

POST-FIRE MORTALITY AND RESPONSE IN A REDWOOD/ DOUGLAS-FIR FOREST,
SANTA CRUZ MOUNTAINS, CALIFORNIA

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COMMITTEE MEMBERSHIP

TITLE: POST-FIRE MORTALITY AND RESPONSE IN
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SANTA CRUZ MOUNTAINS, CALIFORNIA

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Abstract

Post-fire Mortality and Response in a redwood/ Douglas-fir forest, Santa Cruz Mountains, California

Garren Andrews

We investigated how fire severity impacts the survival and response (sprouting/seeding) of multiple species in the Santa Cruz Mountains of coastal California, including coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), tanoak (*Lithocarpus densiflorus*), and Pacific madrone (*Arbutus menziesii*). During August 2009 the Lockheed Fire burned nearly 3,160ha of mixed-conifer stands with variable severity. Data from 37 Continuous Forest Inventory (CFI) plots were collected immediately before and for 2 successive years following the 2009 Lockheed Fire.

This research entails three objectives. First, we quantified post-fire mortality of trees that vary in species, size, and fire severity. Second, data was quantified for post-fire response (sprouting, seeding) of those three tree species in areas of varying fire severity. Third, we developed logistic regression models that predict post-fire mortality and response for each of the three species. Understanding the relationship between burn severity, mortality and regeneration can allow for better post-fire predictive services. This research can support forest managers in post-fire management decisions to facilitate long-term sustainability and protection of environmental infrastructure within coast redwood/Douglas-fir forests.

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Project Overview

Background Information and Problem Statement

In August 2009 the Lockheed fire burned 3,160 ha with variable severity in the Santa Cruz Mountains. The fire burned primarily through redwood/Douglas-fir forests. The fire consumed vegetation of all sizes and arrangements. A portion of the fire burned through permanent forest inventory plots located on Swanton Ranch, an education and research facility owned by the Cal Poly Corporation and managed by the College of Agriculture, Food and Environmental Sciences, California Polytechnic State University, San Luis Obispo.

The Santa Cruz Mountains experience a maritime, Mediterranean climate with cool rainy winters, and dry summers moderated by a fog belt. These climatic conditions support forests of redwood, Douglas-fir, tanoak, knobcone pine, and Pacific madrone. Historic fire regimes resulted from Native American and natural fire starts. Previously the Santa Cruz Mountains experienced frequent fires about every eight to twelve years. However, over the past century fire return intervals have increased to 12 years. (Stephens and Fry 2005)

There has been little prior research conducted to predict post-fire mortality and regeneration in redwood forests (Jameson and Robards 2007, Kobziar et al. 2006). Early twentieth century research supported the belief that fire exclusion aided redwood regeneration (O'Hara and Berrill 2010). Currently the dominant paradigm has begun to shift toward a more fire positive view, thus increasing the need for new research (O'Hara and Berrill 2010).

There has also been little research to help predict the response of redwood to wildfire (Jameson and Robards 2007, Kobziar et al. 2006). Existing research has been focused on

different tree species and ecosystems (Kobziar et al. 2006, Ryan and Reinhardt 1988). However, redwood is unique due to its ability to regenerate using multiple methods, seeding, sprouting, and burl (O'Hara and Berrill 2010). It is important for natural resource managers to have a better understanding of how fire and redwood interact. Through a better understanding, more effective long-term sustainable management can be established within the redwood ecosystem.

Statement of overall research goal

The major goal of this research project is to help forest managers determine the response of redwood/Douglas-fir forests to wildfire.

Sub-goal identification

- Redwood stand response to wildland fire in the Santa Cruz Mountains
- Redwood tree mortality post wildfire
- Redwood fire history of the Santa Cruz Mountains
- Redwood stand response to prescribed fire
- Tree regeneration rates post fire disturbance

Statement of sub-goal to be investigated

Redwood/ Douglas-fir stand response to wildland fire in the Santa Cruz Mountains

Importance of Project

Little previous research has been conducted with the aim of predicting mortality and regeneration for redwood and associated overstory tree species post wildfire and it is this deficit which has contributed to the current study. Recent research has found that wildfire has been historically prevalent within redwood forests. The need for a greater understanding of the

interaction between redwood and fire has become apparent. This project aims to establish a binomial relationship between overstory tree mortality and subsequent regeneration and fire severity.

General Approach

This will be an applied research study investigating redwood stand response post Lockheed fire. Data will be collected in the field from 37 plots located within the Lockheed fire burn area. Tree mortality, tree regeneration, tree growth and fire severity will be assessed to determine stand response to wildfire.

Objective(s) / Hypothesis

Hypothesis statement

Wildfire has an effect on redwood and associated species regeneration, mortality, and tree growth. While wildfire is not required for mortality regeneration, sprouting, and tree growth to occur, it does support these three processes.

Objective statement

The objectives of this project are

- Collect diameter, height, bole scorch, regeneration, and mortality measurements
- Conduct full statistical analysis on collected data
- Determine redwood and associated species' response to fire through mortality, regeneration, and sprouting

Literature Review

Introduction

The following discussion will focus on the review of empirical data that explores the fire history, fire ecology, regeneration, and predictive model development of redwood (*Sequoia sempervirens*), and associated overstory tree species Douglas-fir (*Pseudotsuga menziesii*), and tanoak (*Notholithocarpus densiflorus*).

Mature redwood and Douglas-fir forests typically demonstrate a fairly high tolerance to fire. Thick bark that protects the cambium layer and foliage from heating during fire events as well as prodigious height allow for high survivability during and post-fire. Redwood's ability to re-sprout new foliage from the bole enables rapid recovery. Young-growth redwood is more susceptible to post fire mortality due to their lack of fire resistant features. (Finney & Martin 1993)

Many scientists believe the redwood ecosystem has evolved with disturbance as a part of its natural regeneration cycle. Redwood has adapted to fire as part of a yearly cycle (Brown et al. 1999). The ability of redwood to regenerate through sprouting, allows it to maintain a high regeneration rate post disturbance (Jameson and Robards 2007). With competing vegetation removed, the ability of redwood to sprout from existing stumps or burls has led to a successional competitive advantage (Busing and Fugimori 2002).

Early 20th century literature suggested that fire played a negligible role in the ecosystem of the Santa Cruz Mountains. Evidence suggested that fire damaged the environment and curbed tree growth and regeneration. It was even believed that fire led to encroachment of redwood habitat from Douglas-fir and white fir tree species. Less commercially desirable tree species

could fill gaps left by dead redwood, and eventually would push out redwood altogether. Fire exclusion would be the best form of management to eliminate these negative by-products of wildfire. However, local anecdotal beliefs were that fire caused little to no harm to areas that had been previously logged or had biomass removed. (Fritz 1932)

Early research regarding the role of fire in redwood and Douglas-fir forests suggested that the elimination of fire would preserve land values and promote new tree growth (Jameson and Robards 2007). New management practices were implemented based on these conclusions, which led to an increase in fire return intervals. Intervals have increased from a historical average of 8 years to the current 12 years (Stephens and Fry 2005). These strategies were based on the presumption that fire exclusion would be beneficial to both the redwoods and the local economies they supported (Jameson and Robards 2007).

Redwood/Douglas-fir forests are considered a mixed-effects fire regime (Agee 1993), most commonly experiencing low-intensity surface fires because of the cool and moist coastal climate. A wide range of pre-European fire return intervals has been documented in redwood forests. In the moister, northern range of the species, fire is extremely infrequent, occurring in some sites only every 500 years (Agee 1993). Fire return intervals in the southern part of its range have averaged from 6 years to 29 years (Jacobs et al. 1985, Stuart 1987, Finney and Martin 1989, 1993, Brown and Swetnam 1994), the extent of which largely varied by latitude and proximity to the coast (Veirs 1980).

The need for redwood regeneration research

Over the past few decades there has been a concerted effort to research and understand historical fire regimes across the range of *Sequoia* ecosystems. However, little research focusing on redwood and their associated species response to fire (Lorimer et al. 2009, Ramage et al.

2010). Little direct evidence exists regarding the establishment of redwood sprouts and seedlings after recent fire events (O'Hara and Berrill 2010). There have been limited opportunities to study redwood fire ecology over the past few decades. Specifically, the role of fire in the regeneration dynamics and the long term persistence of redwood and associated overstory tree species have not been investigated (Lorimer et al. 2009, Ramage et al. 2010).

With a limited knowledge base on the response of *Sequoia* stand dynamics to fire, there has been some disagreement about proper fire management techniques. Some studies have concluded that fire can play a significant function in redwood regeneration (Busing and Fugimori 2002, O'Hara and Berrill 2010), while others question fire's role in redwood regeneration (Jameson and Robards 2007).

Fire Disturbance

Small and large-scale disturbances are not foreign to any ecosystem (Laughlin and Fule 2008). Many organisms have evolved and adapted their life cycles to depend on these levels of disturbance. For disturbance dependent plant species, regeneration cannot occur unless parent species are destroyed, leaving their offspring to inherit their place within the ecosystem (Laughlin and Fule 2008). It has long been established that fire is an important disturbance regime in redwood forests (Fritz 1932)

Redwood is typically associated with landscapes that are unfavorable to consistent wildfire. Mesic, fog dominated ecosystems are not commonly associated with frequent wildfire. However, evidence suggests that during pre-European settlement, fire was frequent enough to affect forest composition and structure based upon fire severity. Due to a rapid growing local population, changes in land use, and full fire suppression redwood forests have experienced changes in ecosystem processes and patterns. Increases in fuel loads, tree density, canopy

coverage, and encroachment of fire sensitive tree species are likely consequences of decreased frequency of fire in the redwood ecosystem. (Brown, 2007)

Evidence suggests that redwood do not rely solely on severe fire disturbance to regenerate (Jameson and Robards 2007). Analysis suggests that light to mild fire disturbance can aid in the regeneration process (Busing and Fugimori 2002, Jameson and Robards 2007). Stand replacing fire disturbance does not allow redwood immediate re-establishment (Jameson and Robards 2007). The successional process must start over before redwood can incorporate itself into the ecosystem again (Jameson and Robards 2007). Light fire disturbance allows for soil nutrient cycling, reduction in competing shrub vegetation, and the creation of small canopy gaps (Busing and Fugimori 2002). These elements foster an environment conducive to natural redwood regeneration without the loss of the redwood dominant overstory.

There is ecological concern that redwoods are becoming displaced by more fire sensitive vegetation on their upland sites (Blair et al. 2010, Brown and Kaye 1999). Frequent fire disturbance keeps fire sensitive vegetation from encroaching on traditional redwood habitats (Brown and Kaye 1999). Upland sites in particular are starting to be encroached by western hemlock (*Tsuga heterophylla*), grand fir (*Abies grandis*), and tanoak (*Lithocarpus densiflorus*) among others (Brown and Kaye 1999). These are fire sensitive species that do not possess the ability to tolerate frequent fire disturbance, regardless of severity.

Fire History in Redwood and Douglas-fir Forests

Fire was frequent in redwood forests until the late 19th century (Lorimer et al. 2009). Highly uneven-aged stands of redwood and Douglas-fir were the result of frequent disturbances of low to moderate fire intensity (Lorimer et al. 2009). Around the end of the 19th century redwood became a valuable timber species, and fire was excluded from redwood ecotones

(Jameson and Robards 2007). Fire was believed to be a hindrance on tree regeneration and resulted in lower land values (Jameson and Robards 2007).

A large amount of evidence supports fire as a common occurrence in redwood forests (Stephens and Fry 2007). Fire scars on annual growth rings, charred bark, and burnt-out basal cavities are widespread throughout redwood forests (Stephens and Fry 2007). Historic mean fire return intervals of 6-25 years have been established across the range of redwood (Lorimer et al. 2009). However, over the past 70-80 years as a result of fire suppression efforts, wildfire has become less frequent and more diminutive (Donovan and Brown 2007).

Native Americans introduced anthropogenic fire to the redwood ecosystem which was later continued by early European settlers (Stephens and Fry 2005). Fire was used to enhance food abundance, create and maintain fertile hunting grounds, and open up the understory for easier transportation (Stephens and Fry 2005). Evidence suggests that fire has always been present within a *Sequoia* ecosystem; however the Native Americans made it much more prevalent (Brown and Kaye 1999). Due to moist fuel conditions and modest topography, lightning ignited wildfires were historically rare across the redwood landscape (Stephens and Fry 2007).

Fire was frequent in redwood forests until the late 19th century (Lorimer et al. 2009). Highly uneven-aged redwood stands were the result of frequent fire disturbances of low to moderate fire intensity (Lorimer et al. 2009). Around the end of the 19th century redwood became a valuable timber species and for this reason, fire was excluded from redwood ecosystems (Jameson and Robards 2007). During this period fire was believed to be a hindrance to tree regeneration, and resulted in lower land values (Jameson and Robards 2007).

Regeneration of Redwood Post Disturbance

Disturbance in the form of flooding, windstorms, landslides, wildland fire, and more recently forest management, such as timber harvest, have become a part of the redwood ecosystem. Subsequently, redwood have adapted to these forms of disturbance in order to regenerate. Redwood utilizes three methods of regeneration: coppice, burls, and seed cones to help maintain its role as a dominant overstory tree species within its ecosystem. (Brown and Kaye 1999)

Coppice or sprouting regeneration

Following a disturbance redwood uses coppice as a means for regeneration. Sprouts originate from dormant buds lying under the surface of the bark (O'Hara and Berrill 2010). Once the apical meristem becomes damaged or removed, the dormant buds become stimulated and sprout (O'Hara and Berrill 2010). Once established, sprouts will begin to develop an independent root system from the original root system (O'Hara and Berrill 2010). Since a root structure is already in place, new growth is focused on apical meristem growth. Sprouts of redwood can grow up to eight feet in the first year following disturbance (Busing and Fugimori 2002). Such rapid growth creates an advantage over competing tree and shrub vegetation for nutrients, water, and sunlight. Eventually one sprout will become dominant and shade out other sprouts from the same bud (O'Hara and Berrill 2010).

Burl regeneration

Burl reproduction is similar to coppice, in that a new apical meristem sprouts from living tissue on an existing tree. Burls or lignotuber are growths along the trunk of existing mature live redwood trees. They are typically found below the soil surface, and contain buds that sprout if

the parent tree falls over, or the burl becomes detached. When the parent tree falls over and dies it becomes a nurse log that provides nutrients and a root structure to the resulting sprouts. However, there is little scientific evidence regarding burl regeneration in redwood. Further inquiry is needed to establish the effectiveness of burl reproduction post disturbance. (O'Hara and Berrill 2010)

Seed cone regeneration

Seed cone reproduction is the most well comprehended method of regeneration in redwood. Redwood begins producing seeds at between ten to fifteen years of age. Seeds are winged and light (3.3-5mg) to allow for wind dispersal typically 60m-120m from the parent tree. Once the seed becomes established in the soil the resulting seedling will grow rapidly, up to 65 ft. in height in twenty years. (Lorimer et al. 2009)

Post disturbance redwood regeneration

Coppice and burl reproduction are the two main methods that allow redwood to regenerate post disturbance (O'Hara and Berrill 2010). Buds are stimulated once the parent tree becomes either detached from its root system or falls to the ground (O'Hara and Berrill 2010). Thus allowing for a new sprout to take the parent's place and establish itself rather quickly. Mature redwood displays energetic bole and branch epicormic sprouting even when total crown consumption from fire is present (Finney and Martin 1993). Sprout and burl's ability to use pre-existing root structures provide a significant advantage for rapid growth and quick reclamation of overstory dominance for redwood (O'Hara and Berrill 2010).

Evidence suggests that fire stimulates basal re-sprouting among redwood thereby increasing its abundance. Increased fire severity provides a relative advantage to redwood.

Even though redwood mortality increases with fire severity, survival does not drop as fast as competing overstory vegetation. Tanoak survival rates drop faster than redwood indicating that the hotter the fire the better the chance of redwood resistance post-fire. (Ramage et al. 2010)

In contrast, seed cone reproduction is not as effective for varying reasons. A seedling must establish its own root structure unlike sprouted offspring that uses an existing structure (O'Hara and Berrill 2010). A more specific set of conditions must also exist before a dormant seed can begin root and bud growth (Lorimer et al. 2009). Seeds require a bare mineral soil bed, direct access to water and nutrients, and direct sunlight (Busing and Fugimori 2002). These stringent requirements make redwood reestablishment through seed cone regeneration the less likely regeneration method.

Evidence suggests that even though redwood is a relatively shade tolerant tree species, it still requires canopy gaps to become established and grow (Busing and Fugimori 2002). However the actual required gap size is under dispute. Some research suggests that Sequoia need relatively small gaps and even prefer gap edges for regeneration (Busing and Fugimori 2002, Jameson and Robards 2007). Redwood cannot become established in areas where shrub and non-native plant species easily invade due to these resulting large gaps associated with heavy disturbance (Jameson and Robards 2007). Other research suggests that *Sequoia* regenerates better in large gaps because of its ability to grow extremely fast in its first 20 to 30 years of life (Brown and Kaye 1999). Differences in study sites, soils, and disturbance severity can most likely explain these conflicting conclusions.

Douglas-fir Fire Ecology

Douglas-fir has long been considered “a resister” tree species that has adapted to fire. Pre-settlement fire intensity encompassed a large range of fire severity. Low to moderate fire severity made up large portions of the fires that burned within the Douglas-fir range. Certain tree morphological features such as thick bark and a deep root structure allow Douglas-fir to maintain canopy dominance as long as fire is not too intense. Douglas-fir are typically found in stands with three to five major conifer overstory tree species and three to five hardwood overstory tree species. Precipitation plays a large role in co-dominant tree species composition. As precipitation increases, the co-dominant hardwood tree species shifts from canyon live oak and Pacific madrone to tanoak. (Agee 1993)

Douglas-fir forests experience a combination of natural fire and anthropogenic fire ignition (Agee 1993, Brown & Kaye 1999, Uchytel 1991). The number of fires resulting from lightning varies greatly across the Douglas-fir range (Agee 1993). Native Americans were responsible for the majority of fire within Douglas-fir forests in an attempt to create and maintain travel corridors and increase hazel and beargrass production (Agee 1993). Since European settlement, fire return intervals have increased across the Douglas-fir range (Agee 1993). Fire exclusion has been the accepted form of fire management within the majority of Douglas-fir forests for the past century due to its perceived harmful effects on land values and timber sale (Agee 1993).

Unlike redwood and Tanoak, Douglas-fir does not possess the ability to re-sprout from its bole and root structure (Uchytel 1991). Douglas-fir is considered an obligate seeder; regeneration from reseeded is its only form of restoration from fire disturbance (Uchytel 1991).

Post-fire seedling establishment is dependent on spacing and the number of surviving seed trees (Wright and Bailey 1982). After stand destroying fires, Douglas-fir re-establishment is slow as a result of the potential mortality of seed trees (Wright and Bailey 1982). It may take as long as a hundred years for Douglas-fir to reestablish itself within severely burned areas (Spies and Franklin 1988). However, low intensity surface fires provide conditions that allow for abundant Douglas-fir seedling establishment (Huff 1984). With overstory seed trees left intact and competing surface vegetation removed, Douglas-fir seedlings can become established (Huff 1984). With overstory seed trees, Douglas-fir can reestablish within two years of a low severity fire (Huff 1984).

Due to the limited regeneration options available to Douglas-fir, young stands are vulnerable to major composition changes after fire disturbance. Tree species with the ability to re-sprout enjoy an initial competitive advantage over obligate seeders such as Douglas-fir. Young stands of Douglas-fir are not fire-tolerant and are easily wiped out by low to moderate fire intensity. Madrone and tanoak can re-sprout, and will dominate the post fire stand for decades. (Sawyer et al. 1977, Thornburgh 1982, & Agee 1993)

Due to Douglas-fir's thick bark, deep root structure, and open branches, mature Douglas-fir can survive surface fire relatively without difficulty (Uchytel 1991). Crown fires are the most common category of fire that kills mature Douglas-fir (Uchytel 1991). Continued growth of residual Douglas-fir can be greatly reduced by up to four years after fire (Peterson et al. 1991). However, it is possible that thinning resulting from fire can eventually increase residual growth (Oliver and Larson 1990).

Tanoak Fire Ecology

Tanoak is typically a co-dominant overstory tree species in redwood/ Douglas-fir forests. Tanoak is the most plentiful associate overstory tree species of redwood in the Santa Cruz Mountains, and the most abundant broadleaf tree species throughout the entire redwood range (Sawyer et al. 2000). Tanoak exhibits high shade tolerance and low longevity. Redwood/tanoak forests historically experienced short-return fire intervals (Arno & Allison-Bunnell 2002). Tanoak has been labeled an *endurer*, due to its ability re-sprout from the tree bole and the ground after overstory top-kill from disturbance (Agee 1993). However to date, no relevant studies on tanoak fire response in redwood forests have been conducted (Ramage et al. 2010). Therefore, few conclusions on tanoak fire response can be made.

Post-fire tanoak survivor rates are linked to diameter (Kauffman and Martin 1990). Tanoak mortality decreases with increasing diameter (Kauffman and Martin 1990). With increasing fire severity, bole survival for tanoak drops significantly relative to other associated overstory tree species (redwood, Douglas-fir) with equivalent DBH (Ramage et al. 2010).

Sprouting is the most common method of post-fire tanoak regeneration (McDonald 1983). Tanoak experience vigorous post-fire sprouting (Donato et al. 2009); even with the absence of overstory tanoak mortality (Kauffman and Martin 1990). Tanoak are both resistant (bole survival) and resilient (basal sprouting) to fire (Ramage et al. 2010). Initially after fire, tanoak enjoys an advantage over redwood in terms of abundance basal sprouting, diameter, and height when closed canopy conditions are present (Ramage et al. 2010, Veirs 1982). Small-scale tree fall gaps after fire provide adequate areas for the establishment of tanoak seedlings and sprouts, indicating that tanoak will persist with fire (Ramage et al. 2010).

Successful tanoak regeneration is often established with considerable overstory shade under multiple canopy layers (Tappeiner et al. 1990); indicating high severity fires do not provide preferable regeneration conditions for tanoak. If the overstory canopy is removed by fire other tree species may return to the disturbed site instead of tanoak.

Tanoak is experiencing heavy mortality as a result of sudden oak death through-out the redwood stands in the Santa Cruz Mountains. Sudden Oak Death threatens to change the composition of the forests in the Santa Cruz Mountains and across the entire tanoak range. The high mortality rate has resulted in increased fuel loading leading to a greater risk of high severity fire. If high severity fires burn through areas damaged by sudden oak death the abundance of tanoak might be significantly reduced relative to other tree species. (Ramage et al. 2010)

The overall fire hazard increases with tanoak mortality and dieback. In parts of California, fire exclusion has resulted in increased tanoak density from historic conditions. This increase in tree density has led to an increase in fire hazard. Evidence suggests that increased density of oaks leads to a higher incidence of Sudden Oak Death. As more and more tanoak perish from SOD, fuel accumulates, increasing the fire hazard within tanoak forests. The increased fire hazard results in more severe wildfires than were historically observed. This can become a cyclical process where the increased fire hazard effects tanoak SOD, and tanoak SOD leads to increased fire hazard among tanoak. (Lee 2006, Moritz & Odion 2005)

Predictive Mortality Models

Individual tree and plot level logistic mortality predictive models are critical to post wildfire forest management (Hood et al. 2007). Salvage operations, snag recruitment, and post fire species diversity can be improved with better mortality predictive models (Woolley et al.

2010). Tree mortality is often modeled as a function of tree size to fire damage (Hood et al. 2007, Woolley et al. 2010). The majority of mortality predictive models are specific to individual tree species that combine tree characteristics (tree height, DBH, height to live crown ratio, bark thickness etc....) with morphological injury variables (scorch height, crown scorch percent, etc.). For models where prediction is the goal, predictor variables do not address biophysical and physiological processes associated with mortality resulting from fire injury (Wolley et al. 2010).

Proper implementation of mortality models is restricted to the understanding of limitations and awareness for its proper application. The scope and limitation of predictive models are confined to their predictor variables and the number of years post-fire, and season of the fire. Geographical area, number of plots within the sample, wildfire vs. prescribed fire, and area represented by the fire, also contribute to the scope of the predictive model. Models created from wildfires rarely have the benefit of a large broad range of pre-fire data and are therefore observational to a specific point in time. Post wildfire studies rely on large sample sizes that are distributed across the variation of the predictor variables. (Hood et al. 2007, Wolley et al. 2010)

Limited research exists attempting to create logistic mortality models for redwood and associated overstory tree species. Finney and Martin, (1993) are the only authors to develop mortality predictive equations from the redwood ecotype, which focused on prescribed fire. Currently there are no published predictive equations for redwood, developed as a result of a wildfire event. Predictive mortality equations for Douglas-fir and tanoak exist, but none of the equations were developed from wildfire events occurring within the redwood ecotype.

Multiple mortality predictive models exist for Douglas-fir in response to prescribed burning and wildfire. However, none of these models were developed from the redwood/Douglas-fir forest type. The majority of Douglas-fir mortality predictive models have been developed from forests located across the Cascade and Rocky Mountain ranges. Large variation of topography, climate, growing conditions, and study designs result in many predictive variables being significant in the prediction of Douglas-fir mortality. Depending on the locality of individual Douglas-fir factors of: Diameter at Breast Height, % of crown length scorched, number of dead cambium samples, fuel treatment type, % crown volume scorch, cambium kill rating, presence of Douglas-fir beetle, total crown damage, forest floor consumption by fire, site classification, and bark thickness can be used to predict Douglas-fir mortality (Woolley et al. 2010). DBH was found most often to be a significant predictor of Douglas-fir mortality.

Kobziar et al., (2006) developed the only known post-fire mortality predictive models for tanoak. The predictive models were created from prescribed burning in the Sierra-Nevada Mountains of California. Kobziar et al., (2006) observed that tanoak had the highest recorded mortality of the sampled tree species. Further investigation found tree height and total crown damage to be significant predictors of tanoak mortality. However, unlike many other tree species DBH was not significant, leading the authors to theorize that the relationship between DBH and bark thickness among tanoak was not as strong as other sampled tree species. (Kobziar et al. 2006)

Tanoak mortality models have been generated based on limited tanoak studies. Tanoak mortality rates post-fire may be directly related to the limited availability of effective methods for evaluating tanoak variables. Kobziar et al., (2006) and Ramage et al., (2010) both state that they are unaware of research that studies tanoak survivorship and mortality after fire.

Redwood/Douglas-fir Mortality and Response Following Wildfire

Introduction

Wildfire has largely been absent over the past century in the redwood (*Sequoia sempervirens* (D. Don) Endl.) forest type, which is prevalent throughout the central & northern coasts of California. However, redwood stumps in the Santa Cruz Mountains commonly exhibit fire scars, indicating frequent past fire activity. Historically, fires in redwood forests likely resulted from anthropogenic burning of adjacent open lands, which then subsequently burned into the forest (Stephens and Fry 2005). The median fire return interval in the Santa Cruz Mountains varies by site, but before European settlement was approximately every 12 years (Brown et al. 1999, Brown and Baxter 2003). Fire frequency was generally lower in areas where fog played a more significant role (Jacobs et al. 1985) and has decreased dramatically since the removal of Native American and early European settlement ignitions, along with the advent of modern fire suppression (Greenlee and Langenheim 1990, Brown 2007).

In fire-prone landscapes, forest managers need to be able to effectively predict post-fire tree mortality and response (i.e., regeneration via sprouting or by seed). Predictive models enable managers to develop better methods for prescribed burning, post-fire salvage sales, and reforestation. Established predictive mortality models for western conifer species have typically been based upon how a given morphological feature of the tree (bole diameter, bark thickness, etc.) interacts with some measure of fire intensity (crown scorch, bole scorch, surface fuel consumption, etc.).

Several high-severity fires have burned in the redwood and Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) forests of the Santa Cruz Mountains in recent years, including the

2008 Bonny Doon Fire (210 ha), the 2008 Summit Fire (1730 ha) and the 2009 Lockheed Fire (3,163 ha). Given the increasing frequency and severity of wildfires within this ecotype, which is exceedingly valuable both ecologically and economically, high priority needs to be placed towards developing predictive mortality equations to better ensure sustainable management practices of these forests and their inherent environmental infrastructure. These equations would enable managers to ascertain the necessity and extent of post-fire salvage and planting operations.

Similarly, prediction of redwood and Douglas-fir post-fire regeneration can provide ecological and economic benefits to forest managers. Redwood and tanoak (*Notholithocarpus densiflorus*), major overstory species at the study site, have the ability to regenerate through seeding and sprouting from the bole or root collar after fire. These unique regeneration features allow their continued presence following fire. Douglas-fir is an obligate seeder, meaning that reseeded is the only option for regeneration. To date, there has been little research to create predictive regeneration models for redwood, Douglas-fir, and tanoak regeneration in the Santa Cruz Mountains.

The overarching goal of this study was to quantify mortality and response (regeneration by seed and by sprouting) in the principal overstory tree species impacted by a mixed-severity wildfire in the Santa Cruz Mountains. Specifically, this study aimed to develop equations that predicted mortality by species based upon various aspects of tree morphology (e.g. tree height, Diameter at Breast Height) and fire intensity (e.g., scorch height). Further, it also sought to develop equations that predicted post-fire regeneration by species (by seed and by sprouting) based on various stand characteristics (e.g., Stand Density Index) and fire intensity (e.g., mean scorch height).

Methods

Site Description

The study site is located in the Little Creek drainage of Swanton Pacific Ranch, located approximately 20 km north of Santa Cruz, California, USA (Latitude: 37.06, Longitude: -122.21) (Figure 1). The terrain is highly variable, but generally rugged, ranging in elevation between 30 m and 600 m. The site is in a maritime-Mediterranean climate, with cool rainy winters and dry summers moderated by a fog belt.

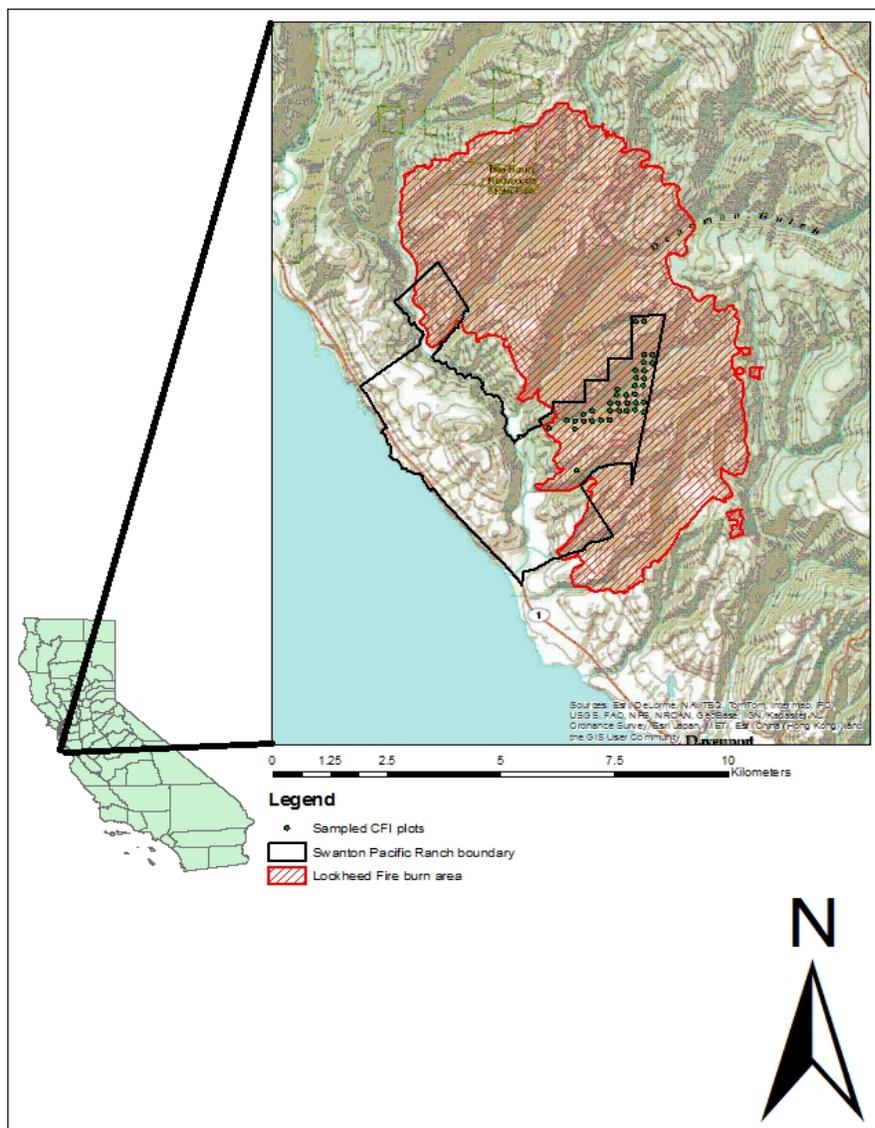


Figure 3.1 Map of study site. Red shaded area represents Lockheed Fire boundaries, black outline represent Swanton Pacific Ranch boundaries, and green dots represent study plots.

The study site encompasses a second-growth forest that resulted after clearcut logging in the 1910-1920 era, the demand for local lumber theorized in part to rebuild San Francisco following the 1906 earthquake, and later to salvage dead or damaged timber following an extensive wildfire (Pine Mountain Fire) in 1948. The overstory consists primarily of redwood and Douglas-fir with a minor component of tanoak, Pacific madrone (*Arbutus menziesii*) and knobcone pine (*Pinus attenuata*). The understory plant community consists primarily of sword fern (*Polystichum munitum*), red huckleberry (*Vaccinium parvifolium*), western trillium (*Trillium ovatum*), chaparral and redwood sorrel (*Oxalis oregana*), and is commonly sparse due to heavy shade from the overstory species.

The study site is located within the footprint of the 2009 Lockheed Fire, which was ignited on August 12th 2009 and burned 3,163 ha over a twelve day period. The Lockheed Fire burned with variable severity across the study site, with increased severity on the upper slopes and ridges and lower severity on lower slopes and drainages. Redwood comprised the majority of the pre-fire overstory basal area in all plots.

Field Measurements

Mortality and regeneration data were collected in 38 permanent 0.08ha Continuous Forest Inventory (CFI) plots within the boundaries of the Lockheed Fire. Plots that were located on roads or those that were heavily altered by post-fire management activities were excluded. Scorch height (m) in 22 plots was measured on every tree > 10 cm Diameter at Breast Height (1.37 m) between September 2009 and April 2010 (Netheway 2010). In July 2011, scorch height was measured on the remaining 16 plots; given the short time period, it was assumed that scorch

height did not change in the 22 plots already sampled. Further, every tree > 10 cm was sampled for survival (alive vs. dead), bole scorch height (m), total tree height (m), and DBH (1.37 m).

Regeneration data were obtained in July 2011 at all plots in an inner 0.004 ha subplot.

Regeneration count by species, type (seedling and sprouting), and height were sampled.

Sprouting regeneration in this study was limited to sprouts emanating from the root collar; sprouts originating from the bole were not considered “regeneration” in this study.

Statistical Analysis

Mortality data were analyzed with binary logistic regression utilizing Minitab® statistical software (v. 16.1.1), but only for species in which $n > 51$ per Woolley et al. (2012).

Thus, while many species were measured in this study, only redwood, Douglas-fir, and tanoak were prevalent enough to warrant analysis (Table 1).

For a given species, multiple binary logistic regression models were created using the base model

$$[1] P\{M_s\} = \frac{\exp(\beta + \beta_1 X_1 + \beta_2 X_2 \dots)}{1 + \exp(\beta + \beta_1 X_1 + \beta_2 X_2 \dots)}$$

Where $P(M_s)$ is the probability of mortality for a given species and X_i is an independent variable quantifying a tree morphological parameter or a fire intensity parameter.

For each species, multiple models of Eq[1] were created using all combinations of two measured tree morphological parameters (tree height, DBH) and four fire intensity parameters (scorch height, ratio of scorch height to tree height, mean scorch height by plot, median scorch height by plot). Thus, for each species a total of twenty-seven mortality models were created and evaluated.

Data met the assumptions for binary logistic regression including linear relationships between parameters, independence among variables, data were intervally or ratio-scaled, variables were normally distributed, error was normally distributed, there were no correlation among the error terms, and there was no endogeneity.

Binary logistic regression precludes a single test to determine the most appropriate model. Only mortality models in which all independent variables were statistically significant ($\alpha=0.10$) were compared. Thus, for each species, relative comparisons between the mortality models were made using log likelihood goodness-of-fit measures and Nagelkerke R^2 . Log likelihood indicates how well a model fits the data; in general, the lower the log likelihood value, the more suitable the model. Nagelkerke R^2 is considered a 'pseudo- R^2 ' because a true R^2 cannot be calculated in binary logistic regression. However, Nagelkerke R^2 is interpreted in the same manner as a traditional R^2 value (ranging 0-1); in general, the larger the value, the more variability can be explained by the model.

Analysis of post-fire regeneration employed Pearson correlation analysis, multivariate regression statistical analysis, and binary logistic regression analysis. Regeneration by species, type and count were used as the response variable for multivariate regression analysis ($\alpha = 0.10$). The presence or absence of regeneration of species and type were used as the response variable for binary logistic regression analysis. Basal area (m^2/ha), mean scorch height (m) by plot, median scorch height (m) by plot, Stand Density Index (# 25 cm or greater DBH trees per hectare), Leaf Area Index ($m^2leaf/m^2ground$), and percent canopy cover were used as independent variables for the Pearson correlation analysis, multivariate regression analysis, and binary logistic regression analysis.

For regression analysis of post-fire regeneration, multivariate regression was first employed. The base multivariate regression model used to predict regeneration (by seed and by sprouting) was:

$$[2] E\{Y\} = \beta + \beta_1 X_1 + \beta_2 X_2 \dots$$

Where E is the predicted number of seedlings (or sprouts) of a given species and X represents an independent variable and β is the coefficient for predictor variable X_i .

After the use of multivariate regression analysis, binary regression analysis was employed. For a given species, multiple binary logistic regression models were created using the base model

$$[3] P\{R_s\} = \frac{\exp(\beta + \beta_1 X_1 + \beta_2 X_2 \dots)}{1 + \exp(\beta + \beta_1 X_1 + \beta_2 X_2 \dots)}$$

Where $P(R_s)$ is the probability of regeneration or sprouting for a given species and X_i is an independent variable quantifying a stand measurement parameter or a fire intensity parameter.

For each species, multiple models of Eq[3] were created using all combinations of Basal area (m^2/ha), mean scorch height (m) by plot, median scorch height (m) by plot, Stand Density Index (# 25cm or greater DBH trees per hectare), Leaf Area Index ($m^2\text{leaf}/m^2\text{ground}$), and percent canopy cover were used as independent variables. Thus, for each species a total of twenty-seven regeneration models were created and evaluated.

Coefficients, p-values, 95% Confidence Intervals, and odds ratios were also calculated for both mortality and regeneration. Confidence intervals of 95% are interval estimates of a population parameter that indicates the reliability of the estimate. The odds ratio is the probability of an event (mortality, regeneration, etc.) occurring versus the probability that the event will not occur for each independent predictor value.

Results

Mortality

Table 1 shows mortality counts and the means of various morphological and fire intensity measures. Variable mortality rates were experienced between species during the Lockheed Fire. Mean scorch height varied between 0.207 m in coast live oak and 5.178 m in redwood. Mortality rates varied between 8% in coast live oak and 66% in California nutmeg. Mortality rates for the most prevalent species include 22% of redwood, 49% of Douglas-fir, and 31% of tanoak.

1 **Table 3.1 Tree count, mortality count, mean tree height (m), mean Diameter at Breast Height (cm), mean scorch height (m),**
 2 **median scorch height (m), standard error of scorch height, and scorch height to tree height ratio by major recorded tree**
 3 **species for Santa Cruz Mountains study site.**

Tree Species	n	Mortality n	Mortality %	Mean tree height (m)	Mean DBH (cm)	Mean scorch height (m)*	Median scorch height (m)	SH/TH
Redwood	551	120	22%	23.85	42.01	5.18 (0.31)	3.9	0.264
Douglas-fir	81	40	49%	26.12	41.51	2.79 (0.54)	1.7	0.115
Tanoak	154	47	31%	17.41	29.40	0.95 (0.32)	0.5	0.075
Coast live oak	39	3	8%	7.43	14.27	0.21 (0.03)	0	0.016
California nutmeg	12	8	66%	10.04	25.57	0.65 (0.13)	0.15	0.056
California Bay Laurel	10	3	30%	14.80	20.72	0.51 (0.12)	0.6	0.045
Birch	9	5	56%	17.58	34.99	1.54 (1.04)	0.9	0.091

4 *Note.* SH/TH = ratio of scorch height to tree height
 5 *Standard error of mean scorch height in parentheses

As expected, the greatest level of mortality occurred in the smaller trees. The highest level of redwood mortality occurred in trees < 20 m in height and 50 cm DBH; no mortality occurred in redwood greater than 40 m in height and 100 cm DBH. (Figure 3.2)

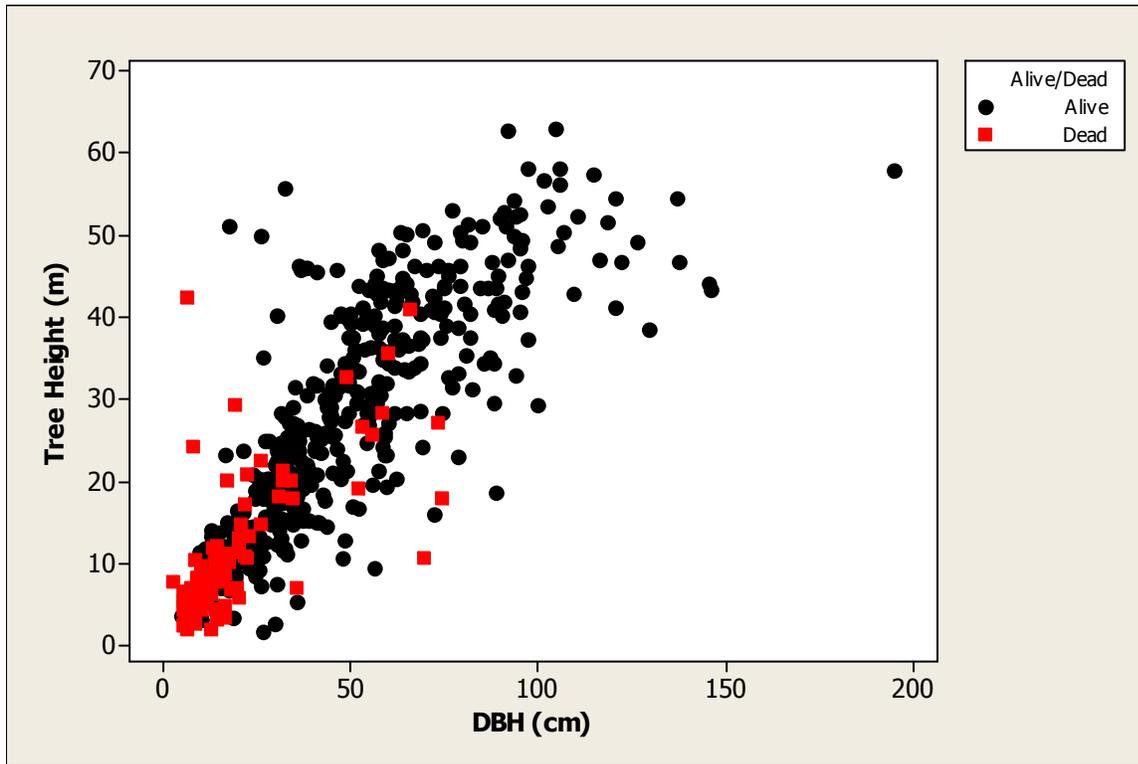


Figure 3.2 Observed alive and dead redwood by tree height (m) and Diameter at Breast Height (cm) for the Santa Cruz Mountains study site.

The majority of redwood mortality occurred in trees < 20 m height and < 10 m scorch height. (Figure 3.3)

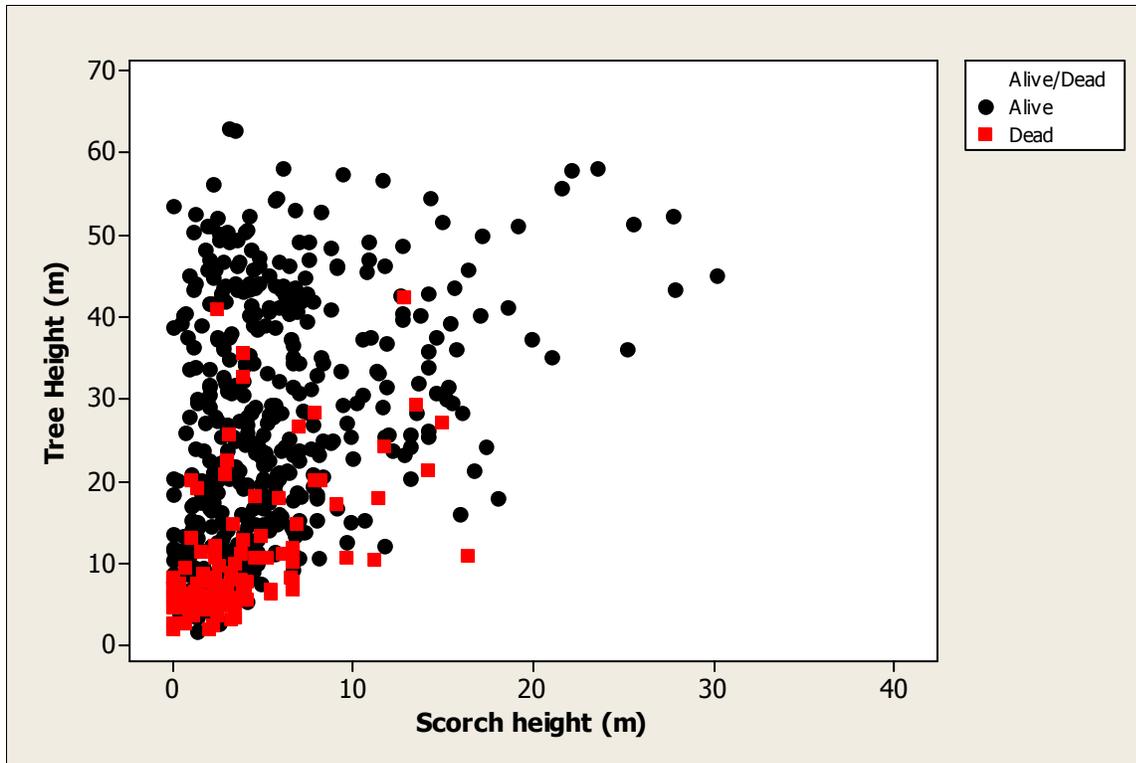


Figure 3.3 Observed alive and dead redwood by tree height (m) and scorch height (m) for the Santa Cruz Mountains study site.

Similarly, the majority of Douglas-fir mortality occurred in smaller trees. The highest level of Douglas-fir mortality occurred in trees < 20 m in height and 20 cm DBH (Figure 3.4). Unlike redwood, mortality was observed in Douglas-fir across a greater range of DBH and tree height, including the largest Douglas-fir sampled.

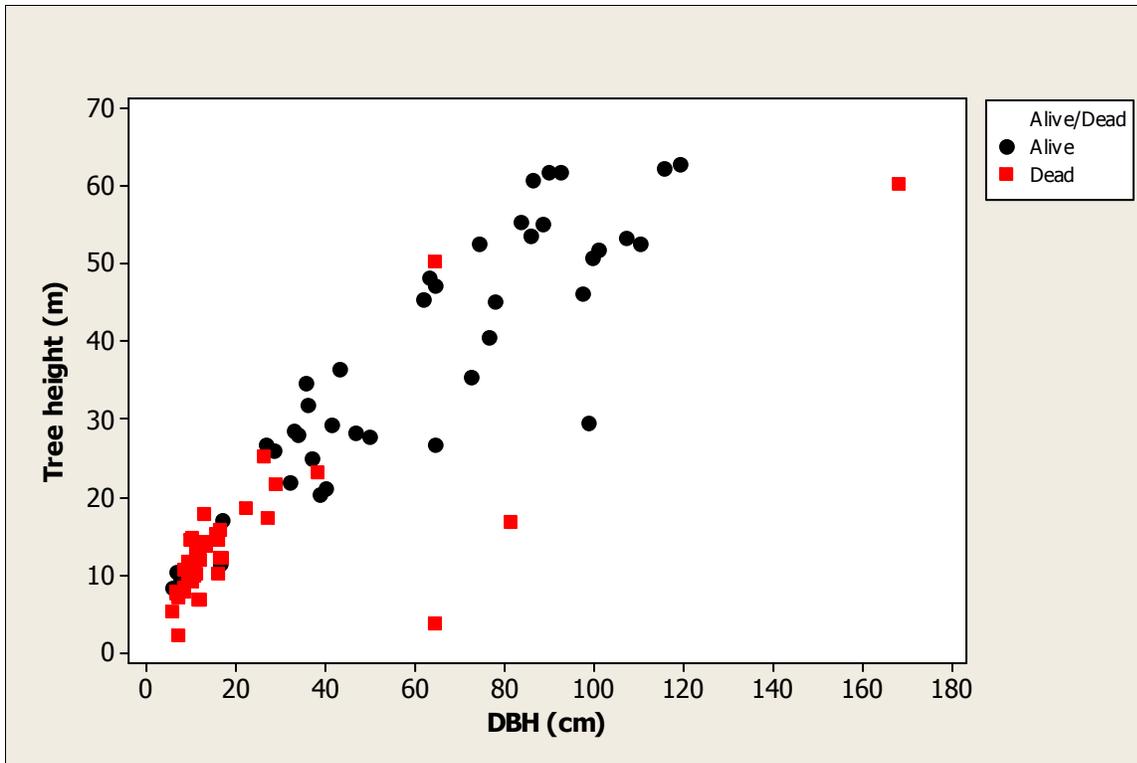


Figure 3.4 Observed alive and dead Douglas-fir by tree height (m) and Diameter at Breast Height (cm) for the Santa Cruz Mountains study site.

The majority of Douglas-fir mortality occurred in trees < 10 m height and < 10 m scorch height. (Figure 3.5)

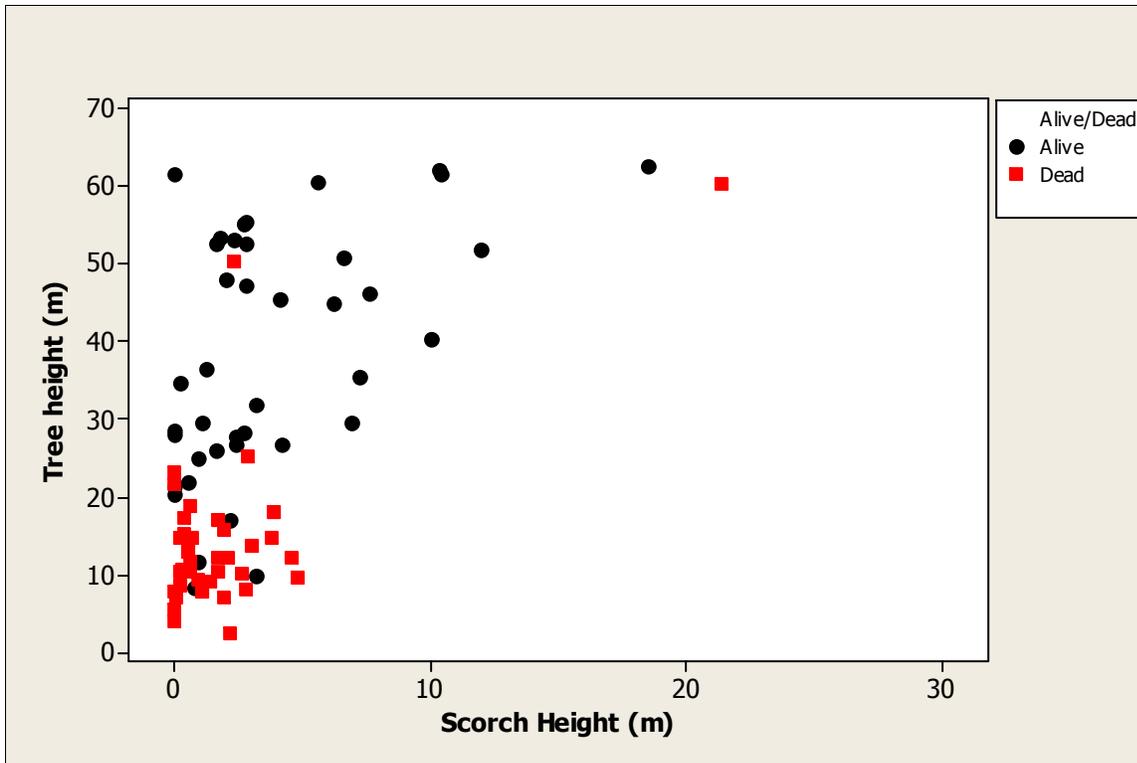


Figure 3.5 Observed alive and dead Douglas-fir by DBH (cm) and scorch height (m) for the Santa Cruz Mountains study site.

Unlike redwood and Douglas-fir, a clear cutoff in tanoak mortality does not exist. On average there was higher mortality in smaller tanoak. However, one of the tallest recorded tanoak died as a result of the Lockheed fire. (Figure 3.6)

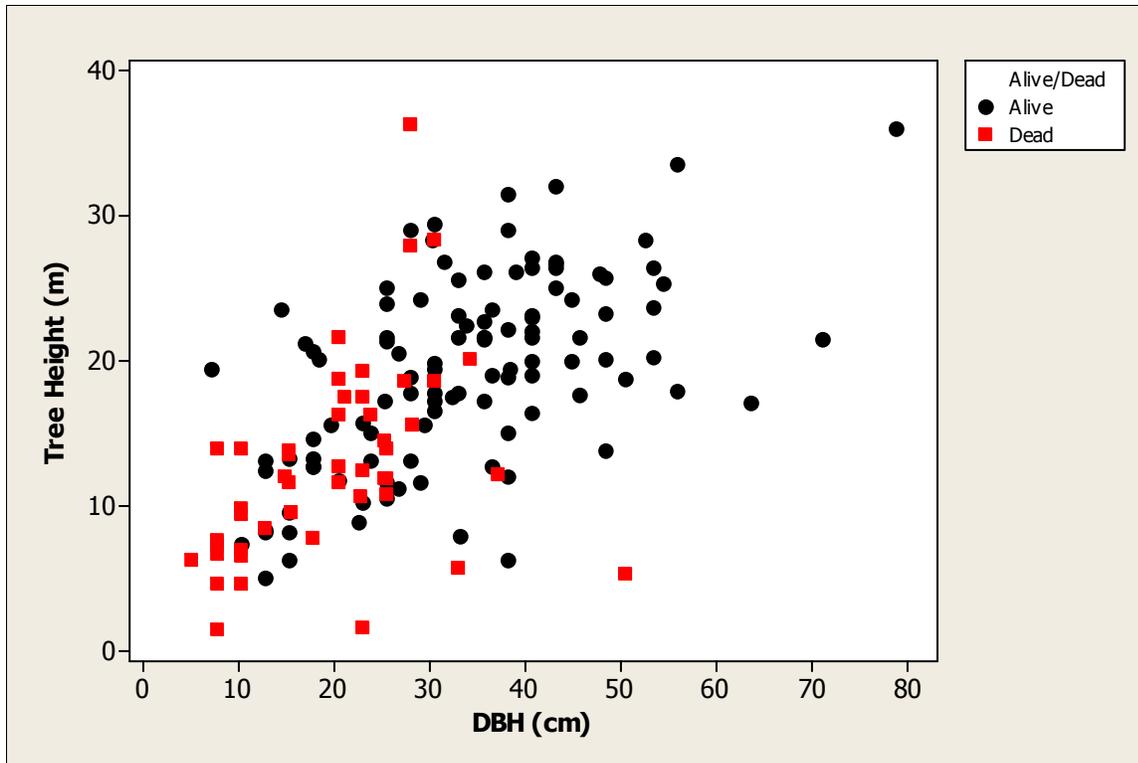


Figure 3.6 Observed alive and dead tanoak by tree height (m) and Diameter at Breast Height (cm) for the Santa Cruz Mountains study site.

Tanoak experienced mortality across a broad range of scorch heights. Most deceased tanoak were less than 20 m in height. However the tallest recorded tanoak died from a scorch height recorded near 0 m. (Figure 3.7)

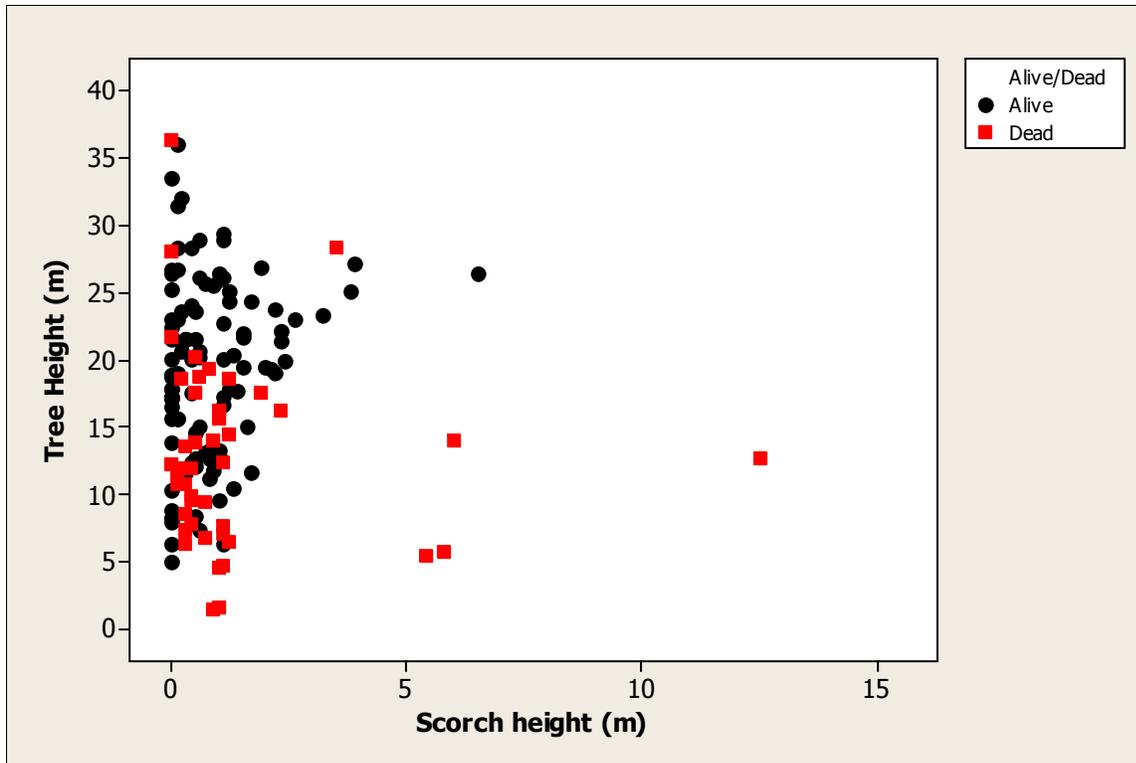


Figure 3.7 Observed alive and dead tanoak by tree DBH (cm) and scorch height (m) for the Santa Cruz Mountains study site.

Binary logistic regression models (in which all independent variables were significant; $\alpha=0.10$) are shown in Table 3.2. Again, while many species were sampled in this study, only redwood, Douglas-fir and tanoak were prevalent enough ($n > 51$) to warrant further analysis on mortality (Woolley et al. 2012). Each model includes at least one tree morphological parameter and one fire intensity parameter.

1 **Table 3.2 Binary logistic regression models predicting mortality from tree morphological features and fire effects.**

Species & model	Model Equation	Goodness-of-fit	
		Log likelihood	Nagelkerke R^2
Redwood			
Model 1	$P = \frac{\exp(1.267 - 0.097 \text{ Tree height} + 0.104 \text{ Scorch height} - 0.052 \text{ DBH})}{1 + \exp(1.267 - 0.097 \text{ Tree height} + 0.104 \text{ Scorch height} - 0.052 \text{ DBH})}$	-386.517	0.451
Model 2	$P = \frac{\exp(0.515 + 1.885 \text{ SH/TH} - 0.085 \text{ DBH})}{1 + \exp(0.515 + 1.885 \text{ SH/TH} - 0.085 \text{ DBH})}$	-390.158	0.444
Model 3	$P = \frac{\exp(-2.056 + 2.635 \text{ SH/TH})}{1 + \exp(-2.056 + 2.635 \text{ SH/TH})}$	-543.035	0.093
Douglas-fir			
Model 1	$P = \frac{\exp(1.187 - 0.168 \text{ Tree height} + 0.284 \text{ Scorch height})}{1 + \exp(1.187 - 0.168 \text{ Tree height} + 0.284 \text{ Scorch height})}$	-64.708	0.592
Tanoak			
Model 1	$P = \frac{\exp(1.859 + 0.541 \text{ Scorch height} - 0.125 \text{ DBH})}{1 + \exp(1.859 + 0.541 \text{ Scorch height} - 0.125 \text{ DBH})}$	-140.714	0.39
Model 2	$P = \frac{\exp(1.644 + 7.972 \text{ SH/TH} - 0.118 \text{ DBH})}{1 + \exp(1.644 + 7.972 \text{ SH/TH} - 0.118 \text{ DBH})}$	-131.227	0.45
Model 3	$P = \frac{\exp(-1.399 + 8.285 \text{ SH/TH})}{1 + \exp(-1.399 + 8.285 \text{ SH/TH})}$	-171.603	0.165

2 *Note:* DBH = Diameter at Breast Height (cm), SH/TH = ratio of Scorch Height to Tree Height.

Specific statistics for each of the independent variables in each mortality model are found in Table 3.3. The odds ratio quantifies how unit changes in a given independent variable impacts the probability of mortality; values <1 indicate that an increase in the independent variable will lead to a decrease in the likelihood of mortality. For example, the DBH odds ratio in Redwood Model 1 (Table 3.3) indicates that for each centimeter increase in DBH, the probability of mortality decreases by 5% on average; similarly, the odds ratio for scorch height indicates that for each additional meter of scorch height, the probability of redwood mortality increases by 11% on average.

Table 3.3 Binary Logistic Regression Results for redwood, Douglas-fir, and tanoak Predictive Mortality Models

Species & Model #	β	S.E. β	p-value	odds ratio	95% C. I.	
					Upper bound	Lower bound
Redwood						
Model 1						
Constant	1.267	0.244	0.000			
DBH (cm)	-0.052	0.014	0.000	0.95	0.92	0.98
Scorch height (m)	0.104	0.043	0.015	1.11	1.02	1.21
Tree height (m)	-0.097	0.026	0.000	0.91	0.86	0.96
Model 2						
Constant	0.514	0.287	0.073			
SH/TH	1.885	0.532	0.000	6.59	2.32	18.69
DBH (cm)	-0.085	0.009	0.000	0.92	0.90	0.94
Model 3						
Constant	-2.056	0.182	0.000			
SH/TH	2.635	0.460	0.000	13.94	5.65	34.40
Douglas-fir						
Model 1						
Constant	3.148	0.705	0.000			
Tree height (m)	-0.168	0.039	0.000	0.85	0.78	0.91
Scorch height (m)	0.284	0.123	0.021	1.33	1.04	1.69
Tanoak						
Model 1						
Constant	1.859	0.538	0.001			
DBH (cm)	-0.125	0.023	0.000	0.88	0.84	0.92
Scorch height	0.541	0.191	0.005	1.72	1.18	2.50
Model 2						
Constant	1.644	0.582	0.005			
DBH (cm)	-0.118	0.023	0.000	0.89	0.85	0.93
SH/TH	7.972	3.205	0.013	2897.41	5.42	1549075.07
Model 3						
Constant	-1.399	0.251	0.000			
SH/TH	8.285	2.956	0.005	3963.71	12.08	1300817.43

Note. Binary logistic regression analysis generates a direct estimate of the probability of an event occurring. β = coefficient, S.E. = standard error, C.I. = confidence interval, DBH = Diameter at Breast Height, SH/TH = scorch height to tree height ratio. Odds reflect probability of Coast redwood mortality.

□ $p \leq 0.1$

Figure 3.8 illustrates the relationship between scorch height, tree height and the probability of redwood mortality (Model 1, Table 3.3). Although DBH was significant in redwood Model 1 ($p < 0.001$) it was excluded from Figure 3.8 model due to DBH's linear relationship with tree height (Pearson coefficient = 0.845). The probability of mortality decreases dramatically as tree height increases. Scorch height does not express a similar dramatic relationship with the probability of mortality. As scorch height increases, the probability of mortality also consistently rises, but rather slowly (Figure 3.8).

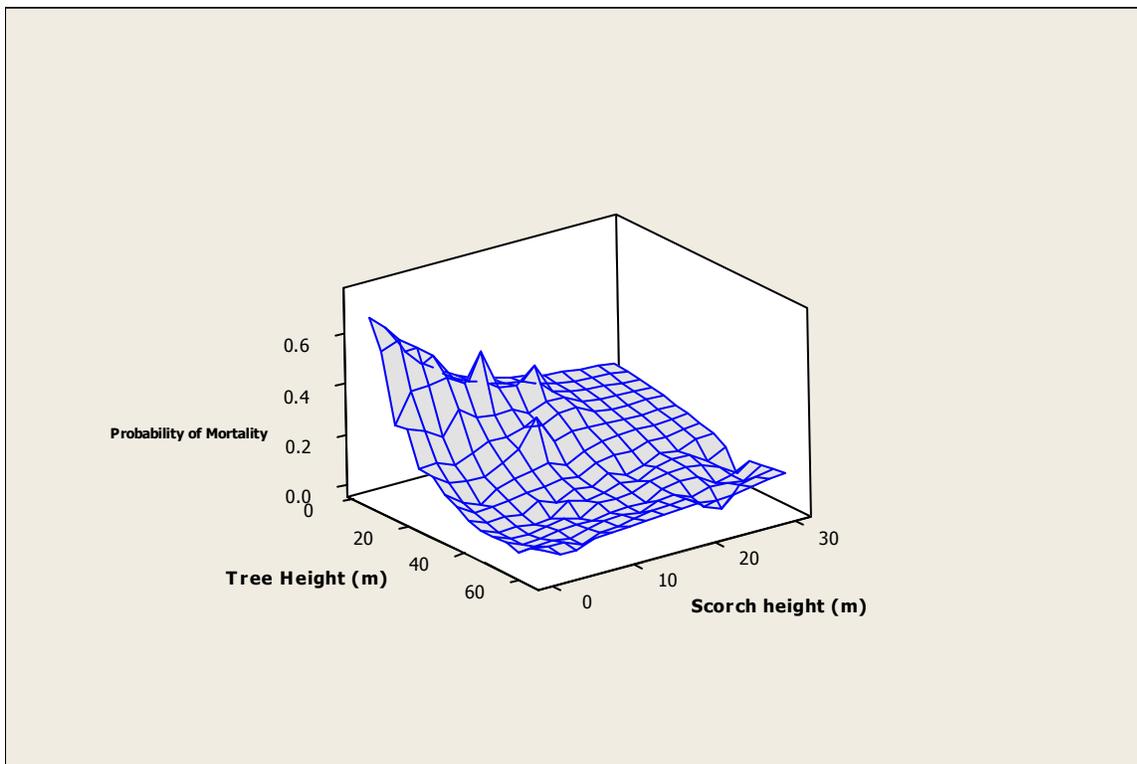


Figure 3.8 Three dimensional predictive Model 1 of redwood mortality using the binary logistic regression outputs.

Figure 3.9 illustrates the relationship between DBH, Scorch Height to Tree Height ratio and the probability of redwood mortality (Model 2, Table 3.3). The probability of mortality decreases rapidly as DBH increases and then levels off once DBH exceeds 100 cm. As the ratio of scorch height to tree height increases, the probability of mortality also rises steadily.

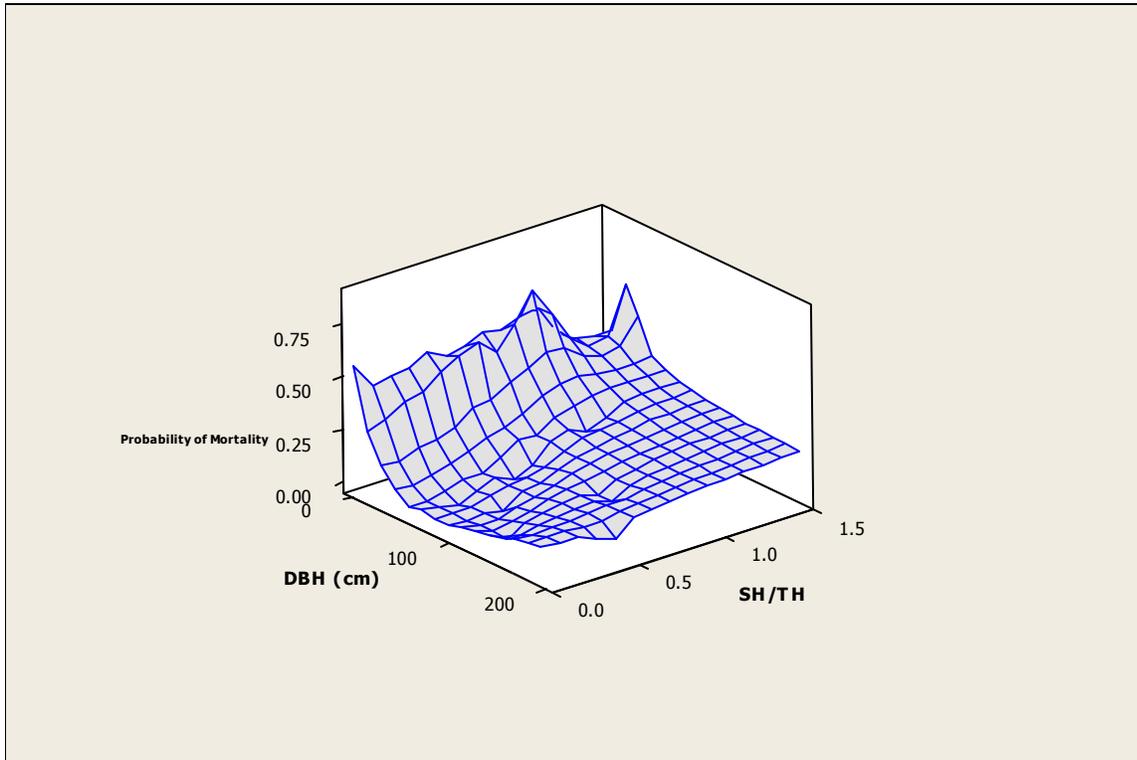


Figure 3.9 Three dimensional predictive Model 2 of redwood mortality using the binary logistic regression outputs.

Figure 3.10 illustrates the relationship between scorch height to tree height ratio and the probability of redwood mortality. The relationship is linear (Pearson coefficient = 0.990), as SH/TH increases so too does the probability of mortality.

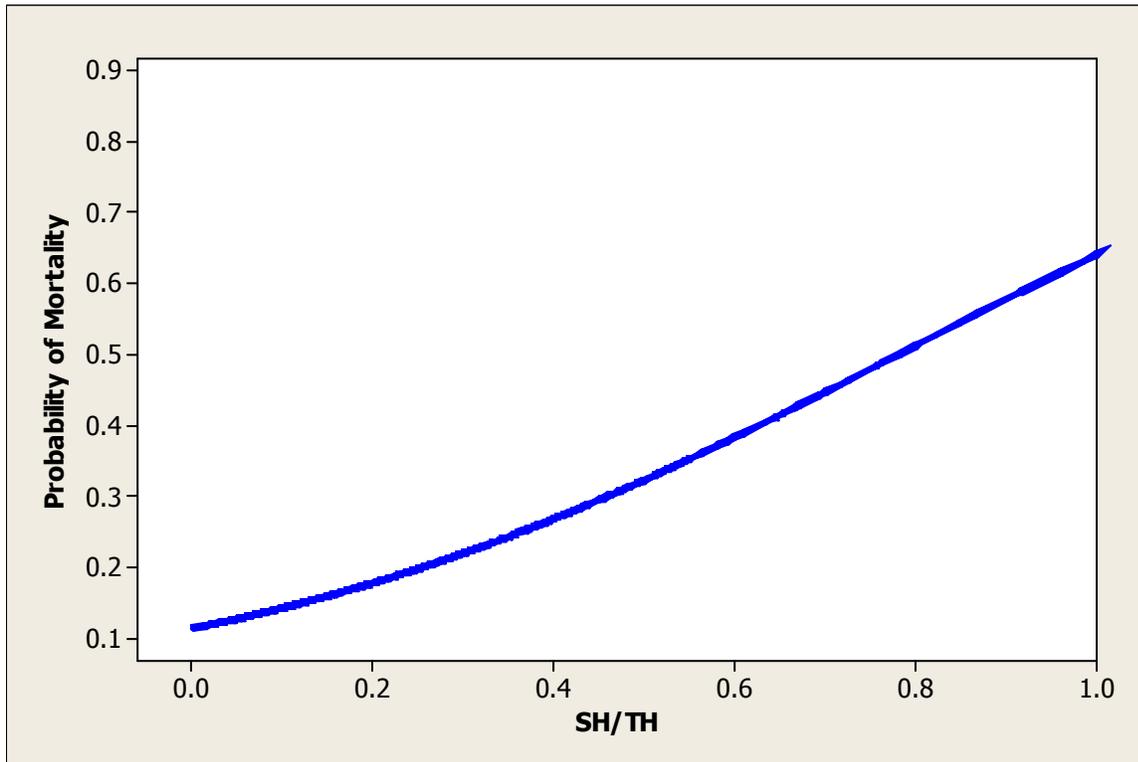


Figure 3.10 Predictive Model 3 of redwood mortality using the binary logistic regression outputs.

Figure 3.11 illustrates the relationship between tree height, scorch height and the probability of Douglas-fir mortality (Model 1, Table 3.3). As tree height increases, the probability of mortality declines dramatically. The relationship between scorch height and Douglas-fir mortality is not as dramatic. As scorch height increases, so does the probability of mortality. However, there are notable drops in the probability of mortality along the scorch height axis.

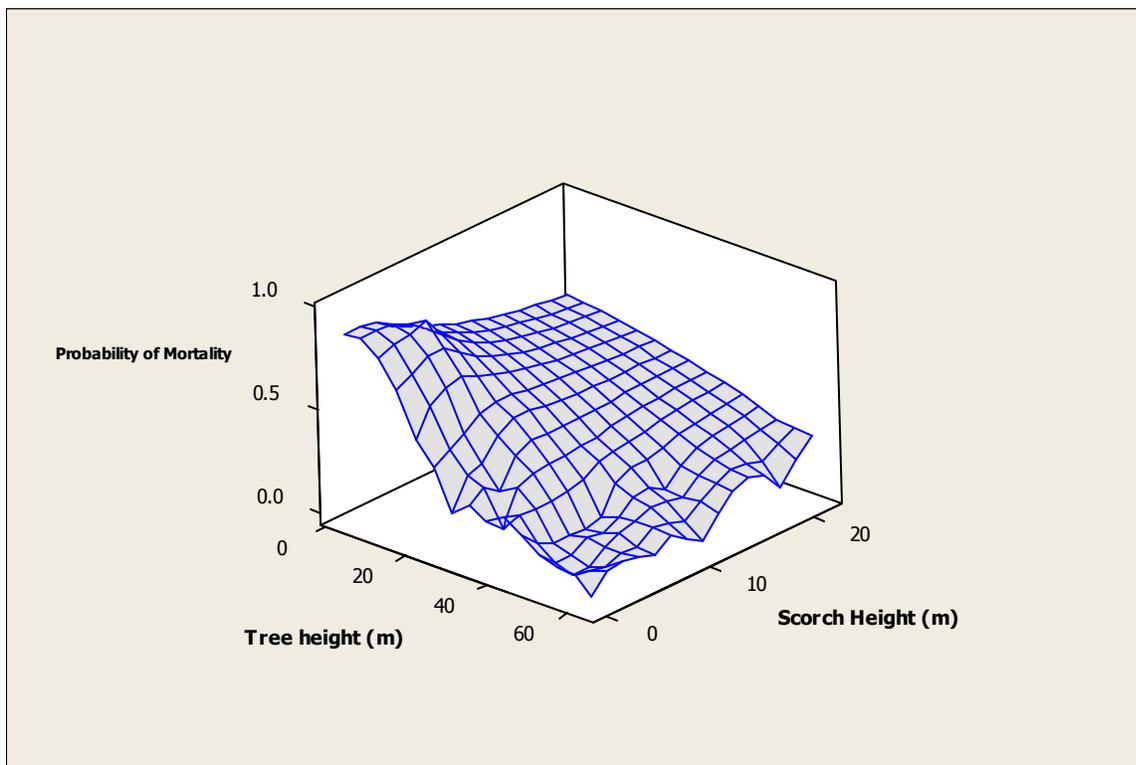


Figure 3.11 Three dimensional predictive Model 1 of Douglas-fir mortality using the binary logistic regression outputs.

Figure 3.12 illustrates the relationship between DBH, scorch height, and the probability of mortality (Tanoak Model 1, Table 3.3). As DBH increases, the probability of mortality decreases rapidly until DBH exceeds 50 cm, in which the probability of mortality levels plateaus. As scorch height increases, the probability of mortality steadily increases.

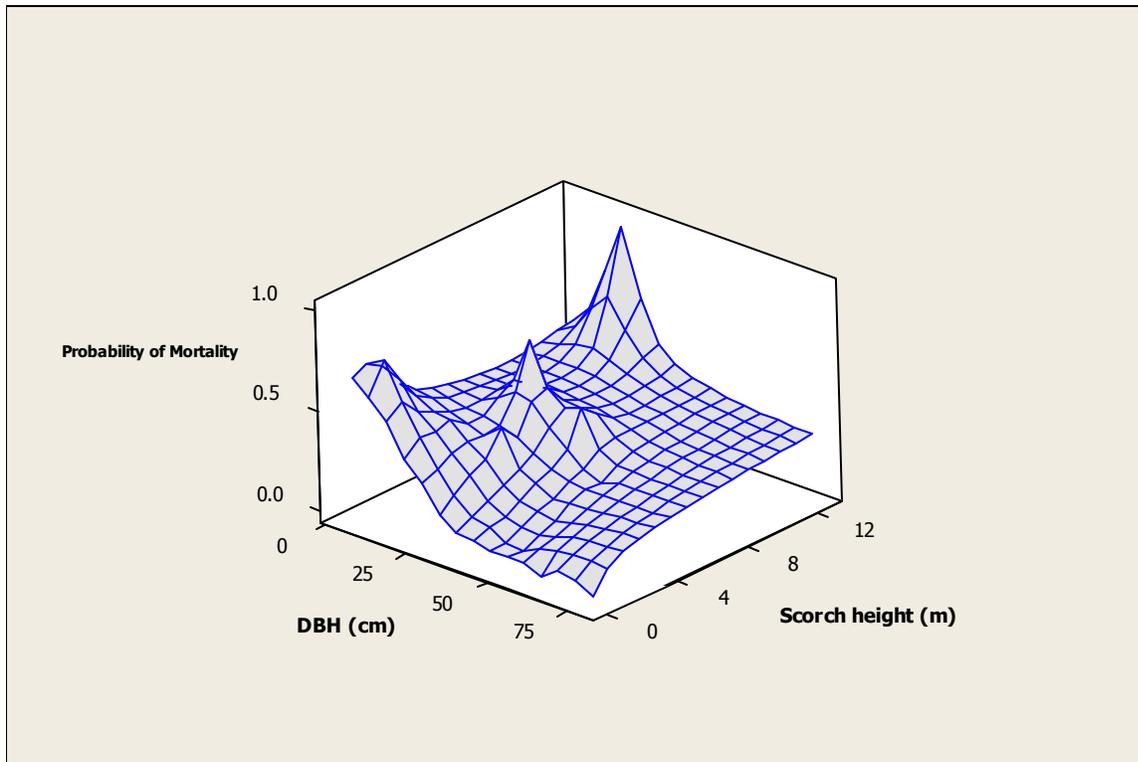


Figure 3.12 Three dimensional predictive Model 1 of tanoak mortality using the binary logistic regression outputs.

Figure 3.13 depicts the relationship between DBH, scorch height to tree height ratio, and the probability of mortality (Tanoak Model 2, Table 3.3). As DBH increases, the probability of mortality decreases rapidly until DBH exceeds 50 cm, at which point the probability of mortality again plateaus. As the ratio of scorch height to tree height increases, the probability of mortality increases slowly and steadily. (Figure 3.13)

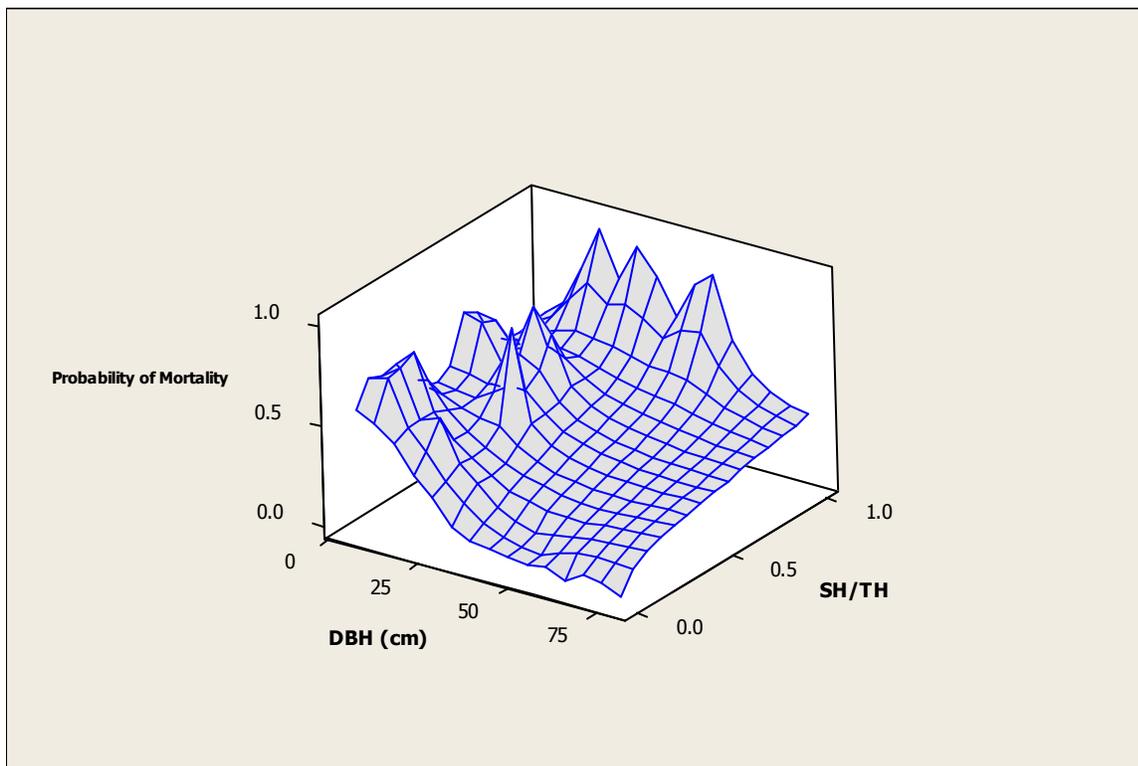


Figure 3.13 Three dimensional predictive Model 2 of tanoak mortality using the binary logistic regression outputs.

Figure 3.14 depicts the relationship between scorch height to tree height ratio and the probability of mortality (Tanoak Model 3, Table 3.3). The probability of mortality increases dramatically as the ratio of scorch height to tree height increases until scorch height to tree height exceeds 0.40, at which point the probability of mortality levels off as predicted mortality nears 100%.

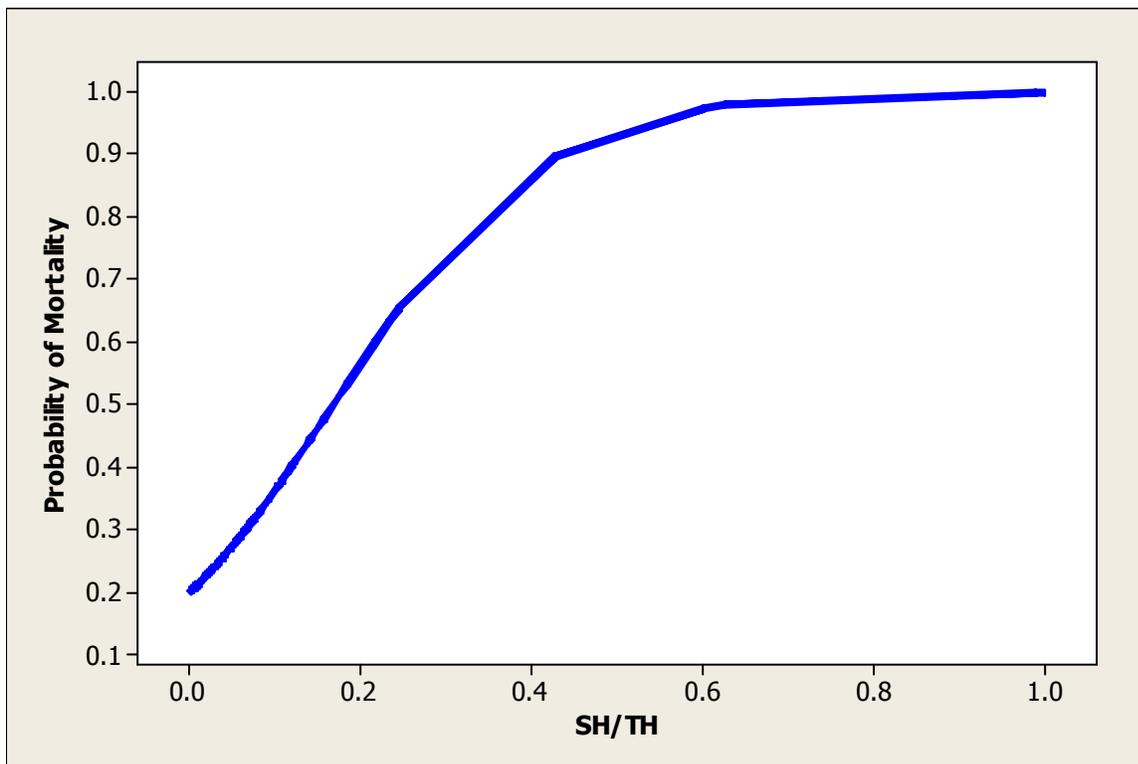


Figure 3.14 Predictive Model 3 of tanoak mortality using the binary logistic regression outputs.

1 *Response*

2

3 Regeneration data were analyzed by species and regeneration type (sprouting, seedling,
4 and planted) (Table 3.4). Only redwood sprouting and seedling regeneration, and tanoak
5 sprouting regeneration were deemed prevalent enough in terms of both count and plot
6 distribution to perform further analysis. Redwood seedlings were found in 47% of the sampled
7 plots (n=12,345). Redwood sprouts were recorded in 53% of the sampled plots (n=1,171).
8 Tanoak sprouting was recorded in 26% of plots (n=185). Although Douglas-fir had a total count
9 of 239 seedlings it was found in only 8% of the plots. (Table 3.4)

10 **Table 3.4 Regeneration counts by species and type (seedling, sprouting), and % of plots**
11 **observed.**

Species and Type	Count #	Plots Observed	% of Plots 12
Redwood seedlings	12,345	18	47%
Redwood sprouts	1,171	20	53%
Tanoak sprouts	185	10	26%
Douglas-fir	239	3	8%
Coast Live Oak	120	4	11%
California Nutmeg	49	2	5%
Monterey pine	6	1	3%
Knobcone pine	1	1	3%

13

14 The Pearson correlation analysis between regeneration counts (redwood sprouts, redwood
15 seedlings, tanoak sprouts) and various stand characteristics (Basal Area (m²/ha), Stand Density
16 Index (# 25cm or greater DBH trees per hectare), Leaf Area Index (m² leaf area/ m² ground area),
17 % canopy cover, mean Diameter at Breast Height (cm/ha), mean scorch height (m), and median
18 scorch height (m), yielded no significant correlations.

19 Similarly, multivariate regression analysis yielded no significant statistical results from
 20 any combinations of the independent variables (Basal Area (m²/ha), Stand Density Index (#
 21 25cm or greater DBH trees per hectare), Leaf Area Index (m² leaf area/ m² ground area), %
 22 canopy cover, mean Diameter at Breast Height (cm/ha), mean scorch height (m), and median
 23 scorch height (m)) for the any of the response variables.

24 Binary logistic regression analysis was conducted once multivariate regression analysis
 25 was performed and also yielded no significant results for redwood seedlings or redwood sprouts.
 26 However, Stand Density Index was found to be significant for presence of tanoak sprouts (Table
 27 3.5).

Table 3.5 Binary Logistic Regression Results for Tanoak Regeneration

Predictor	Coefficient	S.E. Coefficient	P	Odds 95% C.I.		
				Ratio	Lower	Upper
Constant	-5.05713	2.25612	0.025			
SDI (#25cm or greater DBH trees per hectare)	0.0081325	0.0042929	0.058	1.01	1.00	1.02

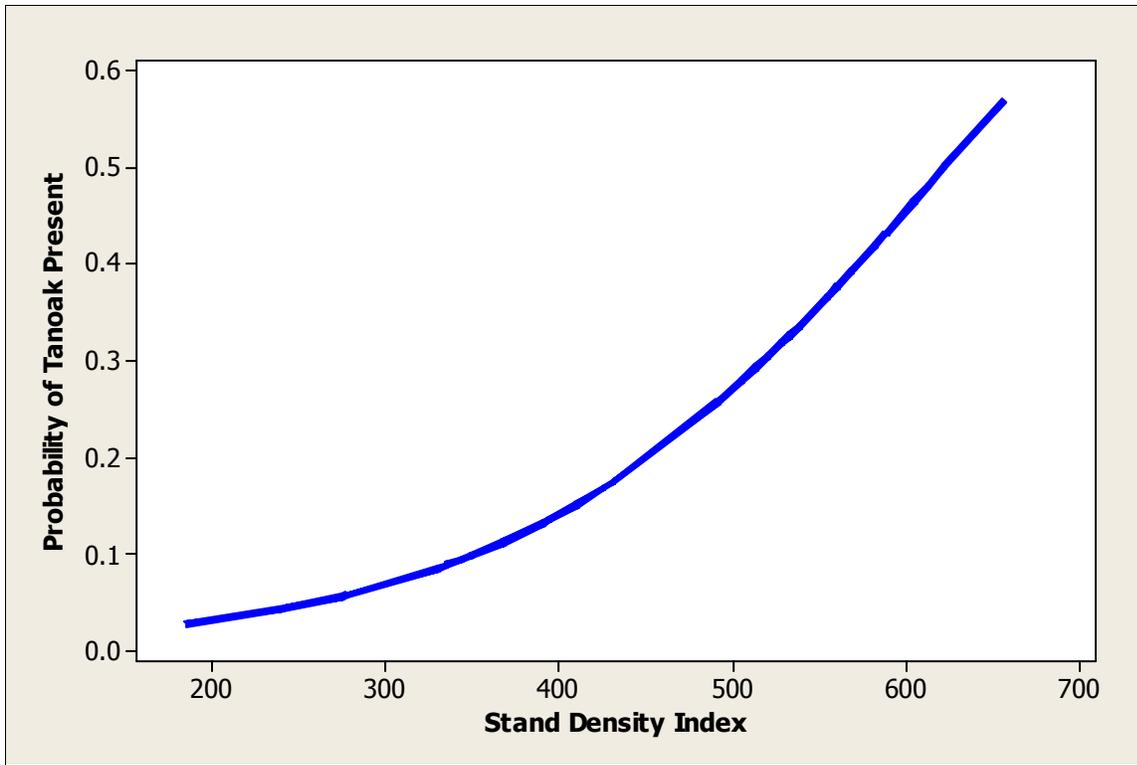
Log-Likelihood = -17.599

Test that all slopes are zero: DF = 1, P-Value = 0.030

28 *Note.* Logistic regression analysis generates a direct estimate of the probability of an event
 29 occurring. ($n = 185$), S.E. = standard error, P = p value, C.I. = confidence interval. Odds reflect
 30 probability of tanoak sprouting.

31 $\square p \leq 0.1$

32
 33 The probability of tanoak sprouting being present increases steadily until SDI exceeds
 34 400, at which point the probability of tanoak being present rises dramatically. (Figure 3.15)



35
36

Figure 3.15 Predictive model of tanoak sprouting using binary logistic regression outputs.

Discussion

Mortality

Of the three major overstory species sampled, redwood had the lowest mortality rate (22%) and the highest recorded scorch height (5.178 m) (Table 3.1). This discrepancy between scorch height and mortality can likely be attributed to morphological features associated with redwood. Mature redwood has thick bark that protects its cambium from thermal damage (Finney & Martin 1993). The typical extraordinary height and distance of tree base to crown of mature redwood prevents flame encroachment into the canopy (Finney & Martin 1993). The combination of these two morphological features protects mature redwood from fire-induced mortality. The higher recorded scorch heights for redwood can be explained by stringy deteriorated bark on mature trees that allowed more vertical fire spread up the bole as compared to other species (Finney & Martin 1993).

In this study, redwood mortality was extremely high in smaller trees, but declined considerably once tree height exceeded 20 m and DBH exceeded 50 cm, indicating mature redwood are relatively fire resilient. Coast redwood may appear deceased immediately following a wildfire, but bole sprouting commonly appears within 12 months in mature trees (Finney and Martin 1993, Jameson and Robards 2007, O'Hara and Berrill 2010). It is this physiological trait that allows mature redwood to withstand high scorch heights and restore leaf area lost by crown scorch (Finney and Martin 1993).

Douglas-fir had the highest recorded mortality (49%) of the major species (Table 3.1). This observation was unexpected and inconsistent with other related mortality studies (Kobziar et al. 2006). The relatively large DBHs and tree heights of the Douglas-fir sample were expected

to lead to a lower mortality rate. A possible explanation for this anomaly is that there was pre-existing stress on Douglas-fir prior to the Lockheed fire at the study site.

DBH was not a significant variable in predicting Douglas-fir mortality in this study, which is in contrast to Kobziar et al. (2006). However, the Douglas-fir with the largest recorded DBH in this study died during the fire, which certainly affected the significance of DBH as a predictor of mortality. This Douglas-fir may have been weakened from a pre-existing condition. The mortality of this individual tree does appear to be isolated because other Douglas-fir with similar DBHs did not die as a result of the Lockheed fire.

Tanoak had the lowest mean scorch height (0.949 m, Table 3.1) of the major overstory tree species and yet experienced a 31% observed mortality rate. The low scorch height can be explained by morphological features associated with tanoak bark; the thin smooth bark that commonly is found on tanoak does not allow for vertical fire spread up the bole of the tree. However, thin bark does not protect the cambium from extended heat exposure, contributing to the high mortality rate.

For multiple reasons, accurate prediction of redwood post-fire mortality would be beneficial for long-term management in this forest type (Finney and Martin 1993). First, an increase in fire frequency and severity across the redwood range has created an increased desire to use prescribed burning to reduce fuel loads (Finney and Martin 1993, Stephens and Fry 2007); accurate mortality prediction would help refine burning prescriptions. Further, the ability to predict post-fire tree mortality based on a physical evaluation process can aid in post-fire salvage operations, forest rehabilitation, conservation, and determining snag and downed wood recruitment (Filip et al. 2007, Hood et al. 2007, Woolley et al. 2012). Additionally, predictive

models can deepen our understanding of the effects of fire on structure and composition of post-fire plant communities (Agee 1993).

A combination of crown, bole, and injury resistance variables have been previously used to accurately predict post-fire mortality in numerous forest types (Wolley et al. 2012). The present study aimed to create empirically-based multivariate binary logistic regression models that incorporated variables of both tree morphology (tree height, and DBH) and fire intensity (scorch height) to mortality. These models were strictly for prediction, and not for explanatory purposes. The variables used in these predictive models do not address the physiological processes at work in fire-induced tree mortality.

Within individual models, independent variables have varying degrees of impact on the overall predictive output (Hood et al. 2007, Stephens and Finney 2002). Fire intensity (scorch height) and stem morphological features (tree height and DBH) are highly correlated to tree mortality (Hood et al. 2010, Wolley et al. 2012). However, morphological features are species-dependent; gymnosperms (Douglas-fir and coast redwood) generally have thicker bark than on average than angiosperms (tanoak) (Romberger et al. 1993). Therefore, bark thickness increases at an accelerated rate in gymnosperms relative to angiosperms (Romberger et al. 1993). Therefore, even large-diameter angiosperms such as tanoak are more susceptible to fire-induced mortality from stem injury than gymnosperms due to thinner bark.

DBH, scorch height, and tree height were all found to be significant predictors of redwood mortality following wildfire (Table 3.2). Finney and Martin (1993), the only other study that has explained post-fire mortality in redwood, also found DBH and scorch height to be significant predictors of redwood mortality.

There were large variations in log likelihood values (a measure of model goodness of fit) and in Nagelkerke R^2 values between the three redwood mortality models (Table 3.2). For example, Redwood Model 1 (which utilized tree height and scorch height as independent variables) had the highest log likelihood value (-386.517) and the highest Nagelkerke R^2 (0.451) of the three redwood models. This indicates Redwood Model 1 had the lowest goodness of fit of the redwood models, but the independent variables associated with this model best explain variability in redwood mortality. Conversely, Redwood Model 3 (which utilized only the scorch height to tree height ratio) had the smallest log likelihood (-543.035) and the smallest Nagelkerke R^2 (0.093), meaning that it had the greatest goodness of fit of the redwood models, but its independent variable least explained variability in redwood mortality. Since no redwood mortality model had both the lowest log likelihood and the largest Nagelkerke R^2 values, it is somewhat difficult to determine which specific model is best for predicting post-fire redwood mortality. Choice of models should be based on the specific needs of the user and the data available.

Tree height and scorch height were found to be significant independent variables in the prediction of Douglas-fir mortality. Other fire-induced mortality studies in the California Coast range and the Sierra Nevada did not sample Douglas-fir tree height as a predictor of mortality. Instead, most studies used DBH as the key tree morphological measure relating to mortality (Kobziar et al, 2006). Currently, there is no known study that used the ratio of scorch height to tree height as a predictor of Douglas-fir mortality.

Only one model was found to be significant for the prediction of Douglas-fir mortality, with the independent variables tree height and scorch height. Douglas-fir Model 1 had a log likelihood value of -64.708 and a Nagelkerke R^2 value of 0.592 (Table 3.2).

Scorch height and DBH were found to be significant independent variables that predict tanoak mortality. Only a single tanoak died from the Lockheed fire with a DBH greater than 50 cm. The greatest amount of tanoak mortality occurred in trees less than 30 cm DBH. Mortality occurred across the entire spectrum of recorded scorch heights. Tree height was not found to be significant in the prediction of tanoak mortality, which was likely caused by a limited range of sampled tanoak tree heights.

Only one other published study exists that predicts fire-induced tanoak mortality (Kobziar et al. 2006). They found tree height to be significant in the prediction of tanoak mortality while DBH was not significant, which contradicts the findings of this study. No known study used the ratio of scorch height to tree height as a predictor of tanoak mortality. The difference between the significance of tree height and DBH in this study and the Kobziar et al. (2006) study is difficult to identify, but can best be explained by differences in fire behavior, topography, and observed tree morphological measures. Burning for the Kobziar et al. (2006) study was conducted in late fall when burning conditions are different from August, when the Lockheed fire occurred. Geographical differences between the two study sites also likely played a significant role; the Kobziar study was conducted in the Sierra Nevada Mountains, where differences in climate and species composition were observed. Also, mean tree height and DBH were greater here than in Kobziar et al. (2006).

Tanoak predictive equations have similar goodness of fit complications as redwood. There were large variations in log likelihood values and in Nagelkerke R^2 values between the three tanoak mortality models (Table 3.2). For example, Tanoak Model 2 (which utilized tree height and scorch height as independent variables) had the highest log likelihood value (-131.227) and the highest Nagelkerke R^2 (0.45) of the three tanoak models indicating tanoak

Model 2 had the lowest goodness of fit of the tanoak models but its independent variables best explain variability in tanoak mortality. Conversely, Tanoak Model 3 (which utilized only the scorch height to tree height ratio) had the smallest log likelihood (-171.603) and the smallest Nagelkerke R^2 (0.165), meaning that it had the greatest goodness of fit of the tanoak models but its independent variable least explained variability in tanoak mortality. Since no tanoak mortality model had both the lowest log likelihood and the largest Nagelkerke R^2 values, it is somewhat difficult to determine which specific model is best for predicting post-fire tanoak mortality. Like redwood, choice of models should be based on the specific needs of the user and the data available.

Due to the uncontrollable nature of wildfires, the replication of some of the study parameters (fire intensity and severity) is extremely difficult (Hood et al 2007). Thus, the use of the predictive mortality models developed here for redwood, Douglas fir, and tanoak are limited in scope by geographic location and site-specific temporal attributes. The models created from this research are applicable to post-fire settings in the Santa Cruz Mountains of California; it is unclear whether these models would be applicable in other parts of the primary species range.

Although this study aimed to create multivariate regressions models that predicted seeding and sprouting regeneration based on various aspects of fire severity (e.g., scorch height) and post-fire stand variables (e.g., residual basal area and leaf area index), no significant results were found. High variability precluded the creation of statistically significant models for any of the species. Only one significant binary predictive model was successfully created (for tanoak based on SDI), but the value of the model is marginal since it does not predict the magnitude of regeneration, but only whether it would be present or not. Regeneration is considered a secondary response to wildfire and thus attempting to predict regeneration from wildfire

measures can be difficult (McKinley et al. 2011). Since regeneration and re-sprouting are not direct consequences of fire, using fire related variables is not advised (McKinley et al. 2011). Currently, there is limited research available to compare to this study.

Conclusions

There currently is very limited existing research on the relationship of tree morphological features and fire related injury measures (scorch height) to mortality and regeneration for redwood or its associated species. For decades forest managers, ecologists, and researchers have been interested in post-fire predictive mortality models, which would aid in planning post-fire harvest operations, rehabilitation efforts, and snag recruitment (Woolley et al. 2012). The mortality models developed in this study contain few and easily measurable variables (DBH, tree height, scorch height) making them desirable for field use and beneficial to forest managers and researchers. These models do not explain the link between fire severity, tree injury, and resulting mortality. Future research should focus on expanding the knowledge of physiological response of tree mechanisms (roots, foliage, and stems) following wildfire.

Seven total predictive mortality models were successfully created for redwood, Douglas-fir, and tanoak. Combinations of tree height, DBH, scorch height, and SH/TH were significant in the three resulting redwood mortality predictive models. Tree height and scorch height were significant in the Douglas-fir mortality predictive model. Combinations of DBH, scorch height, and SH/TH were significant in the three resulting tanoak mortality predictive models.

Unfortunately, high variability in seeding and sprouting hampered the creation of predictive equations for post-fire regeneration. No significant results were observed for Pearson correlation analysis and multivariate regression analysis. Therefore, creating models that could predict the amount of post-fire regeneration and sprouting was unachievable. Regeneration is a secondary response to wildfire and the link between overstory and fire severity measures and regeneration was difficult to express. Binary logistic regression analysis demonstrated that SDI

was a significant predictor of the presence of tanoak, but not its magnitude, therefore providing only limited practical use.

This study also collected regeneration height data that was unable to be put to use within the statistical analysis of the present data. Future research could resample regeneration and sprout height from sampled plots from the current study. The two sets of height data could be used to create a regressive model that predicts regeneration growth in the years following a wildfire disturbance. Future research may also attempt to discern overstory post-fire measurements (e.g., scorch height, canopy consumption, height to live crown, etc.) with regeneration.

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