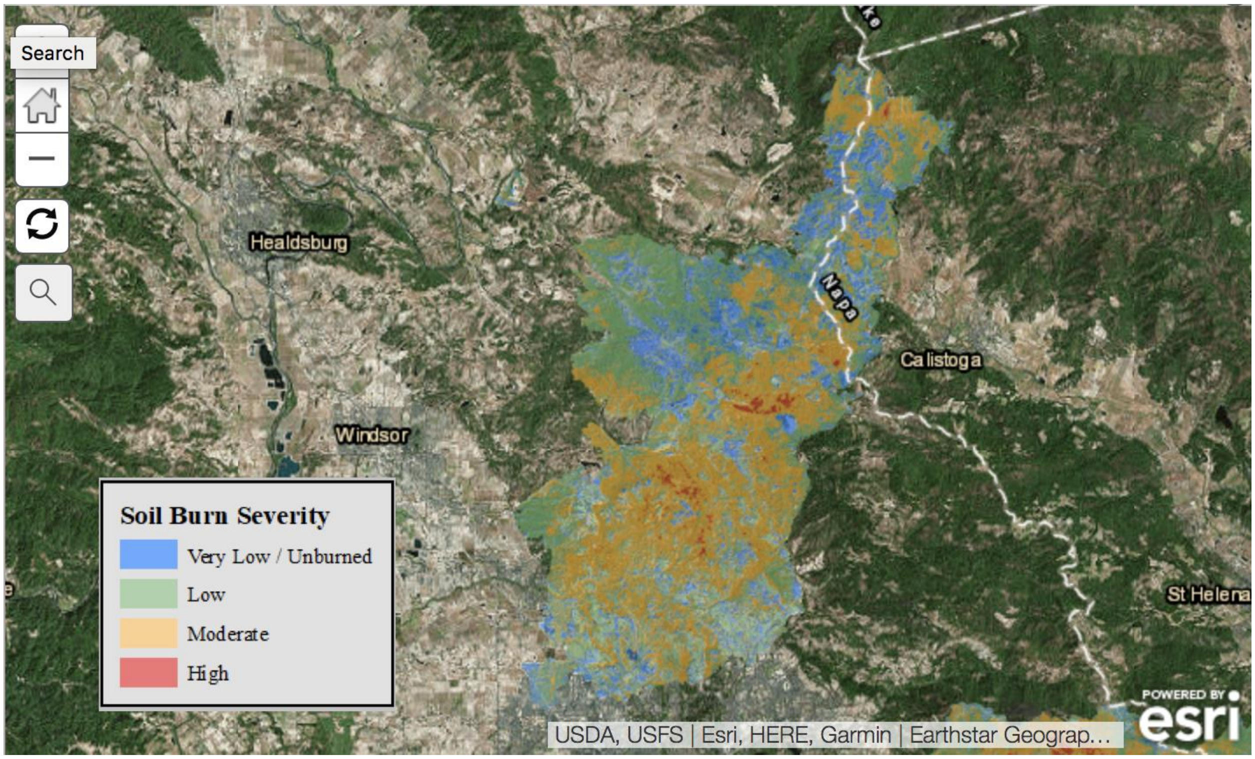

Figure 9: Soil Burn Severity Of Tubbs Fire, 2017 (Sonoma Open Space, 2017).

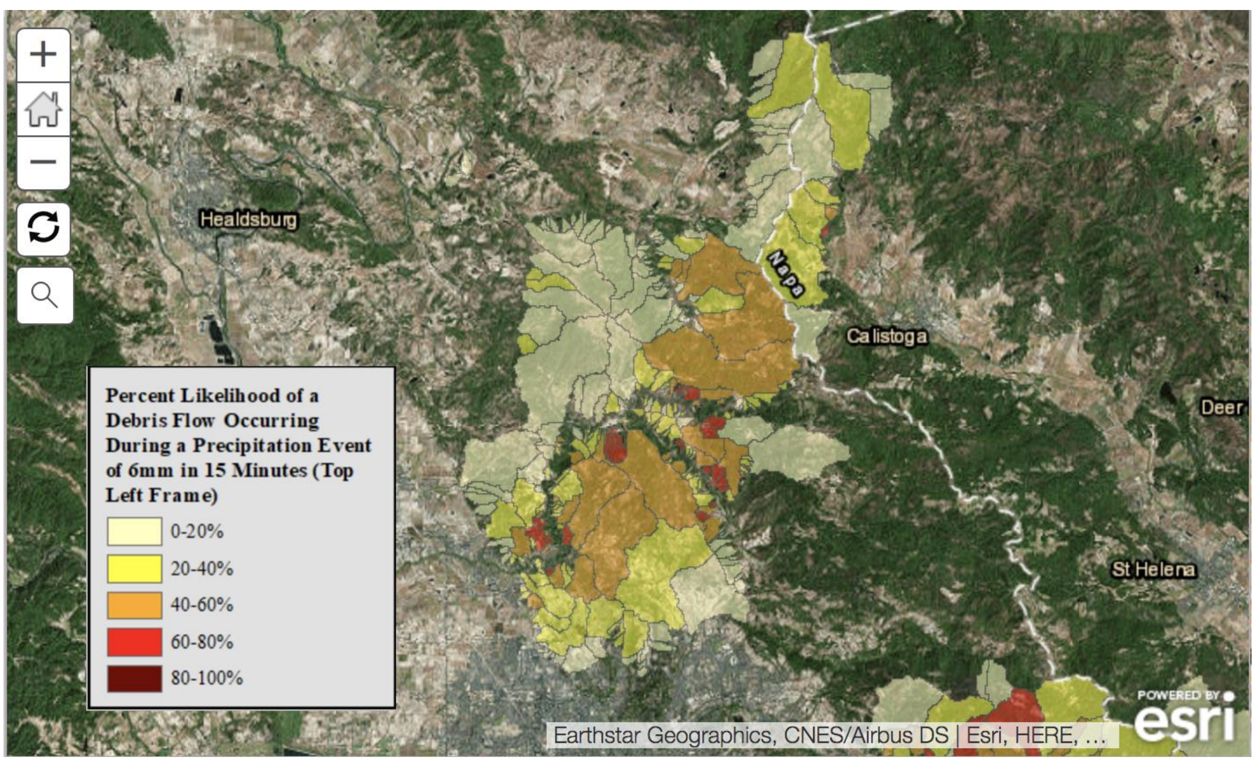

Figure 10: Debris Flow Likelihood Following Tubbs Fire With 6 Mm of Rainfall Within 15 Minutes (Sonoma Open Space, 2017).

4.3.4.4. POCKET FIRE, OCTOBER 2017

Along with both the Nuns Fire and the Tubbs Fire, the Pocket Fire began on October 8, 2017 as part of the Central LNU Complex of the North Bay Fires. The Pocket Fire burned 17,345 acres, destroying or damaging 8 buildings (California Department of Forestry and Fire Protection, 2017a). The watershed areas impacted by the Pocket Fire include Geyserville, the Russian River and the City of Cloverdale. This area is located in the western portion of the Caslamayomi Mountains, with relatively gentle topography and some steep topography.

The fire area ranged in elevation from 400 to 3450 feet above sea level, approximately 3050 feet of vertical relief. The vegetation in the area consists largely of coastal oak woodlands, mixed chaparral, mixed hardwood and conifer forest, grasslands and vineyards (California Department of Forestry and Fire Protection, 2017a). Compared to Nuns, Tubbs, and Atlas fires, the Pocket Fire was located in a region with low levels of development in combination with little values at risk, taking place in unpopulated rangeland.

Although figures were not available to represent soil burn severity and debris flow likelihood with 6 mm of rainfall in a 15-minute period for the Pocket Fire, assumptions can be made based on the Nuns and Tubbs Fire to derive a similar evaluation. The approximate soil burn severities for the Pocket Fire were 75% unburned/low burn severity, 24% moderate burn severity, and 1% high burn severity (California Department of Forestry and Fire Protection, 2017a). Compared to both Nuns and Tubbs Fire, the Pocket Fire had a greater proportion of the burned area in unburned to low burn severity. This observation could be attributed the regional topography of a lower average elevation and a smaller range in elevation when compared to the Nuns and Tubbs Fires. Considering the correlations observed between soil burn severity and debris flow likelihood for both the Nuns and Tubbs Fires, the soil burn severity for the Pocket Fire can be interpreted directly to debris flow. There will be some regions of high debris flow likelihood (80-100%) while the primary debris flow will likely occur between 0 and 60 percent, considering the distribution of soil burn severity.

Following the Nuns, Tubbs and Pocket Fires, three separate Watershed Emergency Response Teams (WERTs) were established to identify general recommendations for the regions based on finds and identified values at risk, threats, and emergency conditions. In the evaluations, all three WERTs identified risks at value with increased flood flows, debris flows, erosion and sedimentation (California Department of Forestry and Fire Protection, 2017a). General recommendations based on debris flows, erosion, flooding, safety and property threats can be seen in table 6. Table 6 allows for the comparison of general recommendations between the three fires that make up the Central LNU Complex. These general recommendations, while not fully comprehensive or conclusive, provide some guidance to assist emergency response agencies to develop more detailed response plans in case of fire. Due to the regional characteristics of the Pocket Fire, large areas of unpopulated rangeland, low levels of development and few potential risks, a less comprehensive report was created as compared to Nuns and Tubbs fires.

Table 6: Central LNU Complex Fire General Recommendations, per WERT

FIRE	GENERAL RECOMMENDATIONS								
	EARLY WARNING SYSTEM	COMMUNICATION	ROAD DRAINAGE & STORM PATROL	TEMPORARY HOUSING	HAZARDOUS MINERAL	CAMPGROUNDS & TRAILER PARKS	MUNICIPAL WATER SUPPLIES	TEMPORARY MEASURES	SOURCE
POCKET FIRE, 2017	System to allow residents time to safely evacuate hazard areas	Communicate hazards and risks to agencies and notify homeowners/ communities	Communicate hazards to Caltrans and Sonoma County	Site specific hazard identification	Communicate hazards and risk to responsible agencies	Close all campgrounds during winter period following fire, for first years	Study of impacts to downstream water supplies, if applicable	Place temporary signage, gates or other measures in high risk areas to control traffic	(California Department of Forestry and Fire Protection, 2017a)
NUNS FIRE, 2017	Utilization of existing early warning systems to alert residents to safely vacate hazard areas, develop methods where cell reception is limited	Utilization of CodeRED, provides a variety of ways to communicate/contact the community in the event of an emergency	Along bridges and other crossings, consider installing warning signs, gates and other measures to reduce traffic flow and people access	Construction should be done by qualified professional and consider hillslopes above and below potential temporary housing/building sites	Portions may be impacted, in particular Hood Mountain area in regard to mercury and asbestos hazardous	Areas should be closed during the winter months for the first years following the fire; includes Hood Mountain Regional Park & Sugarloaf Ridge State Park	Water supply agencies should be notified of potential threat to buried water supply lines and water storage tanks; likely to contain chemical contaminants, ash and fire-related sediment	N/A	(California Department of Forestry and Fire Protection, 2017b)
TUBBS FIRE, 2017	Recommended installation of truck mounted radar for more accurate forecasting of rain events; utilization of existing early warning systems to alert residents to allow for vacation of hazard areas; creation of early warning system to alert homeowners located in the FEMA 100-year flood plain of large storm events		Diversion of flows down roads to reduce erosion, possible blockage and loss of portions of the roads; installation of gates, signage and other measures to control traffic	Construction should be done by qualified professional and consider hillslopes above and below potential temporary housing/building sites	Portions may lie in naturally occurring hazardous materials areas including naturally occurring asbestos	Campgrounds and recreational areas should be closed during winter months and storm events following the first few years post fire	It is expected that runoff from the burn area will contain chemical contaminants, ash and fire-related debris that could post adverse environmental impacts	Postage of signage in areas with potential post-fire rockfall and flooding, as well as areas at risk of flooding, rockfalls and debris flows along bridges, roads and other crossings	(California Department of Forestry and Fire Protection, 2017c)

4.3.5. COMPARING NORTH BAY CENTRAL LNU COMPLEX FIRE TO HISTORICAL FIRES

While regionally it is difficult to compare fire characteristics and relationships among fires, this section will attempt to find correlations between Hanley-Nuns Canyon Fire (1964), Rim Fire (2013), Thomas Fire (2017), Atlas Fire (2017), and the Central LNU Complex of the North Bay Fires (2017).

To synthesize data for a comparative analysis, table 7 shows a comparison of characteristics relating historical California fires to the recent North Bay Fires, in particular the Central LNU Complex (consisting of Nuns, Tubbs and Pocket fires). For each fire, area burned, topography, average rainfall, climate, vegetative cover and soils are defined, as data was available. Figures 11 through 13 compare and contrast these characteristics.

With drought and climate potentially contributing to fire occurrence and fire size, a comparative analysis relating acres burned and average annual precipitation was made for the seven fires considered. Figure 11 is a graphical representation of the correlation between total acres burned and average annual precipitation (in inches). This graph shows that for the 6 fires, the average rainfall was approximately the same. However, there was a greater potential range in annual rainfall total observed as acreage burned increased, except for the Rim Fire where only a singular data point was available. However, this observation could not lead to conclusive results. Because there is no data to show whether increased or decreased precipitation impacts these fire regions individually, no conclusive answers can be derived. While no answers can be derived directly from the fires observed, rainfall quantities and patterns could influence a region's susceptibility and likelihood to experience fire. Future analysis of additional fires in regions that experience increased or decreased annual rainfall would lend to a better understanding of fire and precipitation interconnectedness.

To gain an understanding in topographic and elevational influences on fire, an analysis of acres burned to both average elevation and differences in elevation were evaluated. Figure 12 and figure 13 show graphically the relationship of acres burned and average elevation, and elevation range. The larger fires occupied a larger range of elevations and the average elevation was greater than the smaller fires. This could indicate correlation between slope and fire severity and size impacts. The relationship of these show an increased average elevation in relation to the acres burned. This indicates the role that topographic changes may have on fire movement. The four smaller fires took place at lower elevations and similarly had a lower elevational range. Reasonably, this data indicates that greater elevational changes and slope changes provide a greater chance of larger fire spread due to increased hillside and mountainous region burning.

To identify potential differences in vegetative type and fire size, distribution of vegetative types among the fires was analyzed. Figure 14 shows a pie chart that characterizes the fires by vegetative cover types. Almost all fires were mixed vegetative types based on location, with the exception of the Rim Fire that was in hardwood/conifer forests only. Hardwood/conifer forests were present. Six of the seven fires were located in chaparral regions. And 5 of the 7 were located in coastal oak woodlands. There were also fires that had regions including urban environments, grasslands, coastal shrubland agricultural vegetation.

Generally, no conclusions could be made regarding soil type and depth due to lack of data.

In an attempt to relate structure damage to fire size, an analysis of fire size and structures both damaged and destroyed was completed. Table 8 relates the acreage burned and structures burned for each of the fires (Hanley-Nuns, Rim, Rough, Thomas, Atlas, Nuns, Tubbs and Pocket). Figure 15 provides graphical representation of this information. There was no significant correlation found. It can be expected that more urbanized areas would have greater destruction and damage to structures compared to more rural areas. While there may be a correlation between urbanized areas and number of structures burned and destroyed, there is no correlation observed between acreage burned and the number of structures either destroyed or damaged.

To further evaluate soil burn severity specifically for the North Bay Fires Central LNU Complex, low, moderate and high soil burn severity distribution was analyzed. Table 9 relates the percentage of unburned, low burn, moderate burn and high burn severity among the Central LNU Complex Fires: Pocket, Nuns and Tubbs. While there is some variation in soil burn severity distribution, there was a high correlation among the fire's individual burn severities. Analysis indicates that in fires, the largest area will experience unburned or low burn severity with decreasing area size from moderate to high burn severity. This distribution will be approximately 73% unburned/low burn severity, 26% moderate burn severity and 2% high burn severity. Figure 16 provides graphical representation of this information. In general, the data shows that the Tubbs fire had a greater percentage of moderate soil burn severity when compared to both Nuns and Pocket Fires. This could be in relation to elevational changes in topography. Referring back to Table 7 and Figures 12 and 13, the Tubbs Fire had the greatest average elevation and elevational change among the fires. As a result, there can be seen an increase in moderate soil burn severity. Unfortunately, however, due to lack of data, estimate cannot be made on unburned, very low and low burn severity for the fires.

Table 7: Fire Characteristics of Historic California Fires.

FIRE	REFERENCE(S)	AREA BURNED	TOPOGRAPHY	AVERAGE RAINFALL	CLIMATE	VEGETATIVE COVER	SOILS
HANLEY-NUNS CANYON FIRE, 1964*	(California Department of Forestry and Fire Protection, 2017b)	9,808 acres	120 ft to 4100 ft above sea level	23 to 50 in.	Mediterranean	Mixed chaparral, mixed hardwood/conifer forests, coastal oak woodlands, urban environments	Ranges from shallow (<35 in) to thick (>5ft); weathered bedrock
RIMS FIRE, 2013	(Sierra Nevada Conservancy, 2014; Staley, 2013; Stanislaus National Forest U.S. Forest Service, 2013)	257,314 acres	869 ft to 7874 ft above sea level	37.99 in.	Mediterranean	Coniferous forest	N/A
THOMAS FIRE, 2017	(California Department of Forestry and Fire Protection, 2018e)	281,893 acres	10 ft to 6,383 ft above sea level	3.99 to 72.39 in.	Mediterranean	Mixed chaparral, coastal shrub, coastal oak woodland, and annual grassland	Predominantly shallow depth soils
ATLAS FIRE, 2017	(California Department of Forestry and FIre Protection, 2017d; California Department of Forestry and Fire Protection, 2018a)	51,624 acres	50 ft to 2663 feet above sea level	18.9 to 77.3 in.	Mediterranean	Hardwood woodland, shrubland, grassland, agricultural land and some coniferous forest	Ranges from shallow (<2 ft) to thick (>5 ft); weathered bedrock and eolian deposition

CENTRAL LNU COMPLEX, 2017							
NUNS FIRE, 2017	(California Department of Forestry and Fire Protection, 2017b)	56,556 acres	200 ft to 2730 ft above sea level	23 to 50 in.	Mediterranean	Mixed chaparral, mixed hardwood/conifer forests, Coastal oak woodlands	Generally shallow (<10 in to 35 in); weathered bedrock
TUBBS FIRE, 2017	(California Department of Forestry and Fire Protection, 2017c)	36,808 acres	120 ft to 4100 ft above sea level	31 to 45 in.	Mediterranean	Oak woodland, chaparral, conifer/hardwood, urban environments	Ranges from shallow (<2ft) to thick (>5ft); weathered bedrock
POCKET FIRE, 2017	(California Department of Forestry and Fire Protection, 2017a)	17,345 acres	400 ft to 3450 ft above sea level	Not available	Mediterranean	Coastal oak woodland, mixed chaparral, mixed hardwood/conifer forests, grassland, vineyards	Not available

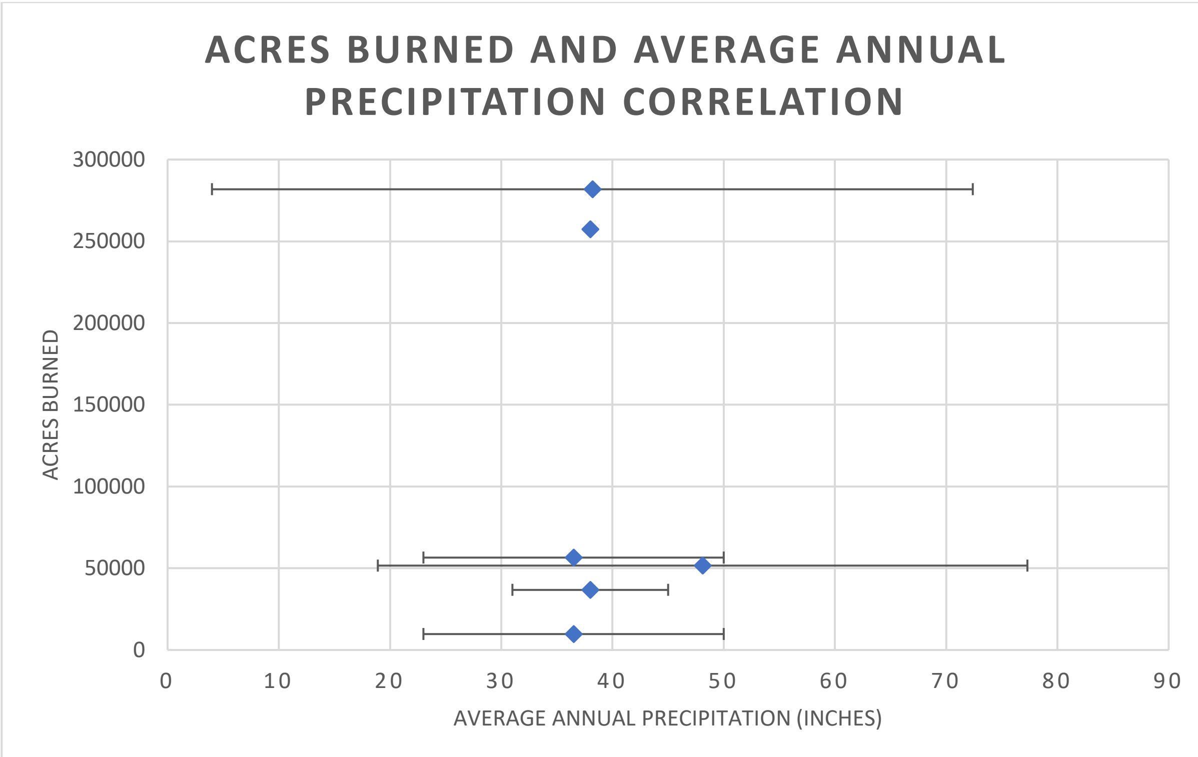

Figure 11: Acres Burned and Average Annual Precipitation Correlation with error bars representing annual rainfall range.

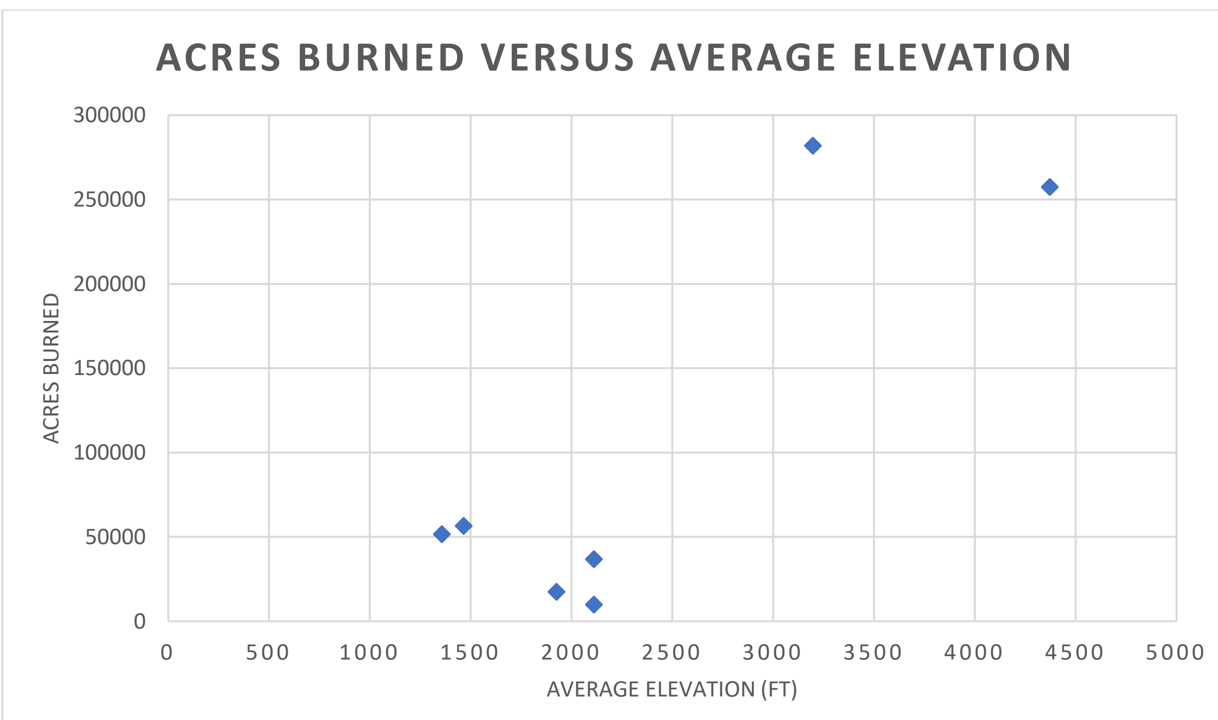

Figure 12: Acres Burned Versus Average Elevation (ft)

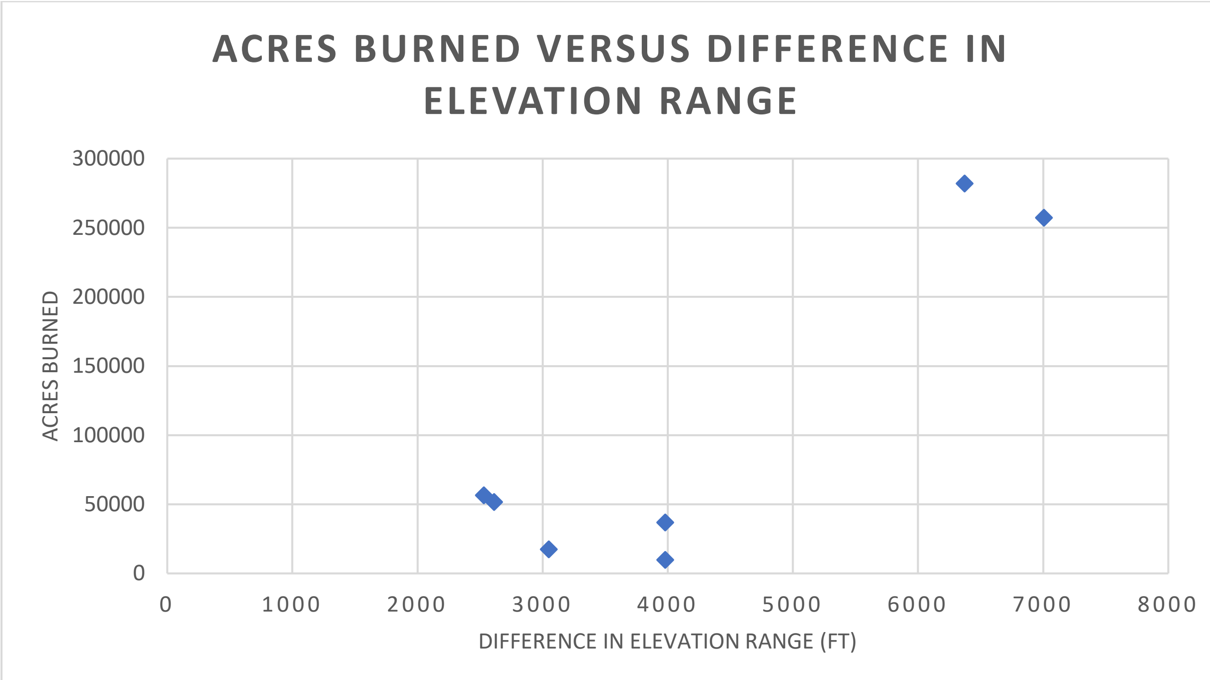

Figure 13: Acres Burned versus Difference in Elevation Range, calculated from lowest and highest elevations at which fire burned.

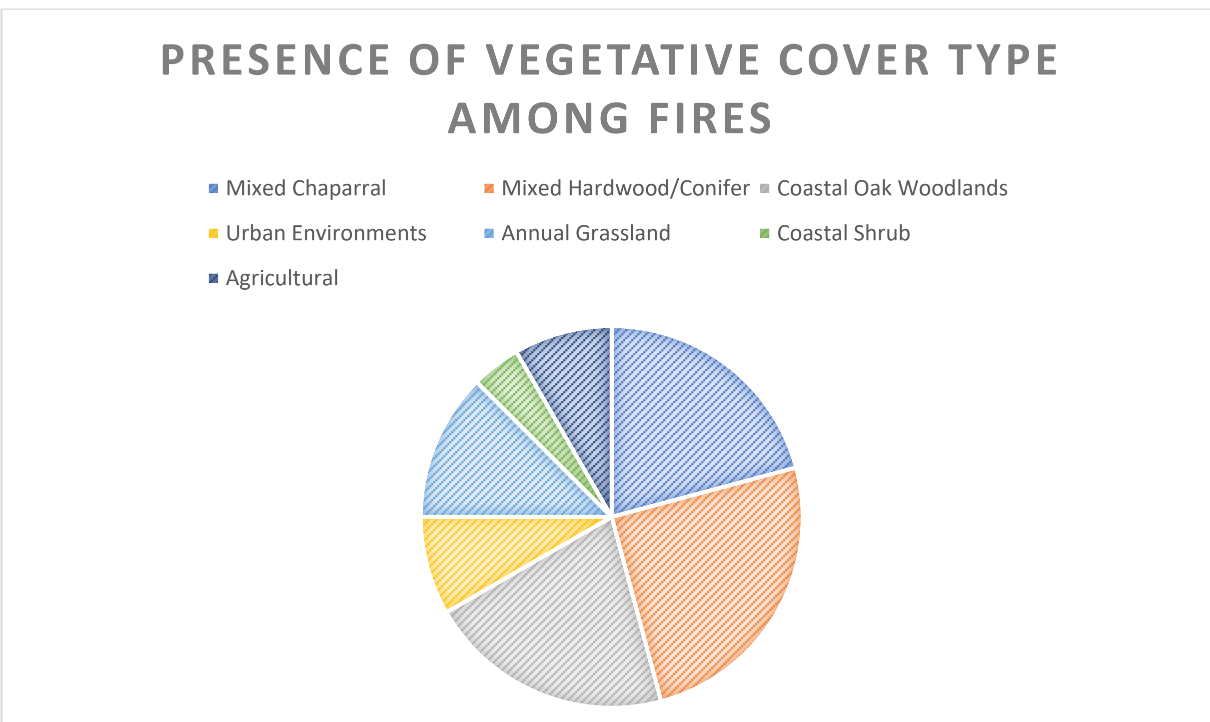

Figure 14: Vegetation Cover Present in Burned Regions for Hanley-Nuns Canyon, Rim, Thomas, Atlas, Nuns, Tubbs and Pocket Fires.

Table 8: Area Burned, Structures Destroyed & Damaged During Fire Event.

FIRE	AREA BURNED	STRUCTURES DESTROYED/ DAMAGED	SOURCE(S)
HANLEY-NUNS CANYON FIRE, 1964	approximately 52,700 acres	295	(Martin & Sapsis, 1995; Weber, 2017)
RIMS FIRE, 2013	257,314	112	(Stanislaus National Forest U.S. Forest Service, 2013)
THOMAS FIRE, 2017	281,893 acres	1343	(California Department of Forestry and Fire Protection, 2018b)
ATLAS FIRE, 2017	51,624	783	(California Department of Forestry and Fire Protection, 2018a)
CENTRAL LNU COMPLEX, 2017	*110,809 acres*	*7497*	(California Department of Forestry and Fire Protection, 2017a; California Department of Forestry and Fire Protection, 2017c; California Department of Forestry and Fire Protection, 2017b)
NUNS FIRE, 2017	56,556 acres	approximately 1000	(California Department of Forestry and Fire Protection, 2017b)
TUBBS FIRE, 2017	36,908 acres	6489	(California Department of Forestry and Fire Protection, 2017c)
POCKET FIRE, 2017	17,345 acres	8	(California Department of Forestry and Fire Protection, 2017a)

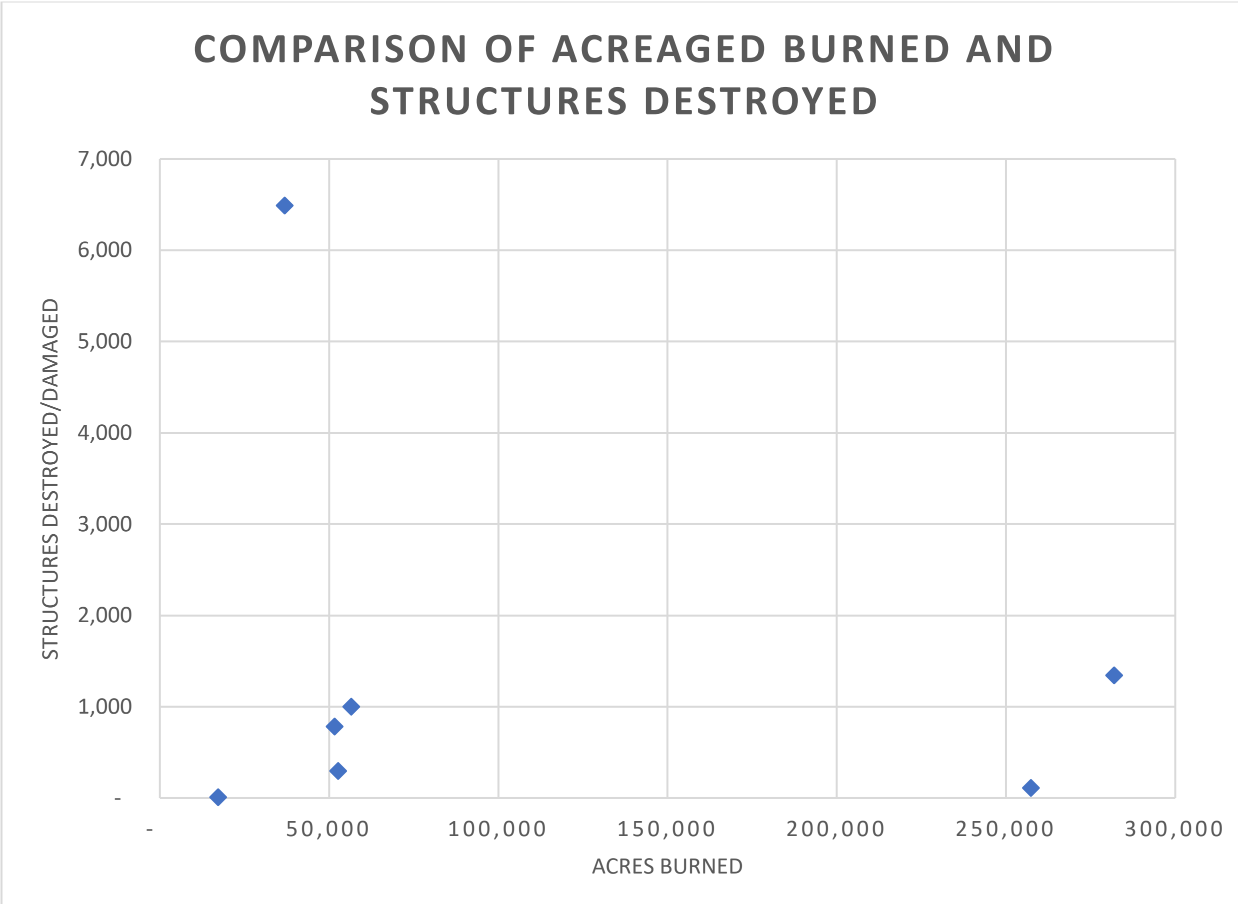

Figure 15: Comparison of Acreage Burned and Structures Destroyed, Adapted from Table 7.

Table 9: Central LNU Complex Percentage of Low, Moderate and High Soil Burn Severity

FIRE	Unburned/ Very Low Burn Severity (Acres)	Unburned/ Very Low Burn Severity (Percent)	Low Burn Severity (Acres)	Low Burn Severity (Percent)	Moderate Burn Severity (Acres)	Moderate Burn Severity (Percent)	High Burn Severity (Acres)	High Burn Severity (Percent)	Source
POCKET FIRE, 2017	5255 acres	30%	7,775 acres	45%	4,150 acres	24%	163 acres	1%	(California Department of Forestry and Fire Protection, 2017a)
NUNS FIRE, 2017*			85,986 acres	82%	17,278 acres	16%	1,713 acres	2%	(California Department of Forestry and Fire Protection, 2017b)
TUBBS FIRE, 2017**			42,591 acres	61%	26,593 acres	38%	1,125 acres	2%	(California Department of Forestry and Fire Protection, 2017c)
Avg. percentages				73%		26%		2%	

[1]

[1] *Due to large quantities of grass and shrub cover within the Nuns Fire area, unburned, very low burn and low burn severity were combined. Additionally, total watershed area (104,979 acres) was utilized, not total acres burned (California Department of Forestry and Fire Protection, 2017b).
**Due to large quantities of grass and shrub cover within the Tubbs Fire area, unburned, very low burn and low burn severity were combined. Additionally, total watershed area (70,009 acres) was utilized, not total acres burned (California Department of Forestry and Fire Protection, 2017c)

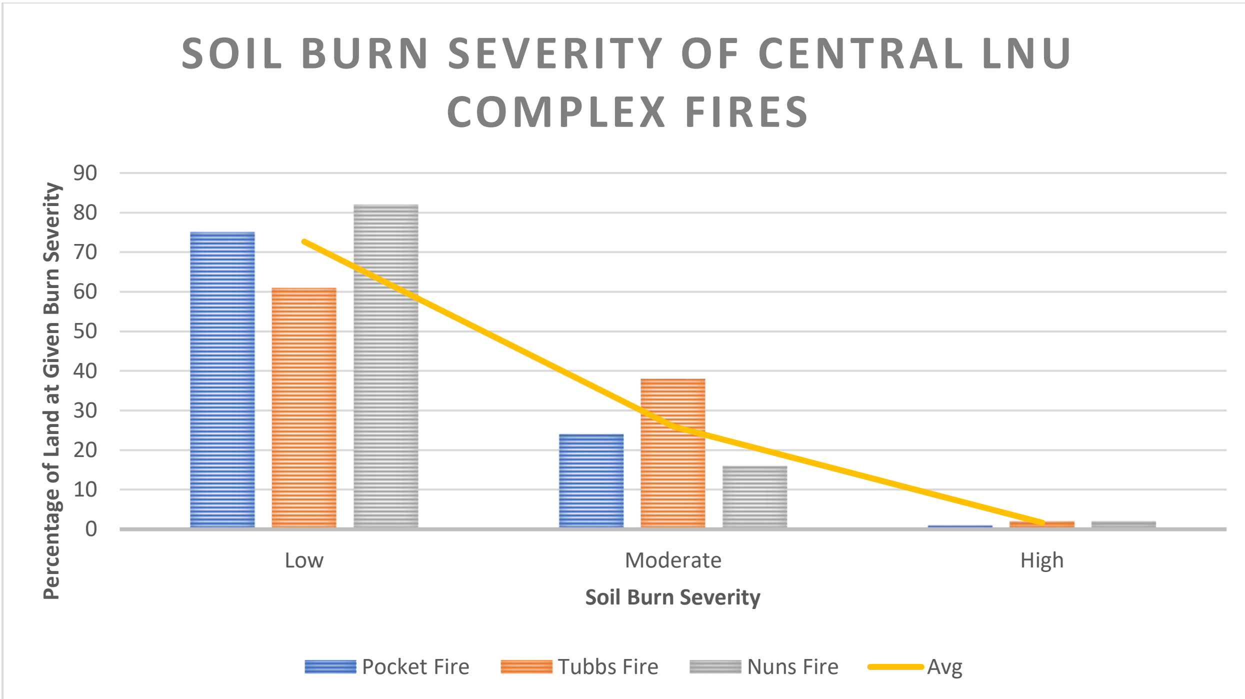

Figure 16: Soil Burn Severity of Central LNU Complex Fires: Pocket, Tubbs and Nuns Fires. Adapted from Table 8.

4.4. POST FIRE LAND MANAGEMENT AND FIRE MANAGEMENT STRATEGIES

Ecosystems are impacted by fires at varying levels resulting in complex relationships, both interdependent and dynamic. When fires are controlled, they can help revitalize the natural landscape through the recycling of minerals, encouragement of new growth plant communities and removal of built up debris. Globally, western societies formed a biased perception of fire due to the concentration of fire data in fire-prone, western countries (Doerr & Santin, 2016). In the nineteenth century, the German forestry school developed the system of forest protection through a 100 percent fire exclusion policy, proven to be impractical, unsustainable and economically detrimental (Doerr & Santin, 2016). However, this fire management became widely used and is only now slowly changing (Doerr & Santin, 2016).

4.4.1. FIRE MANAGEMENT STRATEGIES

Many organizations have created guidelines for fire management plans and set forth fire management strategies. The U.S. Department of Forests and Rangelands created a strategy entitled "The National Strategy: The Final Phase in the Development of the National Cohesive Wildland Fire Management Strategy", in which three goals are stated: (1) creation of resilient landscapes, (2) fire adapted communities, and (3) safe and effective wildlife response (Forests and Rangelands, 2018). Within this plan, the challenges outlined include the management of vegetation and fuels, protection of homes and communities, management of anthropogenic ignitions, and the effective and efficient response to wildfires. However, while a strategy is outlined, the U.S. Department of Forests and Rangelands does not propose specific efforts in order to lend to the management of fires and fire prevention. Instead, it set national priorities. Figures 17-20 show the national priorities for broad scale fuel management, community planning and coordination, management of human caused ignitions and risk of large wildfires. The largest concentrated areas with priority for fuel management, community planning and coordination, and likelihood of large fires are effectively located in the Western, Central and South-Western states. These regions have been identified due to topography, climate and regional characteristics as the greatest risk and thus the highest national priority in regards

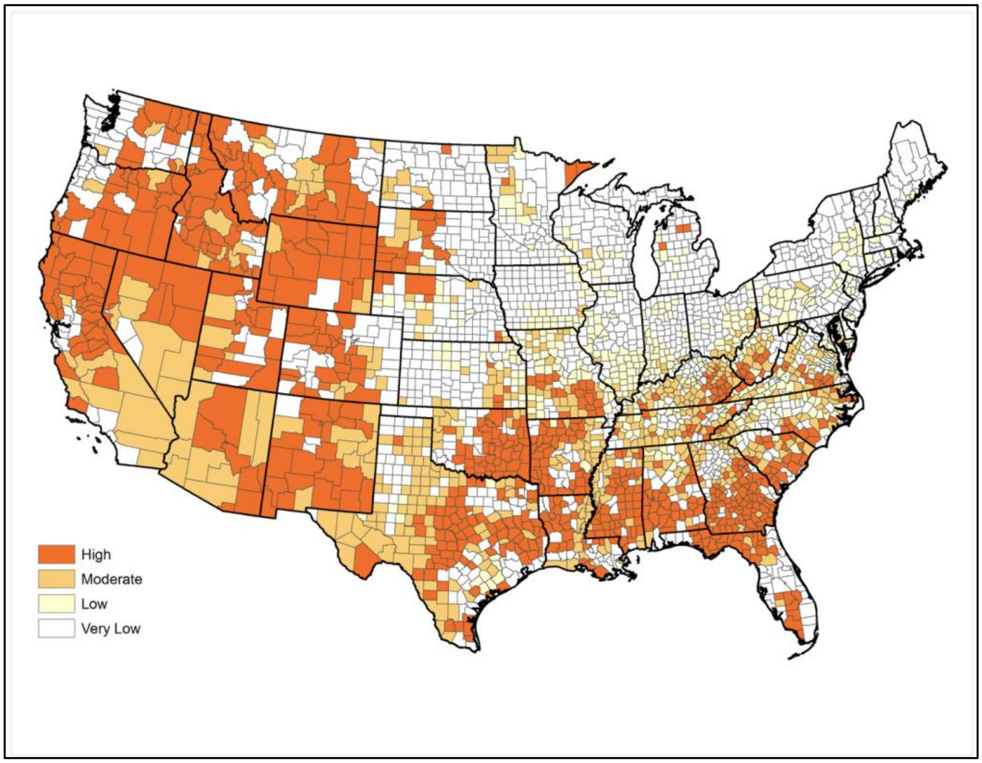

Figure 17: National Priorities for Broad Scale Fuels Management (Forests And Rangelands, *2017*).

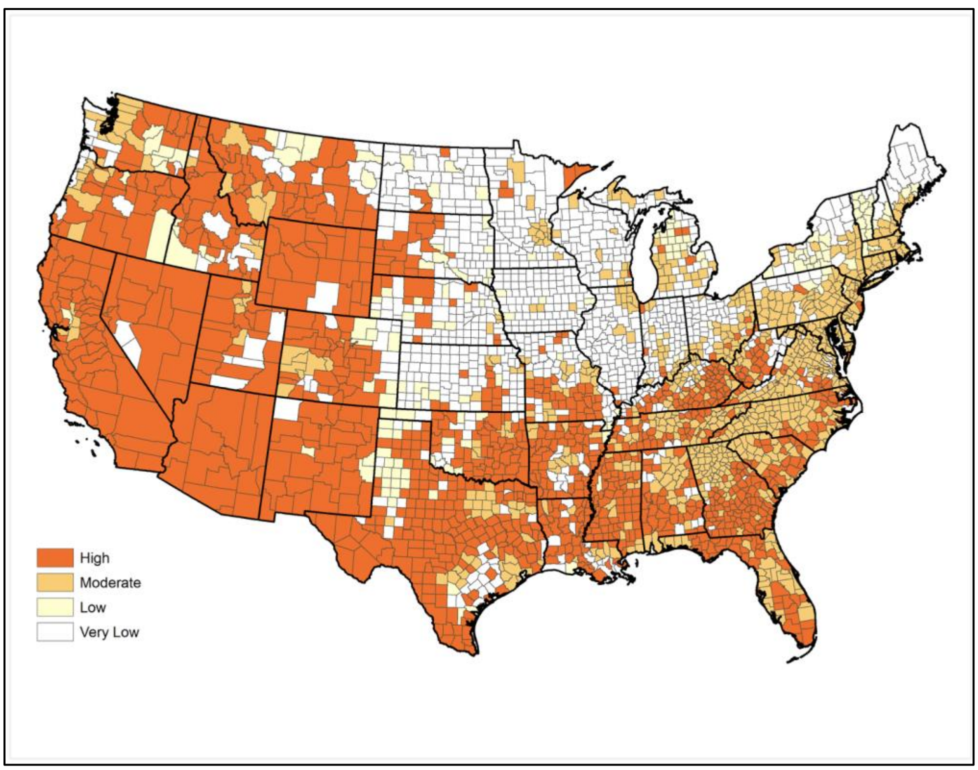

Figure 18: National Priorities for Community Planning and Coordination (*Forests And Rangelands, 2017*).

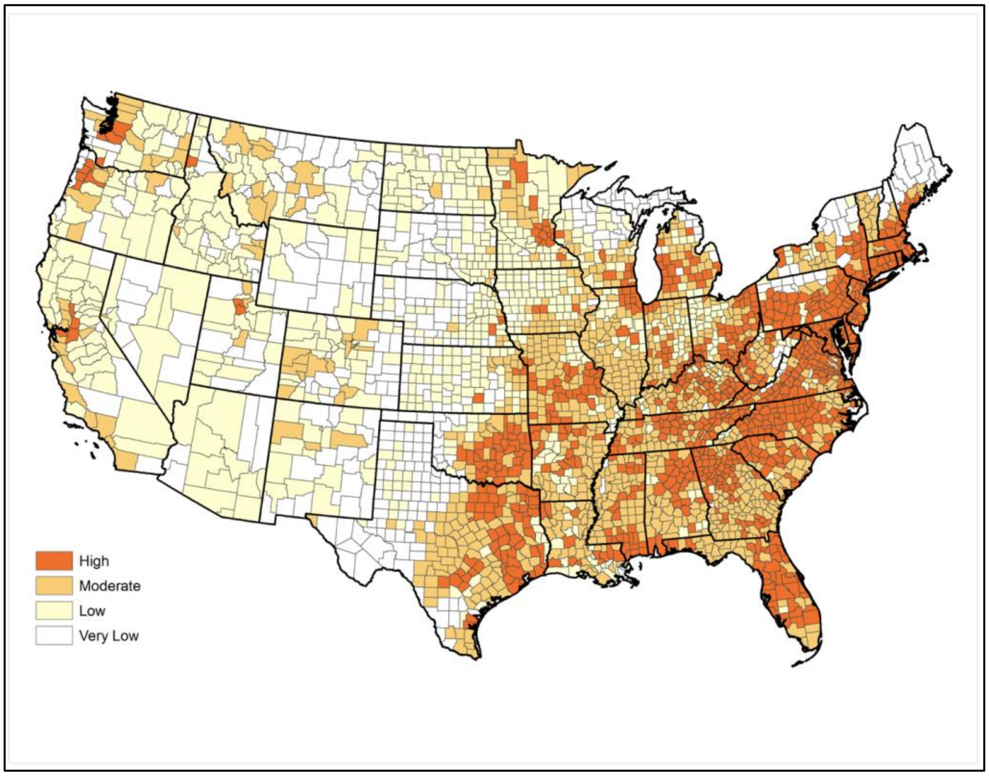

Figure 19: National Priorities for Managing Human-Caused Ignitions (*Forests and Rangelands, 2017)*

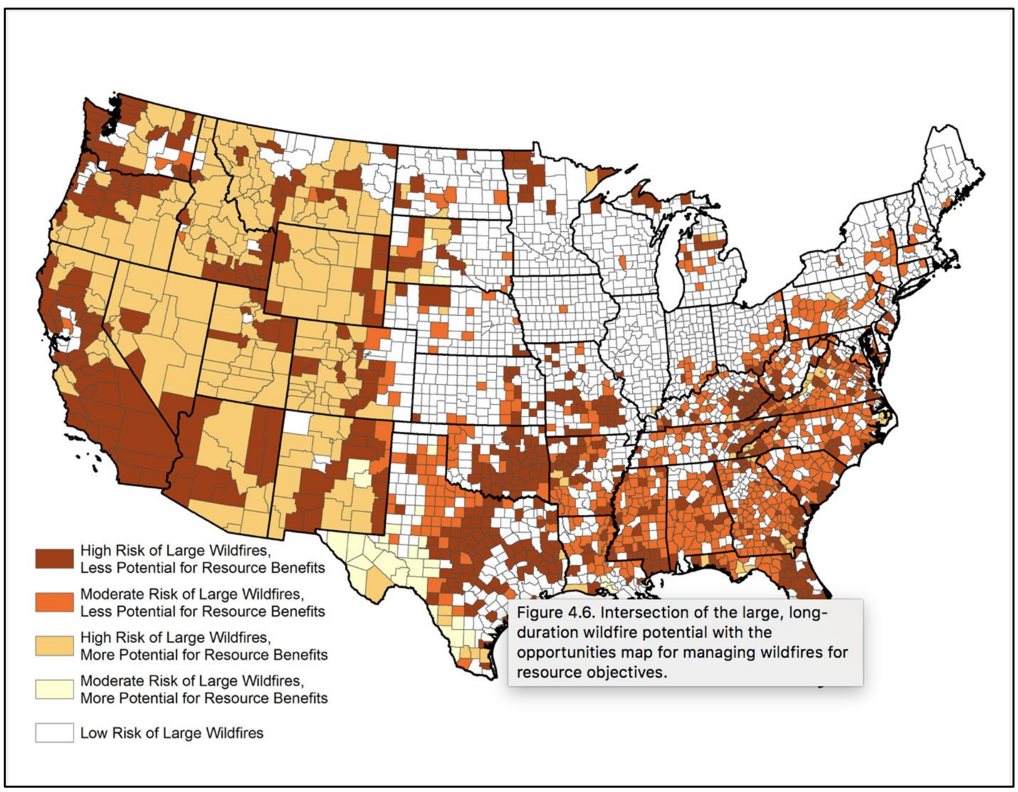

Figure 20: Likelihood of Large Fires and Corresponding Resource Benefits (Forests and Rangelands, 2017)

to fire management. The area with greatest national concern for human caused ignitions lies in the Eastern states, potentially due to lesser risk of wildfire and greater human caused fire risk.

There are three primary methods of wildland fire management and strategies utilized throughout the United States. The wildland fire management strategies proposed by the National Park Service include suppression, wildland fire use and prescribed fire (National Park Service & Fire Management Program Center, 1965). The first strategy, suppression, is when all management actions are to limit the growth or extinguish the fire. The second strategy, wildland fire use, takes place when management allows a fire that is ignited naturally to burn as long as it meets prescription standards. The final strategy, prescribed fire, is where the management uses intentionally set fires as a management tool (National Park Service & Fire Management Program Center, 1965).

Fire is a major component of the natural background conditions of California. Prior to the 20^{th} century, both fire and Native Americans ignited fires to shape the structure and composition of California's ecosystems (Fire Safe Sonoma, 2016). Historical fires were frequent with lesser intensity than fires experiences within the last century, consuming dead material and killing small tress while leaving most large, healthy trees alive and intact. It is estimated that before 1800, nearly 4.5 million acres burned every year in California alone (Fire Safe Sonoma, 2016).

Primary historical land management strategies beginning in the early 20^{th} century have largely been working towards fire suppression, rather than the reduction of fire severity, fire size and community impacts. A fire exclusion policy was first utilized within the United States in 1910 following large fires in Idaho and Montana (Agee & Skinner, 2005). This policy resulted in the suppression of all fires. This exclusion policy applied to all forests and quickly led to tree regeneration in protected forests. And while trees regenerated, early fires were suppressed. Additionally, large fire-resistant trees had been removed, resulting in large spans of smaller treats with a greater fuel load. At one time fires spread along the surface, but with fire suppression these smaller fires became larger and more intense with the capability of jumping into the canopy and becoming crown fires (Agee & Skinner, 2005).

Fire management strategies, locally and federally, have disrupted the natural cycle of fires through fire suppression. Fire suppression has led to a buildup of debris and alterations to the ecological dynamic of specie composition. In the USA, a very small percentage (0.4%) of fires are allowed to burn while all others are actively suppressed (Doerr & Santin, 2016). For example, the Smokey Bear public awareness campaign supported 100% fire suppression (Doerr & Santin, 2016). It was not until recently that governments have begun changing public perception of fires from negative to positive. The ill effects of fire suppression have led to reevaluation of fire management strategies and the identification of other strategies to reduce fire intensity, size, and ecosystem and community impacts. Understanding this shift in perception is largely related to fire and land management strategies that have been utilized historically and new strategies that have been adopted and utilized in various regions.

Traditional thinking has changed regarding fire management over the past decades. The concept of fire control to fire management has altered the common fire suppression mindset to lead to the consideration of the land, resources, incident objectives surrounding the fire in order to make decisions that result in the minimum cost and resource damage or loss (National Park Service & Branch of Wildland Fire, 2014). This idea lends to the concept of letting wildfires burn to an extent, when managed, that does not harm more than benefit both the environment and the people, with minimum loss and financial cost. This would be considered wildland fire use. In many cases, wildland fire use is most beneficial in removing undergrowth and maintaining the structural and compositional integrity of forested ecosystems. Actions are ultimately made based on social, political and environmental considerations in combination with the specific characteristics of the fire, fuel, weather and topography. While there are multiple considerations in wildland fire use, the protection of human life is the overriding priority in fire management. Generally, wildland fire is a desirable process when naturally occurring as it provides the ability to accomplish resource management objectives (National Park Service & Branch of Wildland Fire, 2014). The issue is however that without a fire management plan, approved and current, wildland fires cannot be utilized to accomplish resource management objectives.

The alternative to both fire suppression and wildland fire use is the use of prescribed fires. Prescribed fires can play an important role in hazard reduction, vegetation management, and ecosystem restoration and has forest management and rangeland improvement applications. Prescribed fire has arisen as an alternative to fire suppression, however it does not come without its controversy (National California Prescribed Fire Council, 2013; Harper, Doerr, Santin, Froyd, & Sinnadurai, 2018). Prescribed fire is a complex mechanism for fire management. While when successfully implemented it can be very advantageous, it requires careful planning, specific weather conditions, qualified crews, funding, public support and compliance with applicable laws and regulations. Because of the restrictions, it can be difficult to fulfill management goals and treat entire area planned. These obstacles can consist of burn window (conditions under which a prescribed fire can effectively be burned and managed), air quality regulations, trained personnel availability, public opinion and lack of funding (National California Prescribed Fire Council, 2013). A wildfire that results from a prescribed fire can be managed like any other wildfire in order to control and accomplish resource management objectives.

The final fire management strategy is applicable to more urban environments with greater susceptibility to structure loss. Jack Cohen, a research physical fire scientist with the U.S. Forest Service, developed the concept of the home ignition zone in the late 1990s (National Fire Protection Association, 2018). The idea behind the home ignition zone is the self-protection of homes by homeowners. This concept encompasses three zones, referred to as the immediate, intermediate and extended zones. The immediate zone is the area 0 to 5 feet from the furthest exterior point of a home and considered a non-combustible area. Strategies to prevent structure loss and damage focus on removal of debris from roofs, gutters, and exterior attic vents. It also encourages replacement or repairing of roofs to prevent ember penetration, installation of metal mesh screens in vents, replacement or repairing of window screens and windows and to remove flammable materials from wall exteriors, such as flammable plants, leaves, needles and firewood piles. The intermediate zone is the area 5 to 30 feet from the furthest exterior point of a home. Landscaping and creation of breaks are most important in influencing the behavior of fires. Management includes clearing vegetation from flammable propane tanks, creating fire breaks including driveways and walkways, keep lawns and native grasses moved, remove vegetation under trees, space trees so that the canopies do not touch, limit trees and shrubs within the intermediate zone to break up vegetation availability across the landscape. The final zone is the extended zone, 30 to 100 feet from a house, where landscaping is key in interrupting a potential fire path and keep flames closer to the ground. Management actions include disposal of heavy debris accumulation, removal dead plants and trees, ensure proper spacing between trees. Combined, these actions, partial or whole, can contribute to the protection of individual home. This strategy can also protect the spread and increased intensity of fires by creating breaks, within which fires cannot or will not burn. Similarly, a defensible space, with a radius of at least 100 feet, can help save the lives of individuals and first responders, keeping fires from escaping into wildland, and prevent the loss of homes (Fire Safe Sonoma, 2016).

Effective management strategies are not the same for every region or fire, but vary greatly dependent on the fire, weather conditions, management objectives and risk. Looking at management strategies used, the most effective and potentially most environmentally beneficial include wildland fire use and prescribed fires. While these strategies require planning, research, resources and funding, they provide the most effective and beneficial fire reduction by governmental agencies. However, individuals have the ability to protect their homes through Cohen's Home Ignition Zone or creation of a "defensible space". Utilization of these strategies, by communities, federal and local agencies, and the people within the community can positively influence fire, reducing severity, size and impacts.

4.4.2. FIRE MONITORING PROGRAMS

In the event of a fire, there are fire monitoring programs in place to evaluate and analyze the fire and its potential impacts on the surrounding environment. There are four levels in fire monitoring: Environmental, Fire Observation, Short-term Change and Long-term Change (National Park Service & Fire Management Program Center, 1965). These fire monitoring levels can be referred to as Recommended Standard (RS) monitoring levels. Fire monitoring can help provide background information for decision making through the collection of environmental data. This environmental data can be in relation to the weather, fire danger, fuel conditions, resource availability and concerns or values to be protected. Fire monitoring can then take place in fire condition identification, or reconnaissance monitoring, to provide a basic overview of a fire event (National Park Service & Fire Management Program Center, 1965). Understanding a fire, short term change is required for prescribed fires. This monitoring provides vital information regarding specific vegetation and fuel complex relations and understanding fuel reduction and vegetative change. This data allows quantitative evaluations to be made. Monitoring of short-term change includes pre-burn, during the burn and post-burn (up to 2 years). The last level is understanding long-term change. This monitoring can be used to identify significant trends to guide management decisions. This final stage of monitoring takes place until the area is treated with fire again, and the process begins again.

Often times, monitoring programs are not properly coordinated for a variety of factors. These factors include lack of procedure for post-fire water quality monitoring, scarce resources, no regionally responsible entity and insufficient funding for post-fire sampling (Stein & Brown, 2009). These factors can yield ineffective coordination and lack of standard monitoring protocols and constituents of concern in water quality (Stein & Brown, 2009). This can be particularly problematic in watersheds that are impacted by fires and where drainage travels to sensitive or impairs waterbodies (Stein & Brown, 2009). The Southern California Coastal Water Research Project (Stein & Brown, 2009) set three primary management questions:

1) How does post-fire runoff affect changing contaminant levels?
2) What is the effect of post-fire runoff on downstream receiving waters?

3) What are the factors that influence how long post-fire runoff effects persist?

The Stein and Brown (2009) then proposed a general monitoring program incorporating these questions (Table 10). Through this program general sampling design, site selection and indicators could be identified per each management question asked above. This proposed monitoring program would be implemented in a series of steps outlined by mobilization, data management, quality assurance, funding and communication (Stein & Brown, 2009).

Table 10: Monitoring Program Design: Recommended sampling design, site selection and indicators per priority management questions (Stein & Brown, 2009).

MANAGEMENT QUESTION	HOW DOES POST-FIRE RUNOFF AFFECT CHANGING CONTAMINANT LEVELS?	WHAT IS THE EFFECT OF POST-FIRE RUNOFF ON DOWNSTREAM RECEIVING WATERS?	WHAT ARE THE FACTORS THAT INFLUENCE HOW LONG POST-FIRE RUNOFF EFFECTS PERSIST?
GENERAL DESIGN	Comparison of runoff from burn areas to reference or control sites	Pre- vs post-fire monitoring	Comparison of post-fire condition to regional ambient condition
FLOW CONDITIONS TO TARGET	Stormwater runoff	Non-storm, dry weather flow	Non-storm, dry weather flow
SELECTION OF BURNED SITES	Terminus of burned catchment using established criteria	Bottom of watershed at confluence with receiving water of interest – after fire, before and after first runoff event	Overlay Stormwater Monitoring Coalition's Southern California Regional Monitoring Plan (SCRMP) bioassessment sites and burn maps to select burn locations
SELECTION OF COMPARISON SITES	Natural sites, urban sites, existing MS4 monitoring sites		Using existing pre-burn SCRMP ambient bioassessment data
INDICATORS	Water chemistry, constituent concentration	Water chemistry, sediment toxicity	IBI, CRAM, basic water chemistry
PERIOD AND DURATION OF MONITORING	At least three storms during first and/or second winter following fall	Before 1st storm and annuals until return to baseline (pre-fire levels)	During spring index periods – annual visits over time

4.4.3. MONITORING OF HABITAT RESTORATION

Habitat monitoring is an important aspect of habitat restoration and understanding future habitat restoration effectiveness. Emergency Stabilization and Rehabilitation (ES&R) and Burned Area Emergency Response (BAER) treatments are designed in order to mitigate against adverse impacts of wildfire (Wirth & Pyke, 2006). These treatments are short-term and high-intensity treatments implemented by the federal government following wildfires (Wirth & Pyke, 2006). There is much variability in the monitoring of ES&R programs, increasing with the size and complexity of the habitat and vegetation patterns (Wirth & Pyke). Commonalities among monitoring program designs include objectives, stratification, control areas, random sampling, data quality and statistical analysis. However, difficulties arise in specie identification, stratification and density measurements. These measurements lead to the greatest number of errors and variability in data (Wirth & Pyke).

The Bureau of Land Management (BLM) and the U.S. Department of Agriculture Forest Service (USFS) have established ES&R programs (Wirth & Pyke, Monitoring Post-Fire Vegetation Rehabilitation Projects: A Common Approach for Non-Forested Ecosystems, 2006). Additionally, the U.S. Fish and Wildlife Service (USFWS), Bureau of Indian Affairs (BIA), and National Park Service (NPS) have establish methods of post-fire monitoring and response. The BLM ES&R program has an objective to minimize the threats to life and property while stabilizing and preventing degradation to natural and cultural resources as a result of wildfires. The purpose of ES&R is to restore a habitat to its historical or pre-fire ecosystem in regard to structure, function, diversity and dynamics. The BLM ES&R program is divided into emergency stabilization (ES) and burned area rehabilitation (BAR). ES treatments are treatments that are utilized to stabilize and prevent degradation to natural and cultural resources, while minimizing threats to life and property, following a wildfire. These are implemented within a year of a fire. BAR is defined as the efforts that are made within three years of the containment of a fire to repair and improve lands that would be restored under natural conditions. The USFS BAER program is for immediate rehabilitation of watersheds in order to minimize soil productivity loss, the deterioration of water quality and threats to life and property. USFS focuses primarily on erosion control treatments due to many adverse wildfire effects including soil movement, runoff, sedimentation and mass movement. Erosion control treatments frequently used by the USFS include straw mulch, erosion barriers such as wattles and check dams, culvert repair and catchment basins (Wirth & Pyke, Monitoring Post-Fire Vegetation Rehabilitation Projects: A Common Approach for Non-Forested Ecosystems, 2006). BLM ES&R and USFS BAER treatments vary largely in relation to seeding and seedling establishment.

The formation of quantitative objectives is valuable in identifying the initial success of post-fire seedling establishment, but similarly requires the consideration of specific situations and areas (Wirth & Pyke, 2009). Conditional objectives can include a range of values that can be dependent on environmental conditions. Over time, a study conducted by Wirth and Pyke (2009)believe that a model can be developed to create a system for prediction of seeding success based on conditional variations. However, as it stands, there are difficulties that arise in determining the effectiveness and monitoring of Emergency Stabilization and Rehabilitation (ES&R) During the first 3 years post-fire, plant cover changes are minimal and cannot quantify or qualify successful seedling establishment and growth. As seedlings age and plants grow a comparison on vegetation coverage can be used to determine the long-term effects of ES&R. Attributes found in correlation to patterns of vegetation include the rate of accumulation of liter, the inverse relationship of grass and forb cover, the rate in which bare ground decreases and the relationship of annual grasses with perennial cover and basal-gap intercept. Additional factors to consider include soil, elevation and climate in site specific cases. The identification of these factors and the understand of geographic area and site characteristics can lead to the improve success of seedling establishment in adaptive management (Wirth & Pyke, 2009).

5. CONCLUSIONS & RECOMMENDATIONS FOR SONOMA COUNTY

Fires are extremely important, naturally occurring processes that can lend to the health and maintenance of an ecosystem. However, fire can have negative impacts when certain conditions are met to decrease the predictability and increase the size, intensity, and severity of fires. Factors that contribute to fire occurrence include vegetative land cover, physical settings, soil composition, fire weather, fire suppression, fire intensity and fire severity.

Land cover in combination with fire suppression can greatly influence fire occurrence and severity. With the utilization of fire suppression, understories of forests go unmanaged and can cause an accumulation of flammable materials. The physical settings, including climate, topography and vegetative cover, can also greatly influence fire occurrence and severity. While precipitation patterns evaluated within the paper did not yield any significant results, topographic elevation changes can greatly influence fire occurrence and size. An increase in fire size was observed in regions with greater elevation where fire occurs along with greater elevation ranges. This observation signifies the influence of wind patterns with mountainous landscapes influences fire. Fire weather and fire intensity were not discussed in depth in this paper. Fire severity is influenced by all other fire factors and is the cumulative impacts that a fire can have on both vegetation and soils. Fire severity largely influences erosion and resulting sedimentation post-fire.

In evaluation of the Central LNU Complex, of the larger North Bay Fires, there were many similarities between the Nuns, Tubbs and Pocket Fires that will shape fire management decisions. The interactions of environmental conditions and historic wildfires within the Sonoma County region provide a range of conditions considered optimal for fires, and potentially frequent fires. The region has an extensive fire history with regions impacted repeatedly by fires. Considering this information, it is important to implement a fire management program and strategies that will effectively reduce fire severity, fire intensity, fire size and community impact. Through this paper, a notable correlation between average elevation and elevation range with acres burned was observed. Considering both the elevation and elevation range of the region in combination with population distribution, recommendations can be made. Community awareness to fire potential is key, and with the recent North Bay Fires the community can be reasonably expected to have both awareness and understanding of the impacts that fire can have on the community as a whole and the individual. Despite this awareness, additional education programs should be implemented in order to ensure communication of vital information regarding the regions fire history and both benefits and risks of fire. It is important to identify the community, vegetation, resource availability and risk for proper fire management. The first step for proper fire management is community education and understanding the role of fire, the impacts of fire, and how best to protect homes from fire (utilizing the Home Ignition Zones).

The more complex management of fires involves the balance of wildland fire use and prescribed fires. Unfortunately, the area in which the Central LNU Complex is located is largely urbanized, with a large population of people who can both be impacted by fire management and impact fire management. Approximately one third of Sonoma County's population resides in an area referred to as the Wildland/Urban Interface or Intermix (WUI) (Fire Safe Sonoma, 2016). Due to the large impacts fire can have directly on the community, prescribed fire is not as beneficial in this region as compared to large forests with little to no human inhabitants. This leaves both fire suppression and wildland fire use to consider. Fire suppression has historically been used but can lead to larger, more severe fires. For this reason, fire suppression is not the answer. Instead, wildland fire use is the most applicable and beneficial management strategy for fires. Understanding the setting, history and general region, the most applicable fire management strategies include education of the public in creating defensible space or home ignition zones along with wildland fire use. Wildland fire education can play a pivotal role in the understanding of the general population of the benefits and risks of fire and the understanding of proper management.

Unfortunately, there are many questions that still have not been answered within this paper, including the large interactions and relationships among factors that contribute to fire occurrence and severity. It is recommended that an analysis of historical fires in additional regions be made in order to gain a deeper insight to relationships between fire size, topography, climate, soil burn severity, and average annual rainfall. Fires should be evaluated in the Western and Central United States where fire management remains a national priority and should include a greater range and distribution of fire size to better create and form trends relating the above factors. Understanding these will provide the greatest insight to understanding wildfire occurrence and further identifying the best management strategies for reducing severity and impact of wildfires on the environment and the community.

REFERENCES

Agee, J. K., & Skinner, C. N. (2005). Basic principles of forest fuel reduction treatments. *Forest Ecology and Management, 211*, 83-96.

Anderson, R. (n.d.). *Montane Hardwood-Conifer.* California Wildlife Habitat Relationships Sysyem.

Armenteras-Pascual, D., Retana-Alumbreros, J., Molowny-Horas, R., Gonzalez-Alonso, M., Roman-Cuesa, R. M., & Morales-Rivas, M. (2011). Characterising fire spatial pattern interactions with climate and vegetation in Colombia. *Agricultural and Forest Meteorology, 151*, 279-289.

Barro, S. C., & Conard, S. G. (1991). Fire Effects on California Chaparral System: An Overview. *Environment International, 17*, 135-149.

Butsic, V., Kelly, M., & Moritz, M. A. (2015). Land Use and Wildfire: A Review of Local Interactions and Teleconnections. *Land, 4*, 140-156.

California Department of Forestry and Fire Protection. (1995). *Fire Management for California Ecosystems: Executive Summary .*

California Department of Forestry and Fire Protection. (2017a). *Final Pocket Fire Watershed Emergency Response Team Evaluation: CAL-LNU-010104.*

California Department of Forestry and Fire Protection. (2017b). *Nuns Fire Watershed Emergency Response Team Final Report: CAL-LNU-010104.* California Department of Forestry and Fire Protection.

California Department of Forestry and Fire Protection. (2017c). *Tubbs Fire Watershed Emergency Response Team Evaluation Final Report: CAL-LNU-010104.*

California Department of Forestry and FIre Protection. (2017d). *Atlas Fire Watershed Emergency Response Team Final Report: CA-LNU-010105.* California Department of Forestry and FIre Protection.

California Department of Forestry and Fire Protection. (2018a). *Atlas Fire (Southern LNU Complex)*. Retrieved from California Department of Forestry and Fire Protection: cdfdata.fire.ca.gov/incidents/incidents_details_info?incident_id=1866

California Department of Forestry and Fire Protection. (2018b). *Thomas Fire*. Retrieved from California Department of Forestry and Fire Protection: www.fire.ca.gov/current_incidents/incidentdetails/Index/1922

California Department of Forestry and Fire Protection. (2018c). *Top 20 Largest California Wildfires*. Retrieved April 2018, from http://www.fire.ca.gov/communications/downloads/fact_sheets/Top20_Acres.pdf

California Department of Forestry and Fire Protection. (2018d). *Top 20 Most Destructive California Wildfires*. Retrieved April 2018, from http://www.fire.ca.gov/communications/downloads/fact_sheets/Top20_Destruction.pdf.

California Department of Forestry and Fire Protection. (2018e). *Thomas Fire Watershed Emergency Response Team Final Report: CA-VNC-103156.* California Department of Forestry and Fire Protection.

California Department of Forestry and Fire Protection. (n.d.). *Benefits of Fire*. Retrieved from http://www.fire.ca.gov/communciations/downloads/fact_sheets/TheBenefitsofFire.pdf.

Chester, J., Graham, C., Mazurkiewicz, A., & Tsang, M. (2016). *San Francisco Public Utilities Commission Hydrological Conditions Report for August 2016.* San Francisco Public Utilities Commission.

County of Sonoma. (2017). *Fire Perimeters: Nuns Fire (2017) & Nuns Canyon Fire (1964)*. Retrieved April 2018, from http://www.kenwoodpress.com/files/Nuns_Fire__2017_and_1964.pdf

County of Sonoma. (2018a). *Land Use*. Retrieved February 2018, from https://sonomacounty.ca.gov/CAO/Public-Reports/About-Sonoma-County/Land-Use.

County of Sonoma. (2018b). *Population Growth*. Retrieved February 2018, from https://sonomacounty.ca.gov/CAP/Public-Reports/About-Sonoma-County/Population-Growth/

DeBano, L. F. (1990, April 12). *The Effect of Fire on Soil Properties*. (USDA Forest Service Rocky Mountain Research Station) Retrieved from SoLo: https://forest.moscowfsl.wsu.edu/smp/solo/documents/GTRs/INT_280/DeBano_INT-280.php

Diaz, J. M. (2012). *Economic Impacts of Wildfire.* Southern Fire Exchange.

Doerr, S. H., & Santin, C. (2016, June). Global trends in wildfire and its impacts: Perceptions versus realities in a changing world. *Philosophical Transactions B, 371*(1696), 1-10.

Estes, B. L., Knapp, E. E., Skinner, C. N., Miller, J. D., & Preisler, H. K. (2017). Factors influencing fire severity under moderate burning conditions in the Klamath Mountains, northern California, USA. *Ecosphere, 8*(5), 1-20.

Fire Safe Sonoma. (2016). *Sonoma County Community Wildfire Protection Plan.* Fire Safe Sonoma.

Fischer, M. A., Di Bella, C. M., & Jobbagy, E. G. (2015). Influence of fuel conditions on the occurrence, propogation and duration of wildland fires: A regional approach. *Journal of Arid Environments, 120*, 63-71.

Forests and Rangelands. (2017). *National Priority Maps*. Retrieved from Forests and Rangelands: https://forestsandrangelands.gov/strategy/nationalpriorities.shmtl#map2

Forests and Rangelands. (2018). *The National Strategy: The Final Phase in the Development of the National Cohesive Wildland Fire Management Strategy*. Retrieved from Forests and Rangelands: https://www.forestsandrangelands.gov/strategy/thestrategy/shtml

Griffith, G. E., Omernik, J. M., Smith, D. W., Cook, T. D., Tallyn, E., Mosely, K., & Johnson, C. B. (2016). *Ecoregions of California.* Open-File Report 2016-1021, U.S. Department of the Interior, U.S. Geological Survey.

Harper, A. R., Doerr, S. H., Santin, C., Froyd, C. S., & Sinnadurai, P. (2018). Prescribed fire and its impacts on ecosystem services in the UK. *Science of the Total Environment, 624*, 691-703.

Hawbaker, T. J., Radeloff, V. C., Stewart, S. I., Hammer, R. B., Keuler, N. S., & Clayton, M. K. (2013). Human and biophysical influence on fire occurence in the United States. *Ecological Application, 23*(3), 565-582.

Holland, V. L. (2005). *Coastal Oak Woodland.* California Department of FIsh and Game; California Interagency Wildlife Task Group. California Wildlife Habitat Relationships System.

Ice, G. G. (2004, September). Effects of wildfire onsoils and watershed processes. *Journal of Forestry, 102*(6), 16-20.

Jain, T. B., Gould, W. A., Graham, R. T., Pilliod, D. S., Lentile, L. B., & Gonzalez, G. (2008). A Soil Burn Severity Index for Understanding Soil-fire Relations in Tropical Forests. *Ambio, 37*(7-8), 563-586.

Jain, T. B., Graham, R. T., & Pilliod, D. S. (2006). *The Relation Between Forest Structure and Soil Burn Severity.* USDA.

Jain, T. B., Pilliod, D. S., Graham, R. T., Lentile, L. B., & Sandquist, J. E. (2012). Index for Characterizing Post-Fire Soil Environments in Temperate Coniferous Forests. *Forests, 3*, 445-466.

Kampf, S. K., Brogan, D. J., Schmeer, S., MacDonal, L. H., & Nelson, P. A. (2016). How do geomorphic effects of rainfall vary with storm type and spatial scale in a post-fire landscape? *Geomorphology, 273*, 39-51.

Keeley, J. E. (2009). Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland FIre, 18*, 116-126.

Kolb, T. E., Wagner, M. R., & Covington, W. W. (1995). *Forest health from different perspectives.* USDA, Forest Service, Rocky Moutain Forest and Range Experiment Station.

LeBaron, G. (2014). *Historic wildfire's catastrophic lessons*. Retrieved from Press Democrat: http://pressdemocrat.com/news/2377919-181/lebaron-historic-wildfires-catastrophic-lesson?sba=AAS

Marchal, J., Cumming, S. G., & McIntire, E. J. (2017). Land cover, more than monthly fire weather, drives fire size distribution in Southern Quebec forests: Implications for fire risk management. *PLoS ONE, 12*(6).

Martin, R. E., & Sapsis, D. B. (1995). *A Synopsis of Large or Disastroud Wildland Fires.* USDA Forest Service.

Mechado-Vezzani, F., Anderson, C., Meenken, E., Gillespie, R., Peterson, M., & Beare, M. H. (2018). The importance of plants to development and maintenace of soil structure, microbial communtiies and ecosystem functions. *Soila & Tillage Research, 175*, 139-149.

Miller, J. D., Skinner, C. N., Safford, H. D., Knapp, E. E., & Ramirez, C. M. (2012). Trends and causes of severity, size, and number of fires in northwestern California, USA. *Ecological Applications, 22*(1), 184-203.

National California Prescribed Fire Council. (2013). *Prescribed Fire*. Retrieved from National California Prescribed Fire Council: www.norcalrxfirecouncil.org/rx-fire.html

National Fire Protection Association. (2018). *The ember threat and the home ignition zone*. Retrieved from National Fire Protection Association: https://www.nfpa.org/Public-Education/By-topic/Wildfire/Firewise-USA/The-ember-threat-and-the-home-ignition-zone

National Park Service & Branch of Wildland Fire. (2014). *Wildland Fire Management: Reference Manual 18.* National Park Service.

National Park Service & Fire Management Program Center. (1965). *Fire Monitoring Handbook.* Retrieved from National Park Service: https://www.nps.gob/orgs/1965/upload/fire-effects-monitoring-handbook.pdf

Quinn, R. D., & Keeley, S. C. (2006). *Introduction to California Chaparral.* Berkeley and Los Angeles: University of California Press Books.

Rabot, E., Wiesmeier, M., Schluter, S., & Vogel, H. J. (2018). Soil structure as an indicator of soil functions: A review. *Geoderma, 314*, 122-137.

Scasta, J. D., Weird, J. R., & Stambaugh, M. C. (2016). Droughts and Wildfires in Western U.S. Rangelands. *Rangelands, 38*(4), 197-203.

Schmeer, S. R., Kampf, S. K., MacDonald, L. H., Hewitt, J., & Wilson, C. (2018). Empirical models of annual post-fire erosion on mulched and unmulched hillslopes. *Catena, 163*, 276-287.

Sierra National Forest U.S. Forest Service. (2015). *Rough Fire*. Retrieved from Incident Information System: https://inciweb.nwcg.gov/incident/4456/

Sierra Nevada Conservancy. (2014). *The Rim Fire: Why investing in forest health equals investing in the health of California.* Retrieved from Sierra Nevada Conservancy: sierranevada.ca.gov

Sonoma Open Space. (2017). *2017 North Bay Fires*. Retrieved April 2018, from http://sonomaopenspace.maps.arcgis.com/apps/CompareAnalysis/index.html?appid=d44e73bf388e445c8528efb04aadd85e

Staley, D. M. (2013). *Emergency Assessment of Post-Fire Debris-Flow Hazards for the 2013 Rim Fire, Stanislaus National Forest and Yosemite National Park, California.* USGS.

Stanislaus National Forest U.S. Forest Service. (2013). *Rim Fire*. Retrieved from IncidentInformation System: https://inciweb.nwcg.gov/incident/3660/

Stein, E. D., & Brown, J. (2009). *Effects of post-fire runoff on surface water quality: Development of a Southern California regional monitoring program with management questions and implementation recommendations.* Southern California Coastal Water Research Project (SCCWRP).

Stephens, S. L., Collins, B. M., Fettig, C. J., Finney, M. A., Hoffman, C. M., Knapp, E. E., . . . Wayman, R. B. (2018). Drought, Tree Mortality, and Wildfire in Forests Adapted to Frequent Fire. *BioScience, 68*(2), 77-88.

Tyler, C. M. (1995). Factors contributing to post fire seedling establishment in chaparral: direct and indirect effects of fire. *Journal of Ecology, 83*, 1009-1020.

U.S. EPA. (2016). *Ecoregions of California.* Retrieved from U.S. EPA: ftp://newftp.epa.gov/EPADataCommons/ORD/Ecoregions/ca/CA_eco_front_ofr20161021_sheet1.pdf

USFS. (2015). *Understanding Fire Effect on the Environment*. Retrieved March 2018, from https://www.fs.fed.us/pnw/research/fire/fire-effects.shtml.

Vieira, D. C., Fernandez, C., Vega, J. A., & Keizer, J. J. (2015). Does soil burn severity affect the post fire runoff and interrill erosion response? A review based on meta-analysis of field rainfall simulation data. *Journal of Hydrology, 523*, 452-464.

Vollmar, P. (2014). The influence of climate and land cover on wildfire patterns in the conterminous United States.

Weber, J. B. (2017, October 19). *A look back at the largest North Coast wildfires of the past 50 years*. Retrieved from Press Democrat: www.pressdemocrat.com/new/7538720-181/a-look-back-at-the

Whittier, T. R., & Gray, A. N. (2015). Tree mortality based fire severity classification for forest inventories: A Pacific Northwest national forests example. *Forest Ecology and Management, 359*, 199-209.

Williams, J. T. (1995). *The Role of Fire in Ecosystem Management.* USDA Forest Service.

Wirth, T. A., & Pyke, D. A. (2006). *Monitoring Post-Fire Vegetation Rehabilitation Projects: A Common Approach for Non-Forested Ecosystems.* USGS.

Wirth, T. A., & Pyke, D. A. (2009). *Final Report for Emergency Stabilization and Rehabilitation Treatment Monitoring of the Keeney Pass, Cow Hollow, Double Mountain and Farewell Bend Fires.* USGS.

Wirth, T. A., & Pyke, D. A. (n.d.). *Monitoring Post-Fire Rehabilitation Projects: Testing a Common Strategy in Non-Forested Ecosystems.* USGS Forest and Rangeland Ecosystem Science Center.

Zammit, C., & Zedler, P. (1988). The influence of dominant shrubs, fire, and time since fire on soil seed banks in mixed chaparral. *Vegetatio, 75*(3), 175-187.