AN ABSTRACT OF THE THESIS OF

Leif A. Mortenson for the degree of Master of Science in Forest Science presented on May 31, 2011.

Title: Spatial and Ecological Analysis of Red Fir Decline in California Using FIA Data

Abstract approved:

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Red fir (*Abies magnifica*) is a high elevation conifer generally growing between an altitude of 1,400 and 2,700 meters. In California, red fir grows in the Sierra Nevada, the Klamath Mountains, the eastern edges of the northern Californian Coast Ranges, and in the southern Cascades. Red fir commonly grows in pure stands and is often found in association with white fir (*Abies concolor*), lodgepole pine (*Pinus contorta*) or Jeffrey pine (*Pinus Jeffreyi*). Red fir is present in popular recreational areas including Yosemite, Kings Canyon, Sequoia and Lassen Volcanic national parks as well as the Mt. Shasta area and the Lake Tahoe region. Increasing and higher-than-expected red fir mortality and decline over the past five years has been observed in the central Sierra Nevada. This mortality and decline is seen as being caused by a complex interaction of biotic, anthropogenic and abiotic factors. The abiotic factors include drought, climate change (especially decreased snowpack), and the effects of changing fire regimes. The key anthropogenic factors are air pollution and forest management. The biotic factors include red fir dwarf mistletoe (*Arceuthobium abietinum* f. *sp. magnificae*), Annosus root disease (*Heterobasidion annosum*), *Cytospora* canker (*Cytospora abietis*), and the fir engraver beetle (*Scolytus ventralis*). Using USFS Forest

Inventory & Analysis (FIA) plots at a density of one every 5.47 km (3.4 miles) across California allowed for the first stand-level analysis of the entire red fir distribution zone in California. The results show that mortality is increasing in red fir, which suggests that at least a short term decline is occurring. The rate at which mortality is increasing varies, depending on which analysis approach is used and decreases if recently burned plots are removed from the analysis. At the individual tree level, red fir mortality (all size classes) is occurring at an annual rate of 2.64%. Red fir dwarf mistletoe is the most significant factor in red fir mortality and decline based on our field observations and statistical analysis. There is a clear visual and statistical difference in forest health between areas that possess red fir dwarf mistletoe and those that don't. This remains true even when stands are heavily stocked and Annosus root disease is present, suggesting that Annosus root disease (which is common throughout the red fir distribution range) is greatly exacerbated by the presence of red fir dwarf mistletoe. *Cytospora* canker is associated with red fir dwarf mistletoe, and is likely a significant reason why the red fir dwarf mistletoe impacts red fir forest health so significantly. The only variation in spatial pattern of red fir mortality in California is an area of very low red fir mortality around Mt. Shasta (where red fir dwarf mistletoes does not occur). There was not a consistent correlation between red fir mortality and drought stress. The amount of fir engraver activity in California is not well characterized making it difficult to assess its' role in red fir mortality.

Spatial and Ecological Analysis of Red Fir Decline in California Using FIA Data

by

Leif A. Mortenson

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented May 31, 2011
Commencement June 2012

Master of Science thesis of Leif A. Mortenson presented on May 31, 2011.

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Leif A. Mortenson, Author

ACKNOWLEDGEMENTS

I would like to think my advisor, Dr. Dave Shaw for taking me on as a student and being an absolutely phenomenal advisor. I arrived at Oregon State University (OSU) with substantial field experience, a topic I was set on studying, and yet no funding. Dave was supportive of my field observation-driven hypotheses even though we didn't know what the results would yield, and to me this is how science should be. Dave's knowledge, friendly rapport with everyone, and sense of humor helped greatly, both in the funding, and in the science of my thesis. Dave made some seriously long drives to spend some very useful time in the field with me and I greatly appreciate this.

This project certainly would not have been possible without Dr. Andy Gray. Dr. Sally Campbell helped get the ball rolling with the Pacific Northwest Research Station, Forest Inventory and Analysis (FIA) program as a potential funder of this project, but Andy really made it happen. Writing this thesis would not have been possible without Andy's programming of the immense FIA database to give me the exact datasets I needed. Andy's statistical prowess, knowledge of FIA and ecology in general were vital to the inner workings of my analysis. Thanks also to Quinn Payton and Hong Zhu of the OSU Statistics Department for statistical advice.

I would like to express gratitude to Dr. Matt Betts for serving on my committee even though academia's demands and serious skeletal injury kept us from ever having a committee meeting or thesis discussion on mountain bikes. It would have been a race had there been Tim Horton's donuts at rides end. Additional thanks to Jeff Morrell for serving as

my Graduate Council Representative. Though Dr. Dave Hibbs was not on my committee, I would like to thank him for teaching the best class at OSU (Advanced Community Ecology). Dr Hibbs encouraged thought provoking, boundary pushing paper writing and approached ecology in a manner that I found to be spot on.

Many thanks to Josh Feinberg and Walter Foss of FIA for being supportive and accommodating of my project while in the field. We had some great times digging in stumps, searching for Annosus root disease conks as if they were buried treasure. Thanks also to Phil Cannon of USFS Forest Health and Protection (FHP) for all the encouragement.

Thanks to my parents for predisposing me to writing long papers (i.e. this thesis) and working in the natural sciences. As much as I despised counting hauled-out seal populations while receiving driving lessons as a teenager, I guess it rubbed off on me.

Though there are certainly rewards to being a graduate student, there are also many times that could best be described as frustrating and stressful. During these times my friends and fellow graduate students were paramount. Countless people were essential, both in terms of brainstorming, problem solving and technical advice, as well as in keeping things light and fun. I won’t soon forget all the Bonferroni, Tukey, Fisher’s LSD, MANOVA and Moran’s *I* jokes.

CONTRIBUTION OF AUTHORS

Dr. Andy Gray was involved with database programming and mixed model analysis. Dr. Dave Shaw assisted with editing all sections of this manuscript.

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INTRODUCTION

Forest Decline

The use of the term decline in a forestry context is often met with great resistance, possibly due to the substantial, pollution-caused, forest decline in Europe in the 1980's (Innes 1993). The Society of American Foresters (SAF) defines decline as the "decrease in trees, shrubs, and herbs, or forest health and vigor, caused by one or more biotic or abiotic factors" (www.safnet.dreamhosters.com 2009). It is important to realize that decline does not imply a drastic or abrupt change, nor does it mean the imminent extinction of a species. A decline may also be part of a cyclical pattern. A decline, however, is a significant ecological event and though quantifying a decline is often difficult, it is indeed necessary.

Red Fir

California red fir, or red fir (*Abies magnifica*), is a high elevation conifer growing between an elevation of roughly 1,400 and 2,740 meters (4,600 to 9,000 feet) in southern Oregon and California. John Muir, who knew red fir as "magnificent silver fir," described red fir as the “most charmingly symmetrical of all the giants of the Sierra woods, far surpassing its companion species” (Muir 1894). In California, red fir grows in the Sierra Nevada, the Klamath Mountains, the southern Cascades, and in the higher reaches of the northern Californian Coast Ranges (Figure 1). The mean species elevation follows a latitudinal gradient with a significantly higher mean elevation at the southern end of the range in Kern County than in Siskiyou County along the Oregon border (Figure 2). There is a gap in the range where elevations are low around the Pit River between Burney Mountain and the Mt. Shasta area. In much of northern California, red fir exhibits a slight morphological difference (longer cone bract scales that are visible on closed cones) and as a result is known as Shasta red fir (*Abies magnifica* var. *shastensis*) (Burns and Honkala 1990). In this study, red fir and Shasta red fir were treated as one because differentiating between the two in the field is difficult if no cones are easily visible (which is common) for close examination, and because the morphologic difference is slight. Red fir (var. *shastensis*) grows in southern Oregon, but this study only examined red fir in California where the vast majority of the range lies.

In this study, 92% of the red fir stands analyzed were on federal land with 80% being on Forest Service land and 12% being on land administered by the National Park Service. Only one plot in the study fell on state or local government land and the remaining 7% of red fir stands fell on private land. Red fir is present in popular recreational areas including Yosemite, Kings Canyon, Sequoia and Lassen Volcanic National Parks, the Mt. Shasta area, many wilderness areas and the Lake Tahoe region. Red fir is present in many of California’s popular ski resorts including Northstar-at-Tahoe and Mammoth Mountain. On Forest Service land, red fir can be found in protected wilderness areas, popular recreation areas and in areas that have historically been managed for timber production. Very little harvesting of red fir is currently occurring on either Forest Service land or private timber company land.

Red fir grows in areas that are classified as cool to cold and moist. Roughly 80% of the precipitation in its distribution range falls as snow and the vast majority of this precipitation occurs between October and March with summers being predominantly dry (Burns and Honkala 1990). Although red fir depends heavily on snowpack it also has been shown to grow well in low snowpack years as it appears to benefit from the resulting longer growing season (Oliver 1982). Mean annual precipitation in the red fir distribution range is usually between 1,000 and 1,300 mm and doesn't change significantly with elevation loss/gain in this zone (Barbour et al. 2007). Mean annual temperature is roughly 12°C at the low elevational limit of the red fir distribution zone and rapidly decreases as elevation increases (Barbour et al. 2007). Red fir is generally found on north or partially north facing aspects [only 16% of the red fir plots in this study had aspects that fell between SE (135°) and SW (225°)] and generally in relatively young soils classified as mesic to frigid or cryic (Burns and Honkala 1990).

Fire frequency, severity and intensity are all highly variable throughout the red fir distribution zone. Small fires of moderate to low severity are more common than large or intense fires. Fires are usually spatially complex. Estimates of mean fire return intervals in the red fir distribution zone vary considerably. Sugihara et al. (2006) found median fire-return intervals ranging between 12 and 69 years in the upper montane of the Sierra Nevada. Fire frequency in the red fir distribution zone began decreasing around 1850 and has decreased dramatically since the policy of fire suppression became the norm (Sugihara et al. 2006).

Red fir is generally considered a climax species that is important to some wildlife species such as the pine marten (*Martes Americana*) (Moriarty, personal communication, 2011) and 111 species of birds (Burns and Honkala 1990). Stands experiencing significant mortality, decay and dwarf mistletoe infection are optimal for wildlife (Laacke and Tappeiner 1996). Red fir can be managed for timber production although it is not one of the more heavily harvested timber species. Red fir can grow in mixed-conifer stands as well as pure stands, and is most commonly found in association with white fir (*Abies concolor*), Jeffrey pine (*Pinus jeffreyi*), and lodgepole pine (*Pinus contorta*). In northwestern California, red fir is often found growing on, or near ridge tops. In the Sierra Nevada and the southern Cascades where the mountains are higher, there are often other tree species growing above red fir on the slope. High elevation treeless alpine areas are also more common in the southern Cascades and the Sierra Nevada than in northwestern California. Populations of red fir are considerably smaller and patchier on the east side of the Sierra Nevada than on the west side.

Forest Decline in Red Fir

Recent forest decline in red fir in the central Sierra Nevada has been observed by USFS Forest Health and Protection (FHP) (Bulaon and MacKenzie 2007). The FHP aerial survey found a significant increase in fir (both red and white) mortality in 2009 (Heath et al.

2009) and again in 2010 (Heath et al. 2010). During my time in the field with the Forest Inventory and Analysis (FIA) program, I have observed that red fir mortality was considerably higher than mortality of other conifers in California, and likely increasing.

The observed mortality and hypothesized decline is assumed to be caused by a complex interaction of biotic, abiotic, and anthropogenic factors (Bulaon, MacKenzie, Pronos, Cannon, personal communications, 2009). The direct anthropogenic factors include air pollution and forest management practices. The suspected abiotic factors include drought (especially decreased snowpack), and the effects of changing fire regimes (especially increased severity), all of which have been associated with climate change. The biotic factors, which vary more on a stand by stand basis include Annosus root disease (*Heterobasidion annosum*), red fir dwarf mistletoe (*Arceuthobium abietinum* f*. sp. Magnificae*)*, Cytospora* canker (*Cytospora abietis*)*,* the fir engraver beetle (*Scotylus ventralis*) and occasionally Armillaria root disease (*Armillaria ostoyae*) (Bulaon, MacKenzie, Pronos, Cannon personal communications, 2009).

All of the biotic factors affecting red fir have been present for some time (Ferrell 1980; Scharpf and Parmeter 1976, 1982). Experienced California forest pathologists (Pronos 2009; Woodruff 2009 personal communication) agree that red fir stands have more of a predisposition to be “funky” than do stands of other California conifers and have for as long as they can remember. Despite acknowledgement of the aforementioned factors impacting red fir and the likely higher incidence of damaging agents, there has never been any large scale spatiotemporal tracking of individual factors or overall mortality and possible decline. The FHP aerial survey does track mortality by species each year, but cannot account for factors that need to be physically measured or seen on the ground such as dead basal area or root disease. The use of Forest Inventory & Analysis (FIA) plots and data allows for spatiotemporal analysis of stand level data across the entire red fir distribution zone in California.

Forest Inventory and Analysis

The predecessor to FIA, “Forest Survey”, was created by Congress in 1928 and charged with the task of providing unbiased assessments of all of America’s forested lands. However, different inventory designs were often used in different regions. The 1998 “Farm Bill” mandated that all regions of the country use the same inventory design although additional data was also recorded in California (Christensen et al. 2008). The inventory records the incidence of insects and disease, forest type, forest condition and structure, the distribution of plant species, treatment and disturbance history, forest productivity, coarse woody debris characteristics and many more variables. The systematically randomized placement of FIA plots and the relatively high plot density [one plot roughly every 5.47 kilometers (3.4 miles) across forested conditions of all land ownership in California including private and national parks] allow for significant inferences to be drawn from the data.

Anthropogenic Factors

Air pollution

The west-side, southern Sierra Nevada is one of the most at-risk forested areas in the entire US (Bytnerowicz et al. 2003; Campbell et al. 2007; Jovan 2008) for severe ozone pollution damage as well as, potentially, damage from other air pollutants. Despite this, most experts do not consider red fir to be at risk because it grows at a high enough elevation that the amount of air pollution that reaches it is minimal compared to the amounts received by many of the lower elevation forests (Jovan 2008). In addition, true firs are generally not considered to be greatly affected by air pollution in comparison to species such as ponderosa pine. However; Bernal-Salazar et al. (2004) reported a lessening of annual tree ring width in sacred fir (*Abies religiosa*) (which inhabits sites with characteristics similar to red fir) in the Mexico City basin that started in the 1970's. They suggest that this shrinkage was caused by the severe air pollution in the region.

Forest Management

In general, especially with the current poor wood products market, little effort is put into thinning or planting red fir since commercial harvesting has declined since the 1990's (Christensen et al. 2008). There appears to be little impetus to manage red fir stands to combat insects and disease (Laacke and Tappeiner 1996). It is generally assumed that less dense stands of red fir would be optimal for forest health as is a stand that is of mixed composition instead of pure red fir (Bulaon, MacKenzie, Pronos, Cannon personal communications, 2009). Likely the most important factor in how management has affected red fir stands is simply if they have ever been logged or not. Field observations suggest that if stumps are present then there is a very high probability of Annosus root disease being present as well as other forms of heart-rot. It is possible that some prior treatments may have been prescribed to limit dwarf mistletoe, but there is little evidence of this occurring currently. In addition, it is rare to see fuels treatments in stands with red fir because treatments generally target lower elevation or more high risk (dryer) forest types.

Abiotic Factors

Climate Change/Drought

There are many models (for example, Stewart et al. 2004; Dettinger et al. 2002) and predictions about how global climate change will affect North American weather patterns and almost all of them predict California becoming warmer. This will lead to less precipitation falling as snow and potentially less total precipitation, although the opposite is presented by Crimmins et. al (2011). van Mantgem et al. (2009) suggest that regional warming is the main cause behind their reported widespread increase in tree mortality rates across the western US. They noted significant rates of increased mortality in *Abies* species. Guarin and Taylor (2005) found that drought was only correlated with tree mortality in mixed conifer forests in Yosemite National Park during multi-year drought events.

Barbour et al. (1991) found that the upper montane (see Potter 1998) red fir forest of northern California experienced the highest amount of snowpack of any vegetation type in California. Barbour et al. (1991) also found that the average elevation of freezing level in storms from December to March (the part of the year that the upper montane receives most of its precipitation), was centered upon the upper montane ecotone. In addition, Barbour et al. (1991) found a strong correlation between the elevation where snow turned to rain during much of the winter and the rough elevational line where red fir forests were replaced by white fir forests. They also found that the proportion of red fir (versus white fir) at fifty field sites was more closely correlated to snow pack and April snow water equivalence than to elevation. Barbour et al.'s (1991) work highlighted why the red fir upper montane ecotone was ideal for looking at ecological change due to climate change.

Allen et al. (2009) reviewed global drought and heat-induced tree mortality and found emerging climate change risks for forests. Though they mainly used the van Mantgem et al. (2009) study as evidence of increasing mortality in the western U.S., they highlighted the difficulty of quantifying the direct effect of climate on forest insect and pathogen populations. They also emphasized the lack of understanding of the interactions between climate driven tree mortality and other forest disturbance processes.

Fire

Westerling et al. (2006) showed dramatic increases, starting in the mid-1980's, in large wildfires, the length of the fire season and wildfire durations across the western US. In the northern Rockies, this increase was shown to be much more closely associated with increased temperatures and earlier spring snowmelt than with land use histories (i.e. the policy of fire suppression, grazing and timber harvest). They suggested that this may also be true to a lesser extent across the entire western US. Westerling et al. (2006) also suggest that though climate change may play a significant role, both a warming climate and high fuel levels due to fire suppression have led to this dramatic increase in large wildfire activity.

It is generally agreed that fire does not play as large a role in red fir ecology as it does in the ecology of some other western forest species, such as ponderosa pine, because fire frequency, severity and intensity are highly variable in the upper montane. *Fire in California's Ecosystems* states that "fire regimes in the upper-montane forest tend to be more variable in frequency and severity than those in the lower-montane forest" (Sugihara et al. 2006). There is some variation in estimates of mean fire return intervals in red fir dominated forests (for example, Sugihara et al. 2006; Taylor 2000; Taylor and Solem 2001; Chang 1996) and Newburn (1997) covers the whole spectrum by saying the mean annual fire return interval can be anywhere between 25 and 100 years depending on the characteristics of the stand. In addition to varied fire frequency in the upper montane, Erman and Jones (1996) reported varied fire frequency across the Sierra Nevada in the *1996 Sierra Nevada Ecosystem Report to Congress*. Fire frequency has also drastically decreased since fire suppression became the norm (Agee 1998; Sugihara et al. 2006; Chang 1996). Therefore, fire regime change is certainly a factor in changing forest structure over time.

Fuels in red fir forests are not ideal for supporting intense fires because they are compacted by the snowpack in the winter (which could change with climate change). Snow currently accounts for 65-95% of the precipitation that the upper montane receives in the Sierra Nevada (Sugihara et al. 2006). This compaction does not allow for much fire-fueling oxygen and keeps the fuelbed damp much longer than the light, airy pine forest fuelbeds (Taylor 2001). The red fir fuels that do accumulate are large in size but generally sparse

(Chang 1996). This may be changing if red fir mortality (and as a result, coarse woody material) increases in California.

Most fires in the upper montane are of low severity. Miller et al. (2008) report 13% of red fir stand fires as being high severity compared to 33% of white fir stand fires being high severity. Yet, it is widely acknowledged that intense, severe fires do periodically pass through red fir forests (Erman and Jones 1996; Chang 1996; Laacke and Tappeiner 1996; Sugihara et al. 2006). High severity fires that kill most trees could also benefit red fir in that they have the potential to eradicate or lower levels of dwarf mistletoe, fir engraver and Annosus root disease; whereas low to moderate severity fires tend to exacerbate these potential mortality agents by providing damaged host trees for colonization. There is now more evidence of increased fire severity in the Sierra Nevada as a whole. "Between 1984 and 2004 the annual burned area increased in moister, higher elevation forests dominated by firs but this trend was not true for drier mid to low elevation areas with yellow pines, i.e. stronger correlations between fire severity and climate for firs" (Miller et al. 2008).

There is disparity about the resistance of red fir to fire. *Fire in California's Ecosystems* (Sugihara et al. 2006) notes that red fir is generally fire resistant and responds favorably to fire. They highlight the fact that young red fir with thin bark are susceptible to fire where as older red fir with thick bark can survive most fires. However, young red fir and Jeffery pine are less susceptible to fire than young western white pine and western juniper (Sugihara et al. 2006)**.** Red fir can survive if 30-40% of its buds are scorched (Sugihara et al. 2006). Chang (1996) also noted that red fir bark may thicken as a result of being exposed to low intensity fires. Taylor (2000) implied that red fir was fairly fire intolerant though not as intolerant as white fir.

Fire does not cause sprouting or seeding in upper montane conifers (Sugihara et al. 2006), but it does affect succession in the upper montane. Infrequent fire is generally considered to favor red fir (as well as white fir) over the more fire tolerant pines (for example Taylor 2000; Taylor and Solem 2001; Sugihara et al. 2006) in mixed species stands. Gaps in the canopy created by fire are thought to help lodgepole or other pine seedlings become established. Chang (1996) however, noted that red fir established best in bare post-fire soils. Red fir is considerably more shade tolerant than most pines and as a result will eventually become dominant over pines in a mixed species stand if fire does not kill some of the smaller red fir while they still have thin bark that is vulnerable to fire. Some authors noted that it is rare to see pure red fir stands. However, Newburn (1997) found that red fir made up 95-99% of the total stocking on his upper montane research plots in Sequoia National Park. Pure red fir stands are more susceptible to dwarf mistletoe (due to host specificity) and likely Annosus root disease (different types on firs and pines) than diverse stands and therefore have the potential for high levels of mortality and significant fuels buildup. The lessening fire frequency during the 20th century is assumed to have caused an increase in density of red fir stands compared to earlier times of more frequent fire.

Biotic Factors

Red Fir Dwarf Mistletoe & *Cytospora* Canker

Dwarf mistletoe on red fir is unique because there are two areas in the red fir distribution zone where red fir dwarf mistletoe (*Arceuthobium abietinum* f. *sp. magnificae* and *A. abietinum* subsp. *wiensii*) is not present. These areas are the southern Sierra Nevada and the Mt. Shasta region. It is not known why red fir dwarf mistletoe does not occur in these areas. Fir dwarf mistletoe averages roughly 3 inches in height. Male and female flowers are produced on separate plants and flowering occurs in August and September. Pollination involves both wind and insects. Fruits take 13 to 14 months to mature. Seeds are explosively discharged from ripe fruits in September and October. Most seeds land within 10-to 15 feet although some may go as far as 40 feet (Hawksworth & Wiens 1996). Seeds germinate in early spring. One-year old twigs are much more likely to be infected because the bark is much softer. Aerial shoots will appear in two to three years and the first seed crop will be produced four to five years after initial establishment (Filip et al. 2000).

The signs and symptoms of dwarf mistletoe infection are well documented (Hawksworth & Wiens 1996; Giles et al. 2002; Wood et al. 2003; Scharpf 1993; Filip et al. 2000). *Cytospora* canker has long been associated with true fir dwarf mistletoe (Scharpf 1969). Field observations suggest that there is very seldom mistletoe without *Cytospora* canker and the brick red branch flagging caused by *Cytospora* canker is usually more noticeable than the small dwarf mistletoe plants and the associated branch swelling. *Cytospora* canker invades branches that are swollen from dwarf mistletoe and kills branches during the dormant season (Bulaon & MacKenzie 2007).

Dwarf mistletoe infection can reduce tree volume growth by as much as 40% (Filip et al. 2000). There is no literature on what percentage of this volume loss due to red fir dwarf mistletoe might actually be attributed to *Cytospora* canker. It is generally assumed that *Cytospora* canker is a "weak" pathogen (Goheen and Willhite 2006). As a result, there is little research on *Cytospora* canker in western firs even though it has clearly been present and abundant for some time (Scharpf 1969). If *Cytospora* canker is present in red fir that does not have dwarf mistletoe, it does not exhibit any signs that I observed in the field. *Cytospora* canker alerts FIA field crew personnel to the presence of dwarf mistletoe; however it should not be used as part of the DMR mistletoe rating system. It appears that this has occurred in the past. Since *Cytospora* canker is almost always present when dwarf mistletoe is present, it makes dwarf mistletoe infection consistently more damaging than it would be in other tree species such as ponderosa pine that does not experience *Cytospora* canker in addition to mistletoe infection. Wood et al. (2003) suggest that *Cytospora* canker tends to inhabit trees on poor sites.

There are no chemical or biological controls available for fir dwarf mistletoe (Filip et al. 2000). Since *Arceuthobium abietinum* f*. sp. magnificae* affects only red fir, increased species diversity in stands will limit dwarf mistletoe infection and spread (Scharpf 1969). Less dense stands are often considered less prone to mistletoe infestation simply because of the limited distance of dispersal by explosive discharge (Hawksworth and Weins 1996). Single storied stands are also favorable as any understory trees are likely to become infected because they annually receive a heavy deluge of seeds from the mistletoe in the canopy of the over story. It is rarely done, but in some instances branches with heavy dwarf mistletoe infection are pruned from trees as a way of eliminating dwarf mistletoe seed from a stand.

Buffer strips of trees of another species (with different mistletoes) can be planted or roads or rivers can create natural buffer strips (Bulaon & MacKenzie 2007).

Dwarf mistletoe on red fir is infrequently studied; however it was more commonly researched between 1960 and 1985. Scharpf and Parmeter (1976) examined the vertical spread and population buildup of dwarf mistletoe on both red and white fir. In most situations, true fir dwarf mistletoe expanded vertically upward at an average rate of 3 inches a year. This rate of expansion was slower than most dwarf mistletoe expansion rates. One of the main reasons for this slow rate is that the time period between initial infection and initial seed dispersal is longer than other mistletoes. The dense foliage of firs, that is kept for several years, as well as tight foliage whorls provides a natural barrier against seeds from lower branches more than with other species (e.g., pines). Seeds rarely make it farther than one or two whorls above a branch with a fruit-bearing plant. It is also likely that some years are less favorable for fruit production (Sharpf & Parmeter 1976).

A vigorous red fir can vertically outgrow the rate of vertical mistletoe spread with ease. Studies have shown that little impact on growth occurs in pines if mistletoe infection is limited to the lower one third of the tree (Hawksworth 1961). Older trees that are increasing very slowly in height may not be able to outgrow vertical mistletoe spread and are likely candidates for severe infection. Low vigor trees that are suppressed or growing on poor sites may not be able to outgrow vertical dwarf mistletoe expansion and are likely to become heavily infected (Scharpf & Parmeter 1976, 1982).

California red fir and noble fir (*Abies procera*) are morphologically different from each other, but Shasta red fir shares more characteristics with noble fir. It has been hypothesized that Shasta red fir is the result of California red fir and noble fir hybridizing (Mathiasen and Daugherty 2008). It has also been hypothesized that noble fir and red fir evolved from a common ancestor, likely *Abies klamathensis,* which more closely resembled Shasta red fir. Mathiasen and Daugherty (2008) suggest this hypothesis is backed by the fact that red fir at the southern end of the red fir distribution zone [which have now been identified by Lanner (2010) as a new variety, *Abies magnifica* var. *Critchfieldii*], share traits with Shasta red fir. There has been debate in southern Oregon for some time over where Shasta red fir ends and noble fir begins (Mathiasen and Daugherty 2008). Mathiasen and Daugherty (2008) used mistletoe host specificity to distinguish between the geographic distributions of red fir and noble fir in Oregon.

Although mountain hemlock dwarf mistletoe (*A. tsugense* subsp. *mertensiana*) is generally found on its principal host, mountain hemlock, it does occasionally infect noble fir in central and northern Oregon. Mathiasen and Daugherty (2008) found all populations of red fir to be immune to mountain hemlock dwarf mistletoe as well as the population of what is generally classified as noble fir in southern Oregon. Pacific silver fir dwarf mistletoe (*A. tsugense* subsp. *amabilae*) parasitizes Pacific silver fir and noble fir in central Oregon. Mathiasen and Daugherty (2008) found no Pacific silver fir dwarf mistletoe infection in noble fir in southern Oregon or on any population of red fir. They used dwarf mistletoe host specificity to conclude that the dividing line between Shasta red fir and noble fir was at roughly 44° N in central Oregon (Mathiasen and Daugherty 2008).

Mathiasen and Daugherty (2009) described a new subspecies of *A. abietinum* in northwestern California and extreme southwestern Oregon. The new subspecies is named *wiensii* in honor of longtime dwarf mistletoe researcher Del Wiens. Mathiasen and Daugherty's (2009) primary reasons for the naming of the new subspecies are morphological. They note several differences between *A. abietinum* subsp. *wiensii* and both *A. abietinum* f. sp. *magnificae* and *A. abietinum* f. sp. *concoloris* (white fir dwarf mistletoe). The most noticeable differences were that *A. abietinum* subsp. *wiensii* was consistently smaller than *A. abietinum* f. sp. *magnificae* and *A. abietinum* f. sp. *concoloris,* and it was a different color. It appeared to be a brown-red, almost orange color as opposed to the traditional yellow-green of most fir dwarf mistletoe (Mathiasen, personal communication, 2009).

The primary host of *A. abietinum* subsp. *wiensii* is Shasta red fir (it does not appear to occur on California red fir), but it can infect Brewer spruce (*Picea breweriana*). It appears that infection in Brewer spruce is somewhat uncommon, however Mathiasen and Daugherty (2009) note that all Brewer spruce infections were very severe. *A. abietinum* subsp. *wiensii* can also infect white fir. All dwarf mistletoe found in red fir in northwestern California would be *A. abietinum* subsp. *wiensii*. This population would be geographically separated from *A. abietinum* f. sp. *magnificae* by the Mt. Shasta population of red fir which does not have any known mistletoe infections. It is not known if the southern end of the northwestern population of red fir in the Yolla Bolly Mountains would be considered *A. abietinum* subsp. *wiensii* or if it would still be considered *A. abietinum* f. sp. *magnificae* (Mathiasen, personal communication, 2009).

Annosus Root Disease

Annosus root disease (*Heterobasidion annosum*) occurrence in red fir at a statewide level has not been researched, although it has been acknowledged that it is widespread in red fir in California (Potter 1998). I hypothesize that it has been historically under-coded on FIA plots (though this issue has greatly improved over the last five years). This is due to the substantial disparity between author observations in the field (consistent, widespread evidence of Annosus root disease) and what is reported in the 2000-2005 FIA 5-year report (Christensen et al. 2008, pg. 58). Red fir is affected by the "s" type, which is different from the European "s" type. It should be noted that in 2010 Otrosina and Garbelotto proposed changing *Heterobasidion annosum "*p" and "s" types (most, not all, tree species only host one type) to two different species, those being *Heterobasidion irregular* ("p" type) and *Heterobasidion occidentale* ("s" type). Using this nomenclature, red fir would be affected by *Heterobasidion occidentale.* Due to the timing of this publication and the fact that Annosus root disease is still known as *Heterobasidion annosum* ("s" type), I use the name Annosus root disease throughout this paper and *Heterobasidion annosum* when a scientific name is needed.

Annosus root disease exists as both a saprophyte and a parasite. Annosus root disease is a white rot and a Basidiomycete (Woodward et al. 1998). Spread over longer distances occurs when wind carries spores from fruiting bodies that land on, and infect basal wounds or recently cut stumps. The disease spreads at a local level from infected roots touching uninfected roots (Wood et al. 2003). Annosus root disease centers are generally smaller than those of *Phellinus weirii* or *Armillaria ostoyae.* As would be expected, dense stands where roots are closer together are considered to be more predisposed to Annosus root disease. Annosus root disease generally kills pole sized trees in 10-12 years (Woodward et al. 1998); the mortality of larger trees takes longer and is more variable. It is important to note that close proximity to infected roots does not guarantee mortality, as healthy saplings and seedlings can often be seen near infected stumps (Woodward et al. 1998). Annosus root disease creates good wildlife habitat due to snags resulting from mortality and the hollowed area left by decayed roots. Annosus root disease continues to live in infected root stumps for up to 50 or more years after trees have died or are harvested (Woodward et al. 1998).

Slaughter and Parmeter (1989) reported findings from an Annosus root disease field study conducted in true fir forests in California from 1979-80. They reported 4% of total live firs being infected with Annosus root disease and associated Annosus root disease with 25% of the dead fir trees. Slaughter and Parmeter (1989) reported that 18% of their study area was infected with Annosus root disease. Their description of the stands most affected by Annosus root disease, match in many ways, what I have witnessed in the field roughly 30 years later. They report Annosus root disease being prevalent in red fir stands, pure fir stands, stands with high basal density, stands with stumps and stands with many older trees (Slaughter and Parmeter 1989).

Classic biological control is obviously more difficult with Annosus root disease, since it is native, than with an invasive pathogen. *Phlebiopsis gigantea,* a fungus found in forests worldwide has been applied to pine stumps as a control of Annosus root disease (Woodward et al. 1998). This treatment, however, is not effective with *Abies.* Much less research has been performed on biological control of Annosus root disease than on chemical control of Annosus root disease (Woodward et al. 1998).

Applying borax to freshly cut stumps has been proven to be very effective against Annosus infection. This is commonly used in North America; in Europe solutions with varying percentages of disodium octaborate tetrahydrate (DOT) are also used. Borax (or borates to be more precise) has not been shown to pose any major environmental threats. Obviously, the borates would affect the fungal ecology of treated stumps and more research is needed to better understand these changes (Woodward et al. 1998).

Environmental impact statements (EIS) are required for the application of Borax on federal lands (where roughly 92% of red fir are found). Significant paperwork is required and the timeframe for the EIS to be processed is lengthy. As a result, foresters avoid the process and stumps do not receive borax (Bulaon, MacKenzie, personal communication 2009). At times, especially in areas with short rotations, some forest managers argue that it takes more time and money to apply borax to stumps than it is worth because the Annosus root disease mortality loses will not be significant (Bulaon, MacKenzie, personal communication 2009).

Increased stand species diversity limits the spread of Annosus root disease (Woodward et al. 1998). Annosus root disease will not spread from a pine to a fir or vice versa (p versus s type) (Woodward et al. 1998). Though s-type Annosus root disease can go from a white fir to a red fir, it is unclear if this is less common than from red fir to red fir or white fir to white fir. FHP pathologist Martin Mackenzie (MacKenzie, personal communication 2009) suggested that Annosus root disease was less likely to travel between species than in between trees of the same species.

A less dense stand is likely optimal for limiting Annosus infection since there will be less root contact, trees will be less stressed since there is less competition, and spores will have to travel further to infect other trees. This is especially true on poor sites. However, how Annosus root disease will respond to thinning depends on how it is performed. For example mechanical thinning greatly increases the chance of Annosus infection as it results in fresh stumps and logging scars for spores to colonize. The incidence of Annosus infection in commercially thinned stands in the Pacific Northwest is twice that of un-thinned stands; however the percentage of volume decayed is less than in un-thinned stands (Woodward et al. 1998). Despite the negative effects of thinning, it may still be advantageous. Smaller stumps are considered less likely to become infected, so thinning only small diameter trees may be less detrimental. This is because during the summer months temperatures in the smaller stumps (less distance to surface) reach temperatures lethal to spores before the more insulated, lower roots become infected (Woodward et al. 1998).

Since dense stands of red fir are more predisposed to Annosus infection than non-dense stands (Woodward et al. 1998), the role of other disturbances in the upper montane ecosystem that increase or decrease density is crucial in this study. Red fir dwarf mistletoe likely occurs more in dense stands. The role of fire (as a density reducer in this instance) in the upper montane is important for two reasons. First; although this ecosystem does not experience a high-frequency fire regime, it is likely that the fire regime of the upper montane has been altered to some degree since the advent of fire suppression in the first half of the nineteenth century (Taylor 2000). Even if this alteration is slight, it could certainly have significantly contributed to increased average red fir stand density across the red fir distribution zone. This may have resulted in increased Annosus root disease and dwarf mistletoe infection all across California in the past century. Secondly; the upper montane, with climate change likely causing a decreased snowpack, may become an ecosystem with a higher fire-frequency (Miller et al. 2008). If this does occur, then stands across the red fir distribution zone would be less dense. Theoretically this would mean less Annosus and dwarf mistletoe infection, especially if high intensity stand replacement fires became more frequent. However, if the fires are mostly of moderate intensity and spatially complex, then this could potentially lead to heavy fir engraver damage as fir engraver has a higher rate of successful colonization in stressed trees (Ferrell 1986). Live trees with damages are also very susceptible to Annosus infection.

Armillaria Root Disease

Armillaria root disease (*Armillaria ostoyae*) is usually not found above 6,500 feet elevation (Wood et al. 2003). As a result, it occurs mostly in the northern end of the red fir distribution range in California where red fir grows mostly below this elevation. For this reason, there is little research specifically on Armillaria root disease and red fir. Climatic change could make Armillaria root disease more important at higher elevations. Since it favors drought stressed trees the impacts of this disease on western conifers are expected to increase (Kliejunas et al. 2009). More than 25% of the red fir plots in this study were lower than 6,500 feet elevation and most of them were in northern California with only a few in the Sierra Nevada. As a result, Armillaria root disease could be a factor in red fir mortality on plots below 6,500 feet. Higher incidence of Armillaria root disease is likely in white fir although Shaw and Kile (1991) put little emphasis on Armillaria root disease occurrence in California.

Armillaria root disease can be found occupying sites by itself or in conjunction with Annosus root disease. Like Annosus root disease, and most of the potential mortality agents in this study, it is more likely to cause mortality in stressed trees. Armillaria root disease's functional role is in many ways similar to Annosus root disease or other root diseases. It creates larger "root disease centers" than Annosus root disease (Shaw and Kile 1991). These centers can often be identified from aerial photographs. Armillaria root disease colonizes new hosts by rhizomorphs, produces mycelial fans and fruiting bodies (mushrooms that can be consumed by wildlife) at the root collar (Shaw and Kile 1991). The rot often glows in the dark (Woodet al. 2003). Disease spread through spores is rare. Armillaria has not been shown to form mycorrhizal fungal associations with photosynthesizing plants, though it has been shown to have relationships of this nature with other non-photosynthetic plants (Shaw and Kile 1991).

Fir Engraver

The fir engraver beetle [*Scolytus ventralis* (Coleoptera: Curculionidae: Scolytinae)] is the insect most likely to be involved in red fir decline. Red fir is one of its principal hosts in California, the others being white fir and grand fir. Two other insects are associated with mortality in red fir forests; the roundheaded fir borer [*Tetropium abietis* (Coleoptera: Cerambycidae)] (Ferrell and Hall 1975) and the flatheaded fir borer [*Phaenops drummondi* (Coleoptera: Buprestidae)] (Bulaon and MacKenzie 2007). The roundheaded fir borer is found in *Abies* from Washington to California, often in conjunction with the fir engraver. It is generally found in trees that are weakened by drought and/or root disease (Wood et al.

2003). Though occasionally aggressive, the roundheaded fir borer is not known to become epidemic (Furniss and Carolin 1977), and not considered a major conifer pest (Goheen and Willhite 2006). The same can essentially be said of the flatheaded fir borer which is usually found in trees that also contain fir engraver, *Cytospora* canker infection, heavy dwarf mistletoe infection, root disease, signs of drought stress or a combination of some, or all, of these factors (Bulaon and MacKenzie 2007). Both these fir borers are limited to the lower, thicker barked areas of the tree and are usually not responsible for much mortality (Ferrell 1986a). As a result there is little research and no management actions focused specifically on these insects in red fir.

A number of researchers [Schowalter and Filip (1993), Parker et al. (2006) and Bulaon and MacKenzie (2007)] all noted that healthy trees can often fight off bark beetle attacks. FIA field crews commonly witness unsuccessful bark beetle attacks in healthy trees in California. Bark beetle attacks usually occur on stressed trees. The most critical stage in determining attack success occurs early in a tree's encounter with bark beetles (Raffa et al. 2008). If a tree is not significantly stressed, then resin flow is likely plentiful and a tree can likely defend itself against bark beetles and do so before aggregation pheromones attract other bark beetles. Bark beetles must surpass a threshold of resistance; the density of attacks against which a tree can defend, for establishment to be successful. Population eruptions occur when thresholds are surpassed and positive feedbacks are amplified across multiple levels of scale. However, bark beetle epidemics often do not occur even when appropriate host species are present, available beetle populations are present and ideal climatic conditions exist (Raffa et al 2008). Predators that are attracted by bark beetle pheromones can limit bark beetle success as can secondary bark beetles and wood borers. Bark beetles can be impacted positively or negatively by temperature and precipitation. Bark beetle populations often eventually control themselves as populations decline when all suitable habitat is consumed (Raffa et al. 2008).

Parker et al. (2006) describe how fire damage predisposed trees to bark beetle attack while Schowalter and Filip (1993) discussed how air pollution can make trees susceptible to bark beetle attack (as well being more susceptible to Annosus root disease). All experts agreed that drought (moisture stress) was a predisposing factor for bark beetle attack. Researchers [Schowalter and Filip (1993), Parker et al. (2006), and Bulaon and MacKenzie (2007)] conclude that forest pathogens are almost always found in conjunction with bark beetle attack. Schowalter and Filip (1993) noted that bark beetles transported spores of various pathogens that weaken tree defense systems against bark beetles. Fir engraver are associated with, and often carry the brown-staining fungus *Trichosporium symbioticum,* which can accelerate tree mortality in attacked trees (Berryman 1988). Dwarf mistletoe and Annosus root disease are commonly found in conjunction with fir engraver. Schowalter and Filip (1993) covered the traits of Annosus root disease (and to some extent *Armillaria* root disease) in great detail, and its interactions with fir engraver. They also elaborated upon how lightning and storm damage, poor soil and logging scars are common damages that predispose trees to bark beetles as well as Annosus root disease. Ferrell and Hall (1975) found that white fir mortality increased in years when one or more of the following occurred: the current year's spring precipitation was 32 percent below normal; the current year and the previous year's precipitation were eleven percent below normal; and, the current and two previous year’s radial growth declined by 2.5 percent. Oblinger et al. (2011) found a strong correlation between bark beetle related mortality and dry conditions in the previous three or four years. Schowalter and Filip (1993) found low density, highly diverse stands that were presumed to have existed prior to western settlement to be less likely to be attacked by fir engraver.

Parker et al. (2006) stated that prior to fire suppression becoming the norm in the west, “natural disturbance regimes from fire plus native pathogens and insects such as bark beetles appear to have functioned in a balanced manner and to create ecosystems that were resilient to perturbation” (Parker et al. 2006). MacKenzie (during personal communication with Bulaon, MacKenzie, Pronos, Cannon, 2009) noted one tree that had evidence of being attacked by bark beetles 7 times since 1850. Parker et al. (2006) described two occurrences that bark beetles (not specifically fir engraver) required in order to colonize fire-affected trees. First, in order for any colonization to occur there must be a population of bark beetles within flight distance of trees damaged by the fire. Second, the fire must occur at a time when the adult bark beetles are searching for new host trees. Adult fir engraver fly and bore into trees from June to September (Bulaon and MacKenzie 2007). Bark beetles also need a sufficient supply of undamaged inner bark in fire-damaged trees in order for there to be enough food to consume. In addition, the phloem may dry out if not attacked soon after a fire. An emerging concern is how bark beetle populations will respond (likely expand) to prescribed burning which is becoming a standard practice of forest managers (Parker et al. 2006).

Fir engraver requires a temperature of 24°C for flight and they will not fly during wind storms or in low light situations even if it is warm enough (Berryman 1988). Most beetles fly at crown height. Both resistant and susceptible trees are attacked, apparently at random. The density of attack, interactions with other organisms and the condition of the phloem on which the larvae feed dictates the number of offspring produced (Berryman 1988). The abundance of susceptible hosts (stressed or damaged trees) governs population size. If the number of susceptible hosts decreases, the fir engraver population will decrease since the fir engraver does not attack healthy trees (Berryman 1998).

Fir engraver abundance in red fir (as well as white fir) is a challenging topic because there are unavoidable flaws in data collection techniques in the FIA and FHP Aerial Survey monitoring programs. Since FIA protocol does not allow for destructive sampling, it can be difficult to see current fir engraver attack especially in its early stages or if the attack is unsuccessful. Bulaon and MacKenzie (2007) noted that fir engraver attacks are often difficult to confirm from the ground even with destructive sampling. Often, there is little evidence in the lower ten feet of the bole where it can be easily viewed in detail from the ground. Attacks are often only on the tops of trees (Wood et al. 2003). The horizontal egg galleries of fir engraver are very distinct and easy to identify when found either through destructive sampling or on downed wood. Bulaon and MacKenzie (2007) offered suggestions to help in recognizing fir engraver attack in the field. They noted that fir engraver will breed in slash and wind-thrown trees and will even attack green slash. Secondly “pitch tubes are not formed as they are with pine bark beetles; the usual evidence of attack is boring dust in bark crevices along the trunk and pitch streamers on the mid and upper bole” (Bulaon and

MacKenzie 2007). In addition, trees that are colonized early in summer often show signs of decline by early fall, whereas trees that are colonized later in the summer or fall often don't show signs of decline until the following spring or summer.

Due to the immense size of California and the aerial nature of the job, the FHP Aerial Survey cannot focus too intensely on the causes of mortality at a fine scale. They focus more upon accurately mapping and quantifying mortality. The FHP Aerial Survey found a 10-fold increase in fir engraver activity in California from 2008 to 2009 (Heath et al. 2009). Heath et al. (2010) reported that fir engraver and western pine beetle activity doubled from 2009 to 2010. They also reported that over half of all tree mortality in California in 2010 was due to the fir engraver. This suggests a dramatic increase in fir engraver activity. Ferrell (1986) stated that an estimated 1.2 million trees were killed by fir engraver in northern Californian national forests in 1977 and 1978. Wood et al. (2003) stated that extensive drought-related fir engraver mortality occurred in northern California from 1987-1992. It is not clear whether the high percentage of fir mortality (or damaged trees) noted by Heath et al. (2009 and 2010) should be attributed solely to the fir engraver. This is because fir engraver is always found in conjunction with at least one other stressor which results in lowered tree resistance (Ferrell 1986b; Furniss and Carolin 1977; Wood et al. 2003). Fir engraver is known to only successfully colonize weakened trees, so it is a great indicator of stressed trees. Since the other stressors (excluding fire) of red fir are usually more long term, they likely originated in a given stand first and may be more important when assigning mortality causes.

Unavoidable flaws in data collection techniques, make it difficult to determine the actual amount of fir engraver activity in red fir in California, but that it likely falls somewhere in the middle of the wide gap between FIA and FHP Aerial Survey estimations. This hypothesis is supported by FHP pathologist Martin MacKenzie's observation that fading crowns are a sure sign, though not the only sign, of fir engraver. Extensive field observations suggest this sign is substantially rarer in red fir than signs of forest pathogens commonly found in red fir stands. One reason for this may be that the life cycle of fir engraver is slower in cool temperatures (the life cycle takes two years above 6,000 ft in the Sierra Nevada where much of the red fir population exists) and faster in the warmer, lower elevations where white fir is found (Ferrell 1986a). Berryman disagrees however and stated that stands at high elevation were more likely to be attacked. Regardless, rising temperatures at higher elevations may enable the fir engraver life cycle to occur in only one year, leading to more fir engraver activity at higher elevations.

Research Questions

The three main questions of this study were; 1.) what are the current conditions and characteristics of red fir forests in California? 2.) Is mortality increasing in red fir and at what rate? 3.) What are the statistical and spatial patterns of red fir mortality and potential causal factors? For each of these questions, comparison with Jeffrey pine, white fir and lodgepole pine, which commonly occur with red fir, will increase the ecological context of the results.

METHODS

Field Methods

All field-collected FIA data used in this analysis were collected using standard FIA field protocol (USDA 2009). The data used are all from phase 2 (P2) plots. I visited many of these plots while working on an FIA field crew beginning in 2006. Photographs were taken in each cardinal direction on each of the four subplots on all plots I visited once the study had commenced (16 plots - less than proposed as a result of a major heath issue that severely limited field time in 2010). I spent additional time observing and recording insect and pathogen behavior on red fir plots I visited. This also occurred in red fir stands off of FIA plots with D. Shaw and other forest pathology professionals. I observed red fir forest health in popular recreation areas throughout California during the course of this study. I worked with other FIA field crews on improving insect and disease identification in fir stands.

Although most Forest Service research in California is conducted by the USFS Pacific Southwest Research Station, the FIA program for all of the west coast (including Alaska, Hawaii and the Pacific Islands) is based in the USFS Pacific Northwest Research Station in Portland, Oregon. FIA plot locations are systematically randomized (hexagonal grid over entire study area with one plot location in each 3,000 ha hexagon chosen at random) across all forested land, averaging one plot every 5.47 km (3.4 miles). This includes all types of land ownership including private, National Park Service and wilderness areas.

All land where FIA plots are located was classified as accessible forest land, non-forest land, water (there are two different water classifications) or non-sampled (this can be because access to a plot on private land was denied or because it is considered hazardous). All the area surveyed on each plot is classified as a condition. Many plots contained multiple conditions; if so then the boundaries between these conditions were spatially defined. Land that was classified as accessible forest land may be further sub-classified by reserve status (protected areas such as wilderness areas and national parks), owner group, forest type, stand size class, regeneration status or stand density. Once a condition was classified, additional information on its forest type, stand size, regeneration type, stand condition, stand age, stand structure, soil depth, historical treatments and historical disturbances was recorded.

Each one hectare (2.471 acres) circular plot contained four 0.101 ha (0.25 acre) circular macroplots. Each macroplot contained a smaller 0.016 ha (0.04 acre) circular subplot. On each subplot, a 0.001 ha (0.003 acre) circular microplot was installed where fuel loading measurements were recorded along with a seedling [diameter (DBH) < 2.54 cm or one inch)] count and a sapling (DBH between 2.54 and 12.7 cm or one and five inches) tree tally. A vegetation survey (species, height and percent cover) was performed on each subplot. Two 17.953 m (58.9 ft) coarse woody material (CWM) and ground cover transects were installed. A live and dead standing tree tally was recorded [trees 12.7 cm (5 inches) and greater on the subplot and trees 60.96 cm (24 inches) or greater on the remainder of the macroplot]. Tree diameters, heights, compacted crown ratios, crown class and a limited number of ages were recorded. Individual damages were recorded on each tree. Root disease was recorded with a severity rating (USDA 2009) and also mapped on the plot. Bark beetles were recorded with a severity rating as was branch flagging. Mistletoe presence was recorded using the standard dwarf mistletoe rating (DMR) system (Hawksworth and Weins 1996). Destructive sampling was not permitted on FIA plots and though most pests/pathogens could usually be identified without destructive sampling, there were times when identification was hindered by this restriction. Specific details on all FIA field measurement protocol are contained in USDA (2009).

Climate Variables

A ratio of estimated mean summer (May-September) temperature(°C) to mean summer precipitation (natural log mm) over an 18-year period for each plot location (SMRTP) was the variable primarily used to indicate drought stress (specifically moisture stress during the growing season) in this study. SMRTP was generated by intersecting plot locations with data from Daymet (Thornton et al. 1997; database at http://www.daymet.org/), a high-resolution (1 km grid) model developed for the USA from daily observations from ground-based meteorological stations, elevation data, topographic indices and statistical algorithms. Mean annual temperature (°C), August maximum temperature (°C) and mean annual precipitation (natural log mm), also generated from Daymet were used in some analyses.

Analysis

Plot Selection

In this study, plots were selected if 20% or greater of the standing live/dead tree tally was comprised of red fir/Shasta red fir [referred to as red fir (plots) unless otherwise specified]. The aim was to focus on plots where red fir was a significant part of the stand composition and avoid plots where its presence was more of an outlier. The same method was used for selecting Jeffrey pine, white fir and lodgepole pine plots to use for comparison with red fir. To ensure a sufficient sample for examining condition variables like stand density and stand age, plots where one condition class (USDA 2009) did not make up 60% or greater of the total plot area were removed from the study.

I chose to include Shasta red fir in the study was made for several reasons; first, the differences between red fir (occasionally called Sierra red fir) and Shasta red fir are slight (Barbour and Woodward 1985) and both were observed exhibiting the same insect infestations, pathogens and signs of poor forest health. Secondly, though proper identification of the two subspecies can often be accomplished through geographic location, there is the possibility of misidentification. Field identification between red fir and Shasta red fir is very difficult if no cones can be viewed (red fir cones are very rarely found on the ground). The main visual difference between the two is that the cone bract scales are visible and longer on Shasta red fir. It should be noted that Lanner (2010) has recently identified the southern end of the red fir distribution zone as being a new variety of red fir which he has named Critchfield red fir (*Abies magnifica* var. *Critchfieldii*). The newly proposed variety shares more characteristics with Shasta red fir than it does with red fir. Lastly, if there are unknown differences amongst the varieties that are related to this study, they will become apparent when the data are examined spatially.

Plot Level Mortality

The main measure of mortality and forest change in this study was proportion dead by species. The proportion of dead trees was calculated from basal area of live and dead (decay class 1 & 2) standing trees. Proportion dead was used because it provided a mortality value for each plot that could be used in statistical and spatial analysis. Proportion dead allowed for assigning a mortality value to the plots which had only been measured once (roughly 2/3 of the plots in this study). Comparing proportion dead between the first and second measurement (on plots with two or three measurements) accounted for the volume growth as well as mortality that occurred between the two measurements. Total basal area m^2/ha estimates were also used when appropriate. SAS (SAS Institute Inc., Cary, NC) was used to create the databases for this study. Proportion dead was calculated separately for the following three databases:

Most recent measurement (one measurement), all plots database

As of the end of the 2010 field season, all FIA plots in California had been installed using the current annual inventory plot design (excluding some plots that had issues that have not allowed them to be accessed yet, though it is very unlikely that this included any red fir plots). Of all the FIA plots in California, 304 of the plots were red fir plots. Although this “most recent measurement” database is a snapshot (data recorded at one moment in time and therefore not ideal for measuring change), it was the **most comprehensive** database used in this study because of the large number of plots and coverage of the state. The same methods were used for creating Jeffrey pine, white fir and lodgepole pine plot databases to be used for comparison with red fir plots. In all of the databases used in this study, white fir plots (n = 833) were the most plentiful followed by Jeffrey pine plots (n= 415) and red fir plots (n = 304), with lodgepole pine plots (n = 242) being the least abundant. Standard errors on all comparisons between species represent this disparity in sample size (species range and frequency).

Collective volume estimate database using plots that were measured three times

There were 86 red fir plots in California that were initially established in the 1990’s using the periodic plot design (USDA 2009) that were also measured and remeasured using the current annual design (i.e. a subset of the remeasurement database described next). The periodic plots have the same plot center as the current annual design, and some of the same trees were measured on the center subplot but the plot design was different so the data were not comparable at an individual plot level. There were, however, enough plots to allow for determining **collective** live/dead basal area (and therefore proportion dead) estimates between the three visits. This allowed for **measuring forest change over a longer period of time**. The same methods were used for creating Jeffrey pine, white fir and lodgepole pine databases of plots measured three times for comparison with red fir plots measured three times. The same calculation was done with plots experiencing fire as a disturbance within 30 years of the most recent measurement removed. These calculations were made again with both plots experiencing significant treatments within 30 years of the most recent measurement, and plots burned within 30 years of the most recent measurement removed. This was because treatments were considerably more common in the 1990’s (Christensen et al. 2008). All these calculations were generated for red fir as well as Jeffrey pine, white fir and lodgepole pine.

Remeasured plots database

Roughly 1/3 (n = 114) of the 304 red fir plots had been measured twice (remeasured) using the same exact (annual) plot design as of the end of the 2010 field season. The mean time between measurements was only 4.4 years because plots were installed on an accelerated cycle on all National Forest lands in California. Plots are usually measured on a ten year cycle in California. The same methods were used for creating Jeffrey pine, white fir and lodgepole pine remeasurement plot databases to be used for comparison with remeasured red fir plots. Proportion dead was calculated from this database in addition to the *collective volume estimate database* for two reasons. First; it contained more plots, and secondly; the data were more accurate since they came from plots that were remeasured using the exact same plot design (i.e. the exact same trees were measured). Examining proportion dead from the remeasured plots database allowed for **calculating (rather than estimating) the difference in proportion dead between the first and second plot measurements**, thus more accurately demonstrating how much volume growth and mortality had occurred between the two measurements. This measurement was also recalculated with plots burned within 30 years of the most recent measurement removed from the calculation.

Statistical Analysis of Red Fir Proportion Dead

Statistical analyses of red fir proportion dead were conducted using the most recent measurement, all plots database. Correlations between red fir proportion dead and the explanatory variables were estimated with linear regression models (Ramsey and Schafer 2002) (Table 1). Model fit was assessed with stepwise selection (producing an AIC value for each potential model) (Ramsey and Schafer 2002). In addition, numerous models were used and variables added/subtracted to find a model that both fit well and was ecologically logical. All important variables were plotted, transformed, displayed spatially and checked in order to build the optimal model. Interactions between red fir dwarf mistletoe and SMRTP, stand age, basal area density, elevation group, fire history and cutting history were tested. In addition, interactions between SMRTP and fire history, QMD and red fir percentage were tested. A logit transformation was applied to red fir proportion dead since it initially did not meet the assumption of normality.

The same methods were applied to a database with all plots burned within 30 years of their most recent measurement removed. Since recently burned stands are assumed to have a higher number of dead trees, I hoped that removing these trees would help uncover statistical significance between red fir proportion dead and other variables. The same methods were then also applied to a database with plots from the Mt. Shasta area removed.

Red fir forests in this area have very low proportion dead. I hypothesize that this may be because red fir dwarf mistletoe (and as a result, stress from the associated *Cytospora* canker) does not exist in this area. There was also minimal evidence of fire as a disturbance on red fir plots in the Mt. Shasta area. I aimed to determine if removing these "healthy" plots led to significant differences in the relationship between red fir proportion dead and other variables. S-Plus 8.1 was used for this analysis (TIBCO Spotfire S +, Palo Alto, CA).

GIS and Spatial Patterns of Red Fir Proportion Dead and Associated Variables

The most recent measurement all plots database were used for spatial analysis of red fir proportion dead. ArcGIS 9.3.1 (ESRI Redlands, CA) was used for all GIS analysis. The data were found to be not spatially autocorrelated using Moran's *I* test ($I = 0.01$, $P = 0.05$) (Cliff and Ord 1973). Every variable of interest was spatially displayed at the plot level. Patterns or lack thereof were noted and maps of significant patterns were created.

Plot Level Change in addition to Proportion Dead

Quantitative descriptions of change in red fir trees between measurement 1 and measurement 2 were calculated from the remeasured plots database**.** Annual basal area growth and mortality per species per plot between measurement 1 and measurement 2 were calculated and plot net gain/loss recorded. In addition, annual basal area growth and mortality per plot between measurement 1 and measurement 2 were calculated with plots burned within 30 years of the most recent measurement removed from the analysis. Plot net gain/loss was recorded. This was calculated to give an actual annual area gain/loss**.**

Changes in red fir trees between measurements 1 and 2 were described with simple means, standard errors and percentages. Some results were simply calculated for measurement 1 and measurement 2 whereas others were calculated as an annual rate of change. Where appropriate, results were additionally calculated with plots burned within 30 years of the most recent measurement removed from the calculation. Trees with mistletoe present at measurement 1 were grouped by DMR rating and the proportion of trees that had experienced mortality by measurement 2 in each DMR group was calculated.

Analysis of Individual Tree Level Mortality

An individual tree database was created from the remeasured tree database. All non-red fir trees in these plots were removed from the analysis. This database contained 2,387 red fir trees which were alive and large enough to be tallied at the first measurement. There were 3,098 red fir trees total at the second measurement [this included trees that were dead and ingrowth (trees that were large enough to be tallied at the second measurement that were not large enough at the first measurement)]. An annual mortality rate [(live measure 1/live measure 2)/time between measurements], generated from trees per acre (TPA) was calculated. Although FIA plots are designed to capture data that is representative of the forest, saplings and large trees are tallied on different sized sampling areas [2.07m (6.8 ft) radius microplot for saplings and 17.95 m (58.9 ft) radius macroplot for trees with DBH greater than 60.96 cm (24 inches)] on the same subplots. The majority of measurements are recorded on a 7.32 m (24 ft) radius area. TPA accounts for these differences in sampling area by assigning different weights to measured trees based on which sampling area they were selected (measured) from. Percent of standing tree tally dead at measurement 1 and at measurement 2, including and excluding plots experiencing significant fire in the last 30 years prior to measurement, were calculated by size class. Annual mortality rates by size class were also calculated.

A non-linear mixed model analysis of individual tree mortality was performed. This analysis, known in some disciplines as “survival analysis” (Harrell 2001) used non-linear mixed models with a logit response to identify the significance of variables on trees that were **live** at the initial measurement and **dead** at the second measurement (mean time between visits was 4.4 years) while accounting for the lack of independence of trees measured on the same plot by estimating plot-specific responses through a random-effects model (see Sheil et al. 1995 for calculation of annual mortality %) . Trees occurring on plots that had experienced fire within ten years of their most recent measurement were excluded from the models because having a model report a strong association between recent fire and mortality was not useful. In addition, it was a concern that this strong association might mask other significant associations. The difference in years between measurements was accounted for (the majority of plots were measured at five year intervals but some were not). Interactions between SMRTP, QMD and total damage were tested for significance. The best model was selected using AIC model selection. This analysis was performed using SAS (SAS Institute Inc., Cary, NC).

Individual Tree Level “Red Flagged” Damage Rating System

This rating system was designed to give each tree a total damage score. The damages and points are listed below:

- Dwarf mistletoe rating (Hawksworth and Weins 1996) of 2-4 **(1 point),** or rating of 5 or 6 **(2 points)**.
- Rotten/missing cull, greater than 20% of total estimated bole volume **(1 point)**, greater than 50% of total estimated bole volume **(2 points)**.
- Bark beetles-general, any severity (i.e. presence) **(1 point)**.
- Root disease-general/Annosus /Armillaria, severity 2 (signs/symptoms-**no** visible crown deterioration) **(1 point)**, severity 3 (signs/symptoms-visible crown deterioration, reduced terminal growth and/or stress cones) **(2 points)**.
- Stem decay-general, any severity (i.e. presence) **(1 point)**.
- Foliar pathogens-general, severity of 20% or greater of foliage/branches or code 2 (how this damage was occasionally coded from 2001-2004) **(1 point)**.
- Broken/missing top, **(1 point)**.
- Dead top, **(1 point)**.
- Unknown (describes damages that are likely actually the ones listed above), severity of 20% or more or code 2 (how this damage was occasionally coded from 2001-2004) **(1 point)**.

For example, a tree with a dead top (1 point) and a dwarf mistletoe rating of 3 (1 point) would have a “red flagged” score of 2. *Cytospora* canker was mistakenly included in DMR at times, coded under the foliar pathogen code or stem branch canker code in other instances, and likely ignored by some field crews.

The damage types were all damages that have repeatedly been observed in the field on red fir trees. Though the frequency of the different damages differed, white fir has been observed with the same damages, making this rating system appropriate for use on white fir (for comparison). The “red flagged” score system could not not be used on Jeffrey pine or lodgepole pine because the damage types they routinely experience differ somewhat from red and white fir. The score was also designed to capture the overall health of a tree even if specific damage coding (or the lack thereof) may not have been reliable.

Current Conditions and Characteristics of Red Fir Forests in California

The most recent measurement/all plots database was examined and all the FIA data variables (Table 1) thought to be relevant to this study were presented in the way deemed most effective for describing the current conditions of red fir in California. This was done by taking the plot means of variables and comparing them between red fir and white fir, Jeffrey pine and lodgepole pine. In other cases, categories of data and totals between the four species were compared. Red fir proportion dead was compared with white fir, Jeffrey pine and lodgepole pine proportion dead. This was repeated after plots burned within 30 years of the most recent measurement were removed. The variables presented include elevation, stand age, percentage of plots with stumps, stand condition/stage of development and percent of total trees containing dwarf mistletoe.

The (past) presence of wildfire on FIA plots was accounted for in three main ways and all three were examined. The first was a simple “evidence of fire” code which was assigned if there was any sign of fire at all. This included burnt wood, charred rocks, fire scars, old camp fires etc. The trouble with this method was that one old camp fire was weighted the same as a plot with a recent high severity fire. The second way was to look at fire scars on individual trees. This provides the most detailed data but many scars that were likely fire scars were identified, but not coded as being fire scars specifically. Identifying the exact cause of scars was not emphasized by the FIA. Fire that was significant enough to be classified as a disturbance was the optimal way to look at (relatively recent) fire history in FIA data. The exact estimated dates of fires were fairly rough, but the presence of fire was usually accurately recorded. As a result, my analysis primarily used fire coded as a disturbance to quantify fire history at the plot level.

RESULTS

Plot Level Mortality

Mean Plot Proportion Dead by Species

All FIA plots in California had been installed using the current annual inventory plot design (excluding some plots that had problems that had not yet allowed them to be accessed) as of the end of the 2010 field season. Table 2 represents the complete geographical range of red fir, Jeffrey pine, white fir and lodgepole pine in California. This was the **most comprehensive** view of the current condition of red fir, Jeffrey pine, white fir and lodgepole pine produced in this study. White fir proportion dead was slightly higher (0.123) than red fir proportion dead (0.115), although this trend reversed (as well as the proportion dead values decreasing) when plots experiencing fire within 30 years of measurement were removed from the analysis (RF = 0.097, WF = 0.092). However, the differences between red and white fir were slight and not significant at the 0.05 level. Removing plots that experienced fire within 30 years of measurement cut the Jeffrey pine proportion dead roughly in half (from 0.070 to 0.036), while the lodgepole pine proportion dead was not substantially altered (0.079 to 0.072).

Collective Volume Estimate Database using Plots that were measured Three Times

The plots measured three times database covered the **greatest amount of time** (up to 15 years), but had the smallest sample size (number of plots, n = 86) of the databases used in this study. During this time, red fir as well as Jeffrey pine, white fir and lodgepole pine all showed a trend of increasing mean plot proportion dead (Table 3). Jeffrey pine showed the greatest increase in mean proportion dead. With the exception of lodgepole pine, these increases were statistically significant at the alpha 0.05 level. Removing the plots burned within 30 years of the most recent measurement from the analysis decreased the proportion dead of all species noticeably (Table 3). Lodgepole pine showed no increase in mean proportion dead (0.077 to 0.073). White fir showed only a minimal increase (0.101 to 0.113). Red fir (0.077 to 0.095) and Jeffrey pine still showed consistent, increases in mean proportion dead, especially Jeffrey pine (0.006 to 0.040). However removing the plots burned within 30 years of the most recent measurement from the analysis led to low statistical power and results not significant at the alpha 0.05 level. Since silvicultural treatments were more common in all four species in the 1990's (Christensen et al. 2008), the mean proportion dead was also calculated with plots receiving treatments within the last 30 years removed from the analysis. The results followed the same trends as they did with all the plots included in the analysis. The mean plot proportion dead **for only** the silviculturally treated plots was only minimally different than the mean proportion dead of all the plots.

Remeasured Plots Database

The remeasured plots database had a larger sample size (number of plots, n = 114) than the one used above, but covered a shorter amount of time. It also offered **greater accuracy** since the plots were remeasured using the exact same plot design. Despite these differences between the two databases, the results, not surprisingly, followed the same trends. The mean plot proportion dead increased in red fir (0.090 to 0.120) as well as in Jeffrey pine (0.056 to 0.084), white fir (0.106 to 0.140) and lodgepole pine (0.076 to 0.094). In this database with two measurements, Jeffrey pine's mean proportion dead did not increase as drastically. Removing the plots burned within 30 years of the most recent measurement from the analysis had the same effect of noticeably decreasing the mean proportion dead for all four species. The mean proportion dead for lodgepole pine actually decreased slightly between measurement 1 and measurement 2 (0.079 to 0.074) with the plots burned within 30 years of the most recent measurement removed. With these plots removed, the mean plot proportion dead still increased in red fir (0.082 to 0.094), Jeffrey pine (0.024 to 0.034) and white fir (0.085 to 0.100). However, when combined with high levels of variability, the increases in proportion dead by species in this database were not great enough to be statistically significant at the alpha 0.05 level.

Statistical Analysis of Red Fir Proportion Dead

The most noteworthy result from our analysis at the plot level was the lack of a good predictive model and the lack of statistical significance of most variables tested. SMRTP (estimated 18 year mean ratio of mean temperature to mean precipitation, May–Sep at each plot location) never met the criteria ($P = 0.05$) for model inclusion and was never in top 3 AIC models which was surprising. In the best model (i.e. with the lowest AIC value) dwarf mistletoe rating was positively correlated ($P = 0.03$) with red fir proportion dead (logit transformed) (Table 4). Basal area density was negatively correlated ($P = 0.047$) with red fir proportion dead (logit transformed) meaning less dense stands had a higher proportion of dead red fir trees (Table 4). The results did not change significantly when the plots burned within 30 years of most recent measurement were removed from the analysis. Dwarf mistletoe's *P*-value remained at 0.03 and the basal area density *P*-value increased to 0.058. Dwarf mistletoe was no longer significant when red fir plots in the dwarf-mistletoe-free Mt.

Shasta area were removed from the analysis. Basal area was negatively correlated with a *P*-value of 0.027 as was QMD (quadratic mean diameter) (*P* = 0.024).

Spatial Patterns of Red Fir Proportion Dead and Associated Variables

Other than a cluster of low values in the dwarf-mistletoe-free Mt. Shasta area, there was little spatial pattern in red fir proportion dead other than the area burned by the 2008 lightning-ignited Trinity Alps Complex fires (Figure 3). There was also no spatial pattern in stand condition/stage of development, treatment history, percent red fir (of each plot), south facing plots, fire history, basal area density, QMD and soil rooting depth. Land ownership group and plot elevation group follow expected patterns. Most red fir plots were on National Forest Service land, the plots on National Park Service land stand out, the one state/local government land plot can be seen in the Lake Tahoe area and red fir plots only fall on private industry land in the north half of the state (Figure 4). The elevational distribution of red fir plots showed most plots falling below 7,000 feet in the north half of the state and most falling above 7,000 feet in the south half of the state (Figure 2).

Displaying SMRTP (estimated 18 year mean ratio of mean temperature to mean precipitation, May–Sep at each plot location) spatially showed less drought stress in the northern part of the red fir distribution range in California (Figure 5). This area did not correlate with plots with high red fir proportion dead which were dispersed throughout the red fir distribution range. Mean dwarf mistletoe rating by tree by plot was also fairly spatially dispersed (Figure 6), other than in the Mt. Shasta area where it was virtually non-existent. One plot had red fir dwarf mistletoe which was not known to occur in the area, but this observation was not confirmed so it was not known if there really was an isolated occurrence of dwarf mistletoe or if this was an error.

Plot Level Change in addition to Proportion Dead

I calculated mean annual increase in basal area due to growth and mean basal area lost to mortality per plot between measurement 1 and measurement 2 (with and without plots burned within 30 years of the most recent measurement) from this database. This result was calculated as an annual rate (Table 5). Although overall mortality was increasing, mortality did not occur on many plots. As a result, the differences in mean mortality were not statistically significant at the alpha 0.05 level whereas differences in mean growth were. The results followed the trend shown in the proportion dead by species (Table 2) of mortality being greater than growth, and of this trend lessening when plots that experienced fire as a disturbance within the last 30 years were removed from the analysis (Table 5). These results differed from my proportion dead by species analysis in that white fir stands appeared to be losing less total volume. After the plots burned within the last 30 years were removed from the analysis, white fir, along with Jeffrey pine, was gaining volume. Red fir and lodgepole pine, the two species with the higher mean elevations in the study were still losing volume after the plots burned within 30 years of the most recent measurement were removed (Table 5). This trend for lodgepole pine contradicts the proportion dead by species results for lodgepole pine which showed lodgepole pine proportion dead not increasing once plots burned within 30 years of the most recent measurement were removed.

Analysis of Individual Tree Level Mortality

Mortality based on all remeasured red fir trees occurred at an annual rate of 2.64% and 2.48% after the plots burned within 30 years of most recent measurement were removed (Table 6). Mortality in red fir occurred at an annual rate of 1.61% in trees with DBH ≥ 60.96 cm (24 inches), 1.78% in trees with DBH 12.70-60.95 cm (5-23.9 inches) and 3.42% in trees with DBH 2.54-12.69 cm (1-4.9 inches) (saplings) (Table 6). However, after the plots burned within 30 years of most recent measurement were removed, mortality occurred at slightly higher annual rate, 1.33%, in trees with DBH ≥ 60.96 cm (24 inches) than in trees with DBH 12.70-60.95 cm (5-23.9 inches) (1.15%) (Table 6).

Calculating the percentage of individual standing red fir trees that were dead, produced higher values [16.9% of trees with DBH 12.70-60.95 cm (5-23.9 inches) and 19.9% of trees with DBH ≥60.96 cm (24 inches)] than when proportion dead was calculated by plot (although these percentages should not be directly compared to proportion dead) (Table 7). Roughly 18% of red fir trees equal to or greater than 60.96 cm (24 inches) DBH were dead after the plots burned within 30 years of most recent measurement were removed. It is important to note that the mean DBH of a standing dead (62.74 cm or 24.7 inches) red fir tree was larger than the mean DBH of all live (54.36 cm or 21.4 inches) red fir trees. The percentage of trees with a DBH of 12.70-60.95 cm (5-23.9 inches) that were dead did not change significantly between measurement 1 and measurement 2 once plots burned within 30 years of the most recent measurement were removed.

The non-linear mixed model analysis found increased SMRTP (18 year mean ratio of mean temperature to mean precipitation, May–Sep at each plot location) values to be a significant factor in predicting individual tree mortality (Table 8) (SMRTP was not statistically significant in plot level analysis with red fir proportion dead). QMD was also a significant predictor ($P = < 0.05$) of individual tree mortality (QMD was found to be statistically significant in other analysis techniques used in this study). There was a clear linear relationship between annual mortality percentage (Sheil et al. 1995) and increased SMRTP and decreased QMD (i.e. stands of smaller trees) (Figure 7). Substantial stem rot and trees with dead tops were also significant predictors (P values $= < 0.05$) of individual tree mortality. It is important to note that these two factors were not causes of mortality but rather signs of a declining tree.

Individual Tree Level "Red Flagged" Damage Rating System

Approximately 21% of trees with a damage score of 4 (the highest score any tree obtained) experienced mortality in the 4.4 (average) years between measurement 1 and measurement 2. The percentage of trees experiencing mortality with damage scores of 3 (17%) and 2 (19%) was similar. Roughly 10% of trees with a damage score of 1 experienced mortality between measurement 1 and measurement 2. Although an increased number of damage types on a tree increased chances of mortality, 79% of trees with a damage score of 4 (the highest score that any tree obtained) did not experience mortality between measurement 1 and measurement 2. This may simply be because even red fir trees with many types of damage usually take longer than 4.4 years to experience mortality.

Approximately 6% of trees with no damages at measurement 1 were dead at measurement 2. Some of this mortality of trees without damage is a result of fire. Quality control issues that kept damage scores lower than they should have been or absent all together (a score of zero) hindered how well the "red flagged" damage ratings could predict mortality. However, this model showed that an individual red fir was roughly twice as likely to have three significant damages or more than an individual white fir. The mean "red flagged" damage rating per tree, per plot shows, roughly the difference between the intensity and consistency of damages on red and white fir (Table 9). The total damage score was also shown to be a significant predictor of individual tree mortality if included in the non-linear mixed model analysis.

Current Conditions and Characteristics of Red Fir Forests in California

Jeffrey pine, white fir and lodgepole pine were selected to be used for comparison with red fir because they are the species that red fir is most commonly found co-inhabiting sites with (if it is not growing in a pure stand). However, the mean elevations of the four species (plots with ≥ 20% basal area composition of a given species) were significantly different (Table 10). The difference in mean elevation between white fir [1733 m (5816 ft)] and lodgepole pine [2544 m (8345 ft)] was 771 m (2529 ft) with red fir [2206 m (7236 ft)] and Jeffrey pine [1944 m (6377 ft)] falling in the middle.

Treatments on red fir and lodgepole pine forests were virtually non-existent over the last ten years. Only one remeasured red fir plot (n = 114) had red fir trees on it that were harvested between measurement 1 and measurement 2. Timber harvesting on National Forest lands decreased dramatically during the 1990's (Christensen et al. 2008). The harvesting of red fir, Jeffrey pine, white fir and lodgepole pine followed this trend since more than 70% of red fir, Jeffrey pine, white fir and lodgepole pine plots in this study were located on National Forest land. In the 30 years prior to each plots most recent measurement, 21% of red fir plots experienced at least one treatment while 24% of Jeffrey pine plots, 37% of white fir plots and 9% of lodgepole pine plots experienced treatments during this time. The mean stand age by species reflected these trends with lodgepole pine having the oldest mean stand age at 157 years. Lodgepole pine was followed closely by red fir (145 years), Jeffrey pine (113 years) and white fir (111 years) in mean stand age (Table 11). Plots with stumps roughly (some stumps may result from incidental cutting) captured the presence or absence of treatments. White fir had the highest percentage of plots containing stumps (61%) followed by Jeffrey pine (50%), red fir (37%), and lodgepole pine (21%) (Table 12).

An important difference between red fir and the three other species used for comparison in this study was that 44% of red fir stands were made up of predominantly large, old trees [old growth or large sawtimber stands where the average stand diameter exceeds 60.96 cm (21.0 inches) DBH] (Table 13). Only 19% of lodgepole pine fell into these two categories of stand condition/stage of development, while 24% of Jeffrey pine and 27% of white fir fell into these two categories. This contributed to red fir having significantly higher mean live basal area (m^2/ha) of species by plot (Table 14). This was not a result of mean species percent (composition) by plot of the four species varying dramatically as all four species had similar mean species percent (composition) by plot. Red fir also had the highest mean **dead** basal area of species by plot (13.96), but the gap between it and the other three species was much smaller.

As previously mentioned, quality control issues limited the effectiveness of insect and disease disturbance data in this study. These data were examined and used when possible but only limited conclusions were drawn. Mean per tree, per plot DMR ratings were likely low on red fir, but despite this, 19% of the total tallied red fir trees examined in this study (including saplings between 2.54 and 12.70 cm or 1 and 5 inch DBH) contained dwarf mistletoe (Figure 8). Based on comments by Bulaon and MacKenzie (2009), I hypothesized that this number should be at least 25% or higher. Jeffrey pine, white fir and lodgepole pine all had totals considerably under 10%. Clearly dwarf mistletoe has a much greater role in red fir ecology than it does in the ecology of the other species examined in this study.

Red fir, like Jeffrey pine, white fir and lodgepole pine all had more fires coded as disturbances during the 10 years prior to most recent measurement than they did between 10 and 30 years before most recent measurement (Table 15). It is likely that a low number of fires that should have been classified as disturbances were missed between 10 and 30 years prior to plot measurement. However, because this period was twice the length of the 10 years prior to measurement, I assumed that the number of fires occurring was increasing for all four species. All four species had the most fires coded as disturbances 30 years prior to measurement. This was expected since this represents a much longer time period. The percentage of total plots that had fires coded as disturbances showed Jeffrey pine plots as having the highest fire occurrence followed by white fir, red fir and lodgepole pine (Figure 9).

The percentage of plots by species with at least one tree with a fire-scar coded followed the same pattern. The FIA "evidence of fire" code by species showed red fir having a lower occurrence (56% of plots) than lodgepole pine (61% of plots) followed by white fir (71% of plots), while Jeffrey pine remained the highest (74% of plots). This may accurately reflect that lodgepole pine likely experienced stand replacing fires (that are sometimes difficult to recognize well after they occurred) more frequently than red fir. Often there were some signs of charring and as a result evidence of fire was coded but not "fire as a disturbance". It should be noted that the California population of lodgepole pine, likely does not experience fire as frequently as much of its range in the western U.S., which grows at much lower mean elevations (Sugihara et al. 2006).

Author's Field Observations on Personally-Visited Red Fir Plots during the Course of the Study

There were three main inconsistently documented observations that I continually witnessed in the field. D. Shaw and other forest health professionals that I worked with in the field noted the same observations, but none of the observations have been properly documented in peer reviewed documents. The first was that red fir dwarf mistletoe and *Cytospora* canker were **strongly** associated. *Cytospora* canker was present on every plot (100%) I recorded red fir dwarf mistletoe on. The second key observation was that Annsus root disease was almost always present on plots with stumps. I found Annosus conks on 90% of plots with stumps. The third observation was that fir engraver activity was not overly widespread. I found evidence of fir engraver on only 10% of the plots.

DISCUSSION

Mortality is increasing in red fir. The rate at which mortality increased during this study varied depending on which analysis approach was used and decreased if recently burned plots were removed from the analysis. The most fine-scaled analysis (which was unfortunately not the most comprehensive), from the individual tree database, showed an increase in percent of total red fir trees that were dead ([14.8% to 16.9% of trees with DBH 12.70-60.95 cm (5-23.9 inches) and 16.6% to 19.9% of trees with DBH ≥60.96 cm (24 inches)] and an annual mortality rate of 2.64%. The live/dead collective volume estimates from three plot visits (the database that covers the longest period of time) also suggest increasing mortality. Red fir proportion dead was increasing in all analyses suggesting that at the very least, a short-term decline was occurring. Crown class and basal area density were not significant predictors of individual tree mortality and the mortality rates were greater in trees DBH ≥60.96 cm (24 inches) than in trees with DBH 12.70-60.95 cm (5-23.9 inches) when plots burned within 30 years of most recent measurement were removed. This suggests that the increased mortality was not simply due to suppression. The rate at which mortality was increasing was not drastic, yet one out of every five standing red fir trees DBH ≥60.96 cm (24 inches) or greater in California is currently dead. Mortality is also increasing in Jeffrey pine, white fir and lodgepole pine. However, over a recent five year period growth exceeded mortality in white fir and Jeffrey pine but the opposite was true in red fir and lodgepole pine (after plots experiencing fire within 30 years of measurement were removed from the analysis). Continued monitoring of red fir mortality is needed and the FIA program provides a great dataset for accomplishing this.

The results support recent studies that report increased tree mortality (van Mantgem at al. 2009; van Mantgem and Stephenson 2007) though our approach and study limitations differed from these studies. This study covered a substantially shorter timeframe than van Mantgem at al. (2009) and van Mantgem and Stephenson (2007). However, this study had greater plot density, spatial coverage and systematically randomized plot locations. My analysis included stands of all stages of development where as the van Mantgem-led studies included only unmanaged old growth stands. The van Mantgem-led studies concluded that increased mortality was climatically driven after accounting for every non-climatic variable that could potentially cause mortality. The approach used in this study was to quantify mortality on each plot and see which variables (including climate) were consistently correlated with mortality. The key variables that related to mortality were fire, climate change/drought, red fir dwarf mistletoe, *Cytospora* canker, Annosus root disease, fir engraver, forest management and air pollution. Rather than accounting for past forest management and disturbances as a method of identifying climatically induced mortality, I used past management activities and disturbances as variables to test for correlation with mortality. Although the approach used in this study was less optimal for classifying climate-driven and long-term mortality, it aimed to describe what caused mortality in stands of all stages of development and therefore represented the entire red fir distribution zone in California.

Fire

When plots burned within 30 years of most recent measurement were removed, the reduction in red fir proportion dead was substantial. Although this study was not focused on tracking fire history, our results showed a trend of increasing fire occurrence (and the associated mortality) in red fir as Miller et al. (2008) and Westerling et al. (2006) also suggested. The data also showed a trend of increased percentage of the **total** proportion dead originating from plots that **had** experienced fire within 30 years of the most recent measurement. However, since it can be assumed that mortality results from the occurrence of fire, statistical correlation between recent fire occurrence and mortality was only minimally useful. The extent to which forest insects and diseases were exacerbated by the increase of damaged/stressed trees that resulted from the occurrence of fire was dependent on fire severity and was not clear (Ferrell 1996). As a result, many analyses in this study were performed both with and without plots having burned within 30 years of the most recent measurement. This allowed for the measurement of the influence of fire in red fir mortality and to examine decline with the effects of fire excluded.

Fire-related mortality in the context of decline was not interpreted uniformly. Increased mortality due to fire does fall into what SAF calls decline, that being the “decrease in trees, shrubs, and herbs, or forest health and vigor, caused by one or more biotic or abiotic factors” (www.safnet.dreamhosters.com 2009). Despite this, most pathologists and entomologists would not consider increased mortality due to fire to be decline. Manion (1981) did not include fire or the effects of fire in his decline spiral. Van Mantgem et al. (2009) and Crimmins et al. (2011) both sought to eliminate fire as a cause of their results.

Interestingly, Kliejunas et al. 2009 noted that the forested area annually impacted by pathogens and insects in the U.S. was roughly 45 times the area affected by fire and the economic impact was almost five times as great. Regardless of how fire is viewed in the context of decline, the end result is that an increasing proportion of red fir forests are dead.

When plots experiencing fire within 30 years of measurement were **removed** from the analysis, there was still an increasing proportion dead for all the species in the study with the exception of lodgepole pine. The increases, however, were much smaller than with all the plots included in the analysis. As expected, a higher percentage of the mortality that occurred in white fir and Jeffrey pine (the two species with the lowest mean elevations), could be attributed to fire than in red fir or lodgepole pine. Increased fire, as reported by Westerling et al. (2006), is likely in part climate driven but it is difficult to quantify how much of this increase is a result of increased fuel levels and disrupted fire regimes as a result of fire suppression. Increased fire occurrence would reduce fuel levels and lower mean stand density which would be beneficial in many forested areas of California. It is less clear if this would benefit high elevation forests where fire regimes are believed to be less altered by fire suppression policies (Erman and Jones 1996). Miller et al. (2008) reported an annual increase in burned area only in wetter, higher elevation forests which suggests a strong correlation between fire severity and climate change for red fir. The increasing amount of standing dead and recently fallen red fir trees found in this study could contribute to increased fire severity due to increased fuels and fuel continuity.

Climate Change/Drought

There were no statistical or spatial correlations at the **plot level** with red fir proportion dead and SMRTP (estimated 18 year mean ratio of mean temperature to mean precipitation, May–Sep at each plot location) , the variable used in this study to indicate drought stress. There was also no correlation between red fir proportion dead and mean annual temperature, August maximum temperature or annual precipitation. This lack of correlation was surprising because almost all forest pathogens and insects are exacerbated by drought stress and red fir forests have a high proportion of trees with significant pathogen/insect damage (Ferrell 1996). This result supports Oliver's (1982) data suggesting that red fir benefits from the longer growing season occurring in years when there is less snowpack more than it is hindered by lack of moisture. Following this logic, it may be that the additional growth occurring in red fir during dry periods may offset the increased mortality that results from the higher insect and pathogen levels found in dry years. However, SMRTP was significant in the non-linear mixed model analysis of **individual tree** mortality, suggesting a correlation between moisture stressed sites and mortality. It is unclear why SMRTP was a significant predictor of individual tree mortality while no climate variable was significant at the plot level. Since the individual tree database was our most fine scaled database, this suggests that more analysis of red fir mortality and drought stress should be conducted once all the plots have been remeasured.

Mortality related to drought stress has been shown to be correlated to consecutive years of drought conditions (Gaurin and Taylor 2005; Oblinger et al. 2011). Examining per plot mean mortality by year measured yielded insignificant annual differences and the number of red fir plots measured each year was not large enough to properly make comparisons annually. More complex options using remeasurement data exist for examining correlations between mortality and consecutive years of drought conditions. However, there were not consecutive years of **severe** drought from 2006-2010 when remeasurement data were collected or in 2004 or 2005 which might have shown up in 2006 data (there were consecutive years of moderate drought and 2007 was exceptionally dry).

Red Fir Dwarf Mistletoe & *Cytospora* Canker

Red fir dwarf mistletoe was the most significant factor in red fir mortality and decline based on our field observations and statistical analysis. Dwarf mistletoe rating was positively correlated ($P = 0.03$) with red fir proportion dead (logit transformed). The frequency that dwarf mistletoe occurs in red fir was significantly higher than in other species in this study with 19% (and likely a higher number in actuality since Bulaon and MacKenzie hypothesize that DMR ratings in red fir are consistently low) of live red fir trees containing dwarf mistletoe, while only 8% of live Jeffrey pine (the next highest species) trees contained dwarf mistletoe. There was a significant difference ($P = 0.02$) in red fir proportion dead between the Mt. Shasta area where dwarf mistletoe does not occur (0.04 red fir proportion dead) and the rest of the red fir distribution zone (0.12 red fir proportion dead).

Red fir dwarf mistletoe also does not occur in the southeastern Sierra Nevada, but there were not many red fir plots located there because there is only a narrow band of suitable elevation for red fir due to the steep nature of the eastern slope of the Sierra Nevada. Although there were not enough plots to conclude that the southeastern Sierra

Nevada red fir populations have low red fir proportion dead values, the author has observed that these populations had low amounts of dead red fir trees and good forest health. The southeastern Sierra Nevada red fir populations are likely more similar genetically to Shasta red fir (Lanner 2010), yet it does not appear that Shasta red fir is more resistant to dwarf mistletoe because northwestern Californian populations of Shasta red fir are significantly impacted by dwarf mistletoe and show the same signs and symptoms of poor forest health as red fir in the Sierra Nevada. It should be noted that the northwestern populations are infected by *A. abietinum* subsp. *wiensii* (Mathiasen 2009) rather than *A. abietinum* f. sp. *magnificae* which infects red fir in the Sierra Nevada and Lassen Volcanic National Park. The FIA plots in the Mt. Shasta area contained minimal evidence of fire which may slightly contribute to the low red fir proportion dead there. However, the majority of the Mt. Shasta area red fir population grows in pure stands. Pure stands are usually assumed to be more vulnerable to insect and pathogen damage (Bulaon and MacKenzie 2007), which theoretically should increase red fir proportion dead, as species diversity often limits insect and pathogen damage. The theory that increased insect and pathogen-caused red fir mortality is natural population regulation appears flawed when witnessing the dense and extraordinarily healthy and vibrant Mt. Shasta area red fir population.

One reason red fir dwarf mistletoe is significantly detrimental to red fir forest heath is that it is almost always accompanied by *Cytospora* canker. Although *Cytospora* canker is considered a weak pathogen (Scharpf and Bynum 1975; Goheen and Willhite 2006), my observations indicated that *Cytospora* canker was almost always present (and often widespread) in trees infected with red fir dwarf mistletoe. *Cytospora* canker is known to enter red fir branches through small wounds in the bark left by dwarf mistletoe shoots and/or insects (Wood et al. 2003), but it is unknown if it is present in red fir trees that do not contain dwarf mistletoe. Signs or symptoms of *Cytospora* canker were not observed in dwarf mistletoe free trees in this study. Lab testing for *Cytospora* canker in red fir trees that do not contain dwarf mistletoe would greatly increase the understanding of the relationship between these two pathogens. The presence of both these pathogens appears to cause significant stress on red fir trees and based on field observations, exacerbates Annosus root disease damage.

Annosus Root Disease

Field observations indicated that Annosus root disease was very widespread in red fir forests. FIA root disease data in California has substantial quality control issues, and although these data are improving, it is not currently reliable enough to draw conclusions from. Increasing field trainings and well as less employee turnover would continue to improve the data quality as would improved QA/QC on government contracted plots. The presence of Annosus root disease in red fir stands is not a new occurrence (Slaughter and Parmeter 1989), but field observations suggest that it is now becoming more common than the 4% of total live fir trees reported from 1979-80 (Slaughter and Parmeter 1989). I found Annosus root disease in almost every stand where there was evidence of past cutting (i.e. stumps), yet there was not a strong statistical correlation between red fir mortality and the presence of stumps on plot. Though it seems likely that Annosus root disease is significantly less common in red fir stands with no cutting history, the regularity in which it occurs in these stands statewide is unknown. A study focused specifically on the occurrence of Annosus root disease across the red fir distribution zone is needed.

There was a substantial difference in the appearance of stands that contained Annosus root disease between stands with and without red fir dwarf mistletoe. Annosus root disease was found in stumps throughout the Mt. Shasta area (where dwarf mistletoe does not occur on red fir) and yet there was very seldom mortality in adjacent trees as is the norm in most of the red fir distribution range. This observation suggests that other tree stressors (especially red fir dwarf mistletoe with its associated *Cytospora* canker) may need to be present in order for Annosus root disease related mortality to reach levels that would warrant concern. There is little recorded evidence of Armillaria root disease (again FIA root disease data suffered from quality control issues) in the FIA plots. Armillaria root disease usually does not occur above an elevation of 2,000 m (6,500 ft) (Wood et al. 2003) and as a result, is usually found in red fir stands mostly in northern California where red fir more commonly grows at or below this elevation.

Fir Engraver

The techniques used to quantify fir engraver activity by both FIA and FHP Aerial Survey are lacking in accuracy. Both organizations realize the limits of their data, but the end result is that the actual amount of fir engraver activity in California is unknown. Since fir engraver is known to typically colonize (successfully) weakened trees (Berryman 1988), it is a great indicator of stressed trees. The 2009 and 2010 FHP Aerial Survey results (Heath et al.

2009; Heath et al. 2010) indicate that there is a the considerable quantity of stressed fir trees in California (their results combine red fir and white fir). Additional work is needed to accurately determine the amount of fir engraver activity in red fir in California.

The extensive fir engraver mortality that occurred in northern California in 1977 and 1978 (Ferrell 1986a) and 1987-1992 (Wood et al. 2003) was drought related. Unfortunately red fir and white fir are usually not separated in reports of fir engraver-caused mortality. It is possible that much of the reported fir mortality is actually white fir. In addition, I have not witnessed fir engraver occurring in the field as consistently as red fir dwarf mistletoe or Annosus root disease. For these reasons, and because fir engraver is not usually considered one of the more aggressive bark beetles (Furniss and Carolin 1977), I don’t (currently) consider it one of the most significant threats to red fir forest health although more research is needed.

Influence of Forest Management

In this study only one remeasured red fir plot (n = 114) had evidence of harvest activities during 2005-2010. Evidence of harvesting was documented on 30 remeasured white fir plots (n = 281), suggesting considerably more frequent timber harvest of white fir than red fir. Prescribed fire in red fir forests is not common. As a result it appears that little active management is occurring in red fir. The lack of management aimed at improving forest health as well as past management activities does help shape the current condition of red fir forests.

Forests where fire is suppressed that are usually presumed to be denser than they would have been historically (Sugihara et al. 2006). However, both QMD and basal area density were negatively correlated with red fir proportion dead. Some of this correlation may be because plots with high red fir proportion dead are now less dense since mortality has been occurring for some time (perhaps from Annosus root disease which kills trees over a long period of time). The *P*-value representing basal area density increased slightly when plots experiencing fire within 30 years of most recent measurement were excluded from the analysis. This implies that plots that experienced significant mortality due to fire often have a high red fir proportion dead value as well as low basal area density, which would be expected in a burned stand. Another possible explanation for this negative correlation is that denser stands represent better sites. Red fir trees may, despite competition, be able to grow faster than the upward expansion of dwarf mistletoe on these sites (Scharpf and Parmeter 1976). Therefore, the red fir proportion dead values may be relatively low even though there is noticeable red fir dwarf mistletoe infection in the stand. In addition a limited number of trees experiencing mortality due to insects/diseases will not lead to high plot proportion dead values when there are initially many live trees. The lack of correlation between QMD/basal area density and red fir proportion dead, the ability of red fir stands to naturally maintain unusually high densities and the fear of spreading Annosus root disease through cutting associated with thinning (assuming Borax is not being applied), makes it unclear if thinning really is beneficial in red fir stands.

Air Pollution

Initially it was hypothesized that red fir mortality could be tied to air pollution since the west-side, southern Sierra Nevada is one of the most at-risk forested areas in the entire US (Bytnerowicz et al. 2003; Campbell et al. 2007; Jovan 2008). Bernal-Salazar et al. (2004)reported a lessening of annual tree ring width in sacred fir (*Abies religiosa*) (which inhabits sites with characteristics similar to where red fir occurs) in the Mexico City basin that began in the 1970's, which they suggested may have been caused by air pollution. However, red fir is not believed to be at risk in California because true firs are generally not considered to be greatly affected by ozone pollution (Bytnerowicz et al. 2003; Cannon, Bulaon, MacKenzie, Pronos, personal communication 2009) and because red fir grows at a high enough elevation so that the amount of air pollution reaching it is minimal (Jovan 2008). There is a knowledge gap concerning how air pollutants other than ozone may affect red fir. However, there was no spatial correlation between red fir mortality and the west-side southern Sierra Nevada, and therefore air pollution is not likely a significant factor in increased red fir mortality.

Study Limitations

The foremost shortcoming of this study was that it did not cover a long enough period of time. It is possible that the analysis captured part of a short term cycle rather than long term decline. Red fir stands showing signs of poor forest health is not a new phenomenon as stands exhibiting signs of poor forest health were reported in the 1960's and 1970's (Ferrell 1980; Scharpf and Parmeter 1976; Scharpft and Parmeter 1967; Slaughter and Parmeter 1989). Continued monitoring of the red fir population will be necessary in order to determine if this trend of increased mortality continues. The FIA program provides a great dataset for accomplishing this.

The use of multiple databases was the result of only one third of FIA plots in California having been installed and remeasured (as of Fall 2010). Multiple databases allowed us to spatially and statistically cover the red fir distribution range as thoroughly as possible, use the largest sample size available and examine plots over the longest time period possible. Unfortunately, conducting analyses using multiple databases produced results with varying levels of confidence that were not optimal for comparison. Once all California FIA plots have been remeasured, analysis would be considerably more straight forward and robust. One plot level database could be used and more analyses could be conducted at the individual tree level to ensure that accuracy is not sacrificed to averaging.

Quality Control

Quality control issues with measures of forest health limited the ability to accurately access the quantity of insects and forest diseases in red fir forests statewide. This was less of a problem with red fir dwarf mistletoe because, based on field observations; it was usually under-coded during DMR assessment but not missed altogether. FIA does not require binoculars to perform DMR scoring, and though using binoculars to perform DMR scoring is uncommon in forestry, it is likely necessary to accurately assess dwarf mistletoe in red fir. Dwarf mistletoe does not cause significant brooming in red fir which makes it hard to assess with the naked eye, especially on higher branches. High branches are abundant in red fir because tall, old growth and large sawtimber-sized [average stand diameter of each condition must exceed 60.96 cm (21.0 inches) DBH] red fir trees are significantly more common than old growth and large sawtimber-sized trees of the other species examined in this study.

Field observations and past reports (Ferrell 1980; Slaughter and Parmeter 1989), suggest that Annosus root disease is widespread in red fir in California, but our results and models were hindered by its frequent erroneous omission during data collection. Annosus root disease, usually extremely apparent, was found on many plots visited during this study where it had not been coded at the initial plot measurement. This was especially common in plots that had been measured/installed by contractor crews. Due to the relatively slow spread of Annosus root disease, it is extremely unlikely that there was actually no Annosus root disease present at the initial visit.

The lack of reliable fir engraver data is due more to procedural protocol than data collection error. Destructive sampling is not permitted on FIA plots and fir engraver can be difficult to identify without using destructive sampling to search for the distinct galleries. Unfortunately, the end result is that actual frequency of fir engraver-caused mortality in red fir stands in California is unknown.

Management Implications

Currently, little active management is occurring in red fir forests. Cutting has slowed on National Forest Service land in California (Christensen et al. 2008) and 80% of the red fir plots in the study fall in National Forest Service land. Much of the red fir distribution falls either in wilderness areas or in national parks where cutting does not usually occur. Roughly 7% of the red fir plots in this study are on private land where cutting has mostly ceased due to the poor timber market (red fir has never been one of the most heavily harvested timber species). I have seldom observed prescribed fire in red fir forests, although some red fir stands burn each year as a result of lighting-ignited fires in wilderness areas and national parks that are allowed to burn. The effects of fire suppression and past forest management do help shape the current conditions of red fir forest though neither are active management.

What options exist? Little management is allowed in wilderness areas other than allowing existing fires to burn. Prescribed fire does occur in national parks although it is unclear if this would benefit red fir as little literature exists on this topic. Thinning may be advantageous in some situations on national forests or private land; however the negative correlation between stand density and red fir proportion dead does not support the conventional opinion that a less dense forest is closer to the historical norm and more conducive to increased forest health. Based on this study, managing for red fir dwarf mistletoe would be the most effective way to improve red fir forest health.

The proper way to manage for dwarf mistletoe is site specific (see Scharpf and Parmeter 1967). It is likely that many trees can “outgrow” dwarf mistletoe on good sites where as on poor sites they likely will not (Scharpf and Parmeter 1976). This is especially true in even aged stands or stands that do not contain tall trees with mistletoe infections high in the crown (this produces “seed rain” that often infects most trees below). There may be substantial levels of dwarf mistletoe on a good site without significant growth loss or mortality, especially if Annosus root disease is not present. Thinning or cutting of dwarf mistletoe infected trees should be conducted only if Borax is applied to stumps because otherwise the potential benefits of thinning may be lost due to the spread of Annosus root disease (this is one potential reason why stand density is negatively correlated to red fir proportion dead in this study). Even aged stands or the creation of buffer strips of other species (which are not susceptible to red fir dwarf mistletoe) would improve forest health in more heavily managed areas, (as suggested in Hawksworth and Wiens 1996). Pruning mistletoe and sanitation cutting are uncommon, but would be advantageous on any site. Although it is common for red fir to grow in pure stands, species diversity is usually considered beneficial to red fir forest health (although the relationship between stand composition, percent red fir, and red fir proportion dead was not linear in this study) (Cannon, Bulaon, MacKenzie, Pronos, personal communication 2009).

CONCLUSION

This study showed that mortality is increasing in red fir. The rate at which mortality increased during this study varied with the analysis approach (database) used and decreased noticeably if recently burned plots were removed from the analysis. Currently, one out of every five standing red fir trees DBH ≥60.96 cm (24 inches) or greater in California is dead and mortality is occurring at a rate of 2.64% in all red fir. These results suggest that at least a short term decline is occurring. Red fir dwarf mistletoe was the most significant factor in red fir mortality and decline based on our field observations and statistical analysis. Though our approach is not optimal for tracking fire history, our results do show a trend of increasing fire occurrence (and the associated mortality) in red fir as suggested by Miller et al. (2008). Once all of the plots have been remeasured, performing analyses at the individual tree level would provide the most accurate results and ensure that accuracy is not sacrificed to averaging. Continued monitoring of red fir mortality is needed.

There were clear visual (Figure 10) and statistical differences in forest health between areas that possess red fir dwarf mistletoe (both *A. abietinum* f. sp. *magnificae* and *A. abietinum* subsp. *wiensii*) and those that don't. The extremely healthy and heavily stocked Mt. Shasta (where red fir dwarf mistletoe does not occur) area plots showed that on good sites red fir can grow at a high density, with Annosus root disease present, and not experience significant mortality. *Cytospora* canker almost always accompanied red fir dwarf mistletoe and was a significant reason why the presence/absence of red fir dwarf mistletoe impacted red fir forest health so drastically. There was little spatial pattern of red fir proportion dead by plot in California other than this area of very low red fir proportion dead around Mt. Shasta.

Though the quality of FIA root disease data was not reliable (although improving), our field observations suggested that Annosus root disease was widespread, yet the exact quantity and severity of Annosus root disease in California remain unknown and needs additional research. Annosus root disease was almost always present when stumps were present and appeared to be exacerbated by the presence of red fir dwarf mistletoe. The amount of fir engraver in California was also not truly known due to limitations in FIA and FHP data collection methods. The lack of spatial or statistical correlation between our main measure of drought stress, SMRTP (estimated 18 year mean ratio of mean temperature to mean precipitation, May–Sep at each plot location) and red fir proportion dead at the plot level was unexpected though dead red fir trees and SMRTP were correlated in our non-linear mixed model analysis suggesting a correlation between mortality and drought stress at the individual tree level. This relationship should be additionally explored once all FIA plots have been remeasured.

The negative correlation between stand density and red fir proportion dead makes it unclear if a less dense red fir forest really is closer to the historical norm and more conducive to increased forest health. Based on the findings of this study, managing for red fir dwarf mistletoe would be the most effective way to improve red fir forest health and the proper way to manage for red fir dwarf mistletoe is site specific. On a good site it is likely that many trees can “outgrow” red fir dwarf mistletoe where as on a poor site they likely won’t. Dwarf mistletoe can be present without significant growth loss or mortality on a good site, especially if Annosus root disease is not present. Poor sites will require more management to maintain good forest health. Managing to enhance species diversity, pruning heavily infected branches or the creation of buffer strips would be advantageous. Thinning or cutting of dwarf mistletoe infected trees should only be used if Borax will be applied to stumps because otherwise the potential benefits of thinning may be lost due to the spread of Annosus root disease.

TABLES AND FIGURES

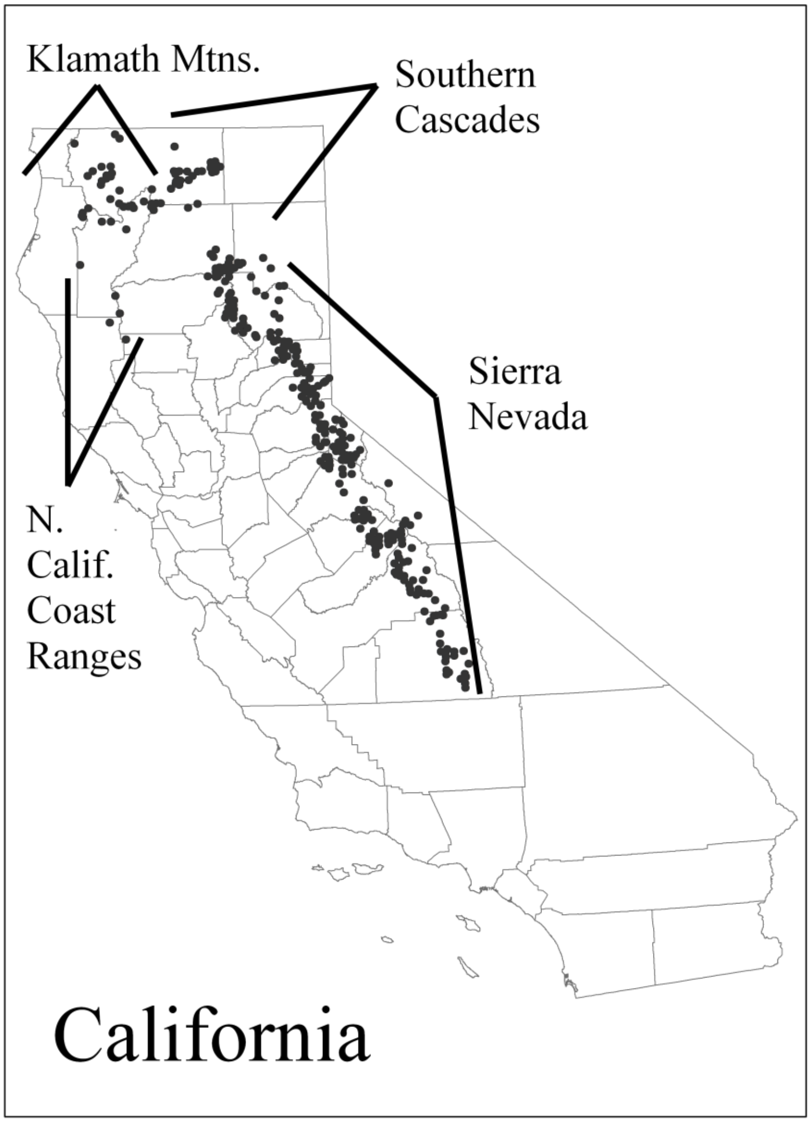

Figure 1. Plots used to represent red fir distribution in California.

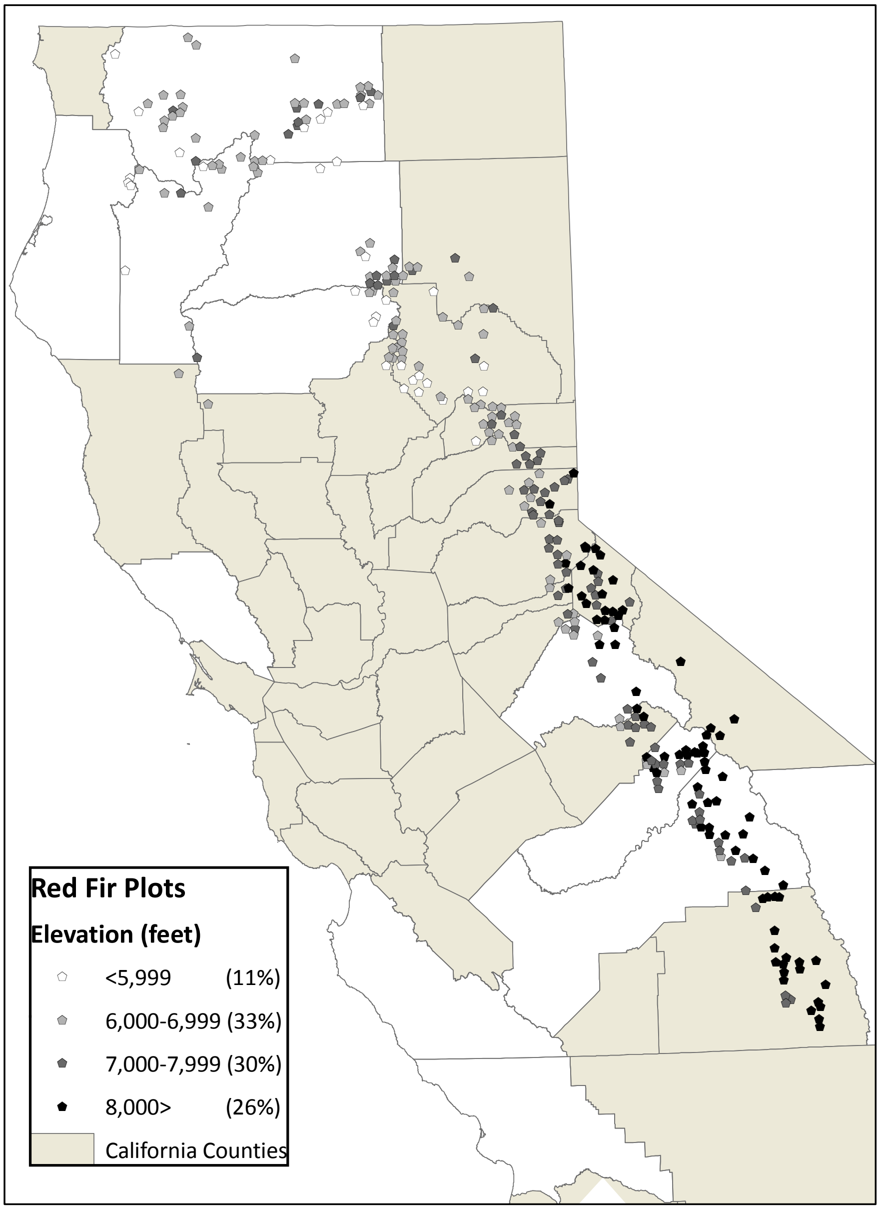

Figure 2. Red fir plots by elevational group.

Table 1. Plot level variables and definitions used in model selection, regression analysis and description of the current Conditions and characteristics of red fir forests in California.

Response Variable	
red fir proportion dead	Proportion of RF live and class I+II snag volume on plot that is dead (snags)
Explanatory Variables	
dwarf mistletoe	Mean dwarf mistletoe rating for live RF trees
number of trees with dwarf mistletoe	Number of live RF trees with mistletoe rated
red fir percentage	Percent of live and class I+II snag and CWD volume on plot that is RF
basal area density	Basal area density class: <100, 1-200, 2-300, 300+ ft^2/ac
SMRTP – moisture stress during growing season	18 year mean ratio of mean temperature (°C) to mean precipitation (natural log, mm), May–Sep at given plot location (from Daymet)
August maximum temp	Mean maximum temperature in August (°C) (hottest month)
mean annual precipitation	Mean annual precipitation (natural logarithm, mm)
mean annual temperature	Mean annual temperature (°C)
latitude	Actual UTM latitude, NAD 83
elevation	Elevation (feet)
land ownership group	Forest service, other federal, state and local government, private
stand age	Mean stand age of all non-overtopped trees on plot (years)
slope	Slope (percent)
south facing	Indicates whether condition is south-facing (135°-225°) or not
soil rooting depth	≤20 inches or >20 inches
stand condition/stage of development	Not applicable, grass-forb, shrub, open sapling-poletimber, closed sapling-pole-sawtimber, open sawtimber, large sawtimber, old-growth. See USDA 2009 for exact definitions
elevation group	Elevation group (5=<6000, 6=6-7000, 7=7-8000, 8=>8000)
stumps	Indicates presence or absence of stumps
cutting history	Indicates whether logging has occurred <10, 10-30, or >30 years before most recent measurement
fire history	Indicates whether fire has occurred <10, 10-30, or >30 years before most recent measurement
trees with fire scars	Proportion of RF trees with fire scars coded
QMD	Quadratic mean diameter of mainstand trees (in)
section name	Ecoregion section name (Cleland); Klamath Mountains, Northern California Coast Ranges, Sierra Nevada, Southern Cascades

Table 2. Mean plot dead proportion by species (all plots in study) with and without plots burned within 30 years of most recent measurement removed (SE = standard error).

	All Plots		SE	With plots burned within 30 years of most recent measurement removed		SE
Red Fir	**0.115**	**(n = 304)**	**0.010**	**0.097**	**(n = 278)**	**0.008**
Jeffrey Pine	0.070	(n = 415)	0.010	0.036	(n = 330)	0.006
White Fir	0.123	(n = 833)	0.007	0.092	(n = 718)	0.006
Lodgepole Pine	0.079	(n = 242)	0.009	0.072	(n = 230)	0.008

Table 3. Mean proportion dead by species of plots measured three times with and without plots experiencing significant fire in the last 30 years prior to measurement removed (SE = standard error).

	Periodic Measure	SE	1st Annual Measure	SE	Remeasure	SE
Red Fir (n =86)	**0.079**	**0.013**	**0.094**	**0.017**	**0.130**	**0.022**
Jeffrey Pine (n =97)	0.013	0.005	0.059	0.019	0.108	0.026
White Fir (n =201)	0.101	0.010	0.106	0.013	0.155	0.018
Lodgepole Pine (n = 61)	0.077	0.012	0.083	0.019	0.102	0.023

Plots Experiencing Fire Within 30 Yrs. Removed	Periodic Measure	SE	1st Annual Measure	SE	Remeasure	SE
Red Fir (n =78)	**0.077**	**0.014**	**0.084**	**0.014**	**0.095**	**0.013**
Jeffrey Pine (n =71)	0.006	0.002	0.024	0.013	0.040	0.015
White Fir (n =173)	0.101	0.011	0.092	0.011	0.113	0.014
Lodgepole Pine (n = 58)	0.077	0.013	0.087	0.020	0.073	0.016

Table 4. Linear regression results for the best model fit (AIC value) produced by a stepwise selection, for logit-transformed red fir proportion dead.

Coefficients	**Value**	**SE**	**t**	**Pr(>|t|)**
(intercept)	-0.9483	0.1217	-7.7890	0.0000
red fir d. mistletoe	0.0992	0.0454	2.1828	0.0298
basal area density	-0.1004	0.0503	-1.9951	0.0469
QMD	-0.0085	0.0063	-1.3596	0.1750

Residual standard error: 0.7308 on 300 degrees of freedom
Multiple R-Squared: 0.05063 Adjusted R-squared: 0.04114
F-statistic: 5.333 on 3 and 300 degrees of freedom, the p-value is 0.00136

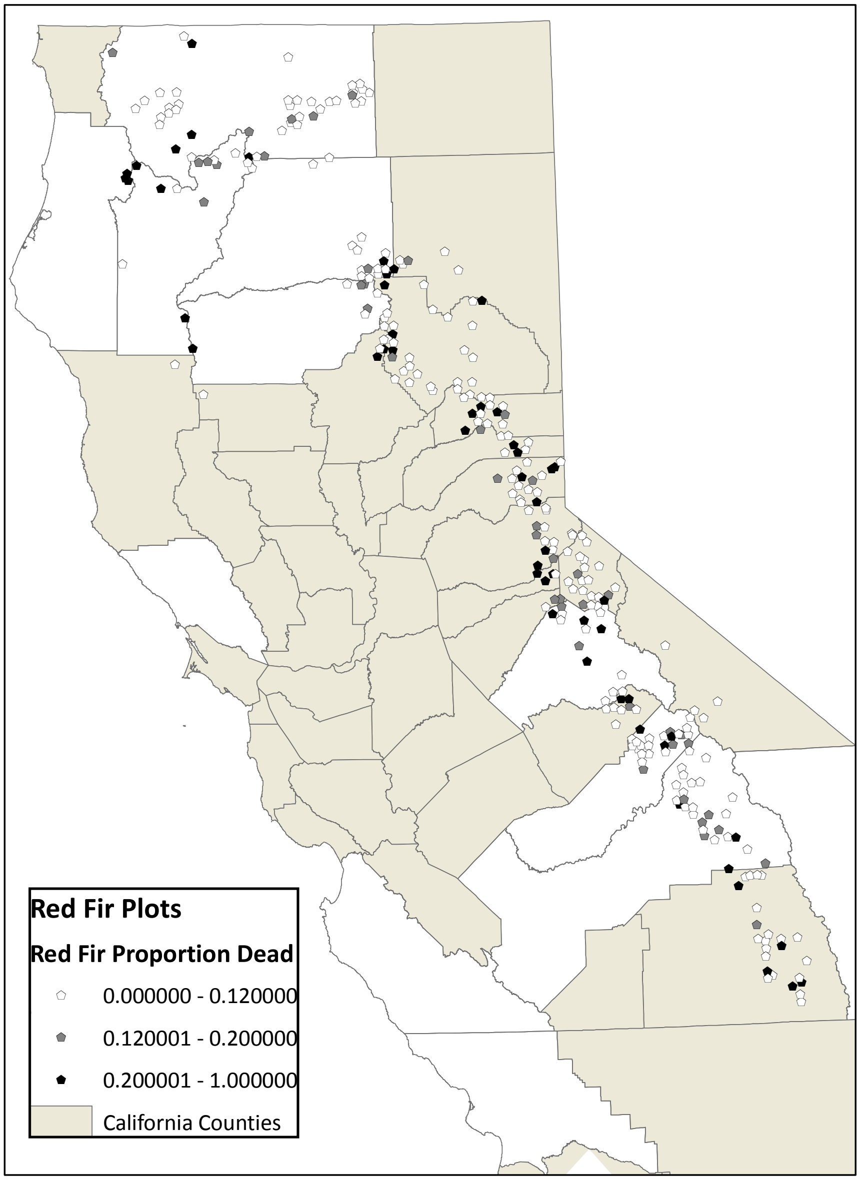

Figure 3. Red fir mean plot proportion dead.

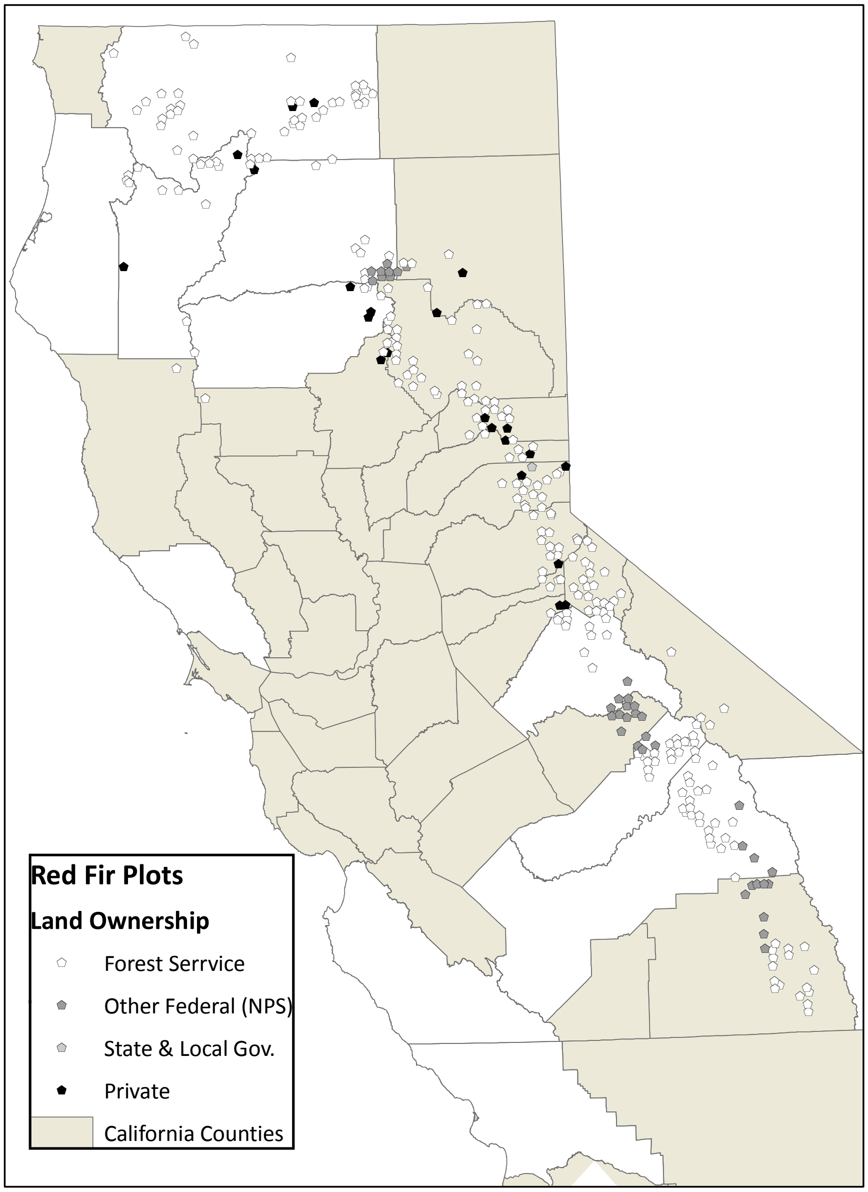

Figure 4. Land ownership of red fir plots.

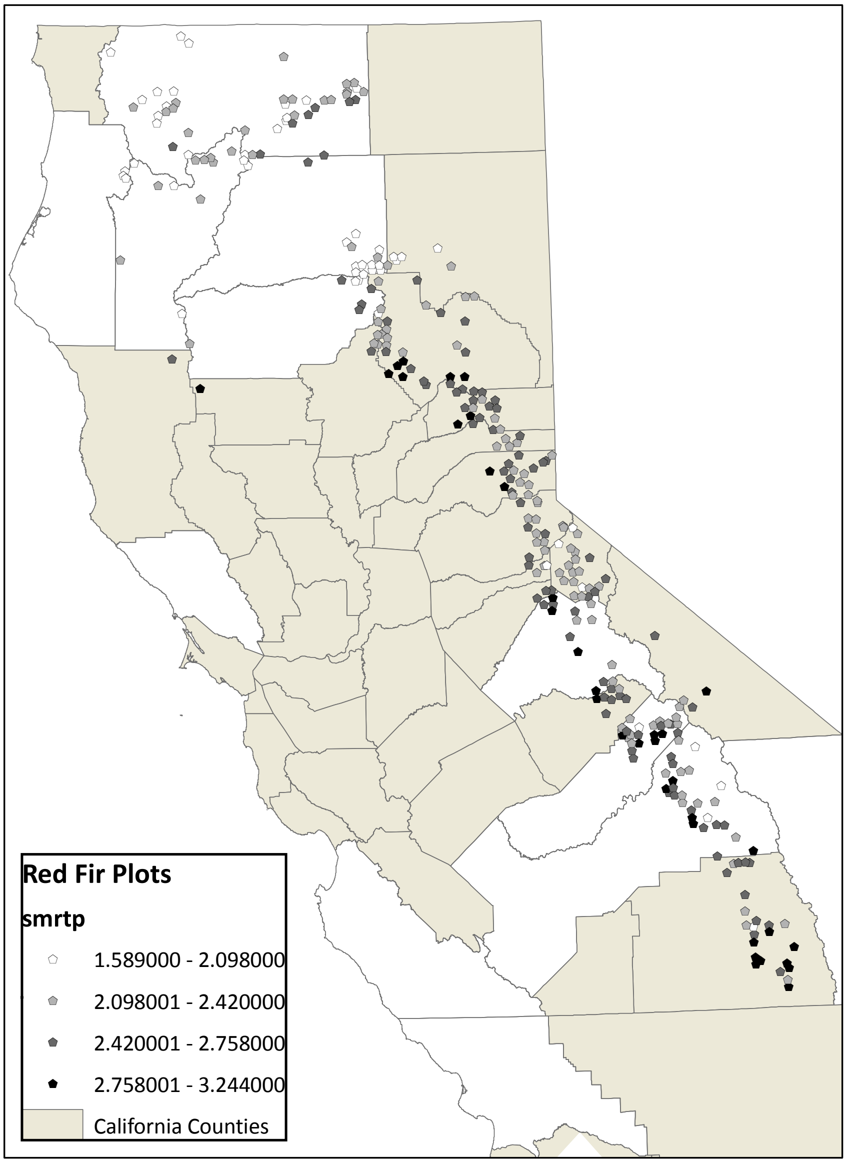

Figure 5. Red fir plots by SMRTP (estimated 18 year mean ratio of mean temperature to mean precipitation, May–Sep at each plot location).

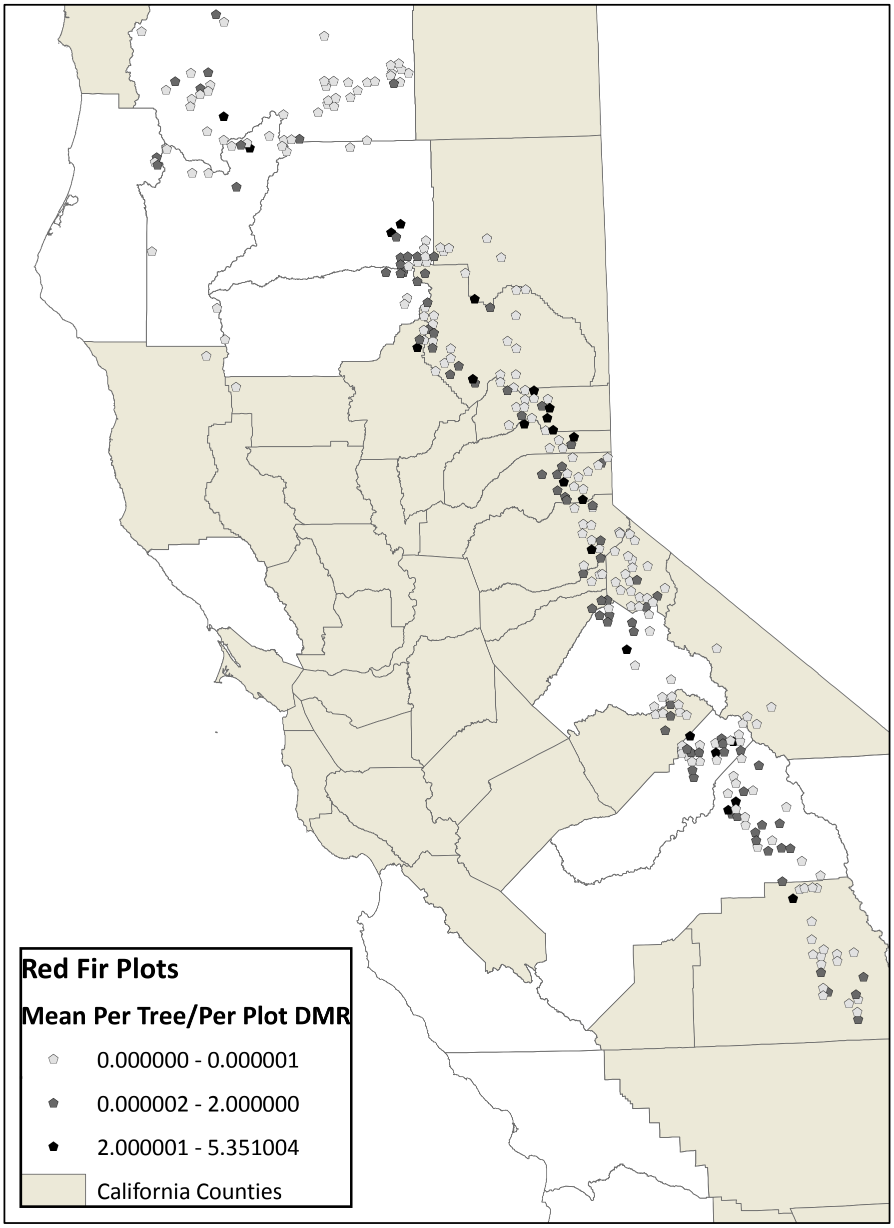

Figure 6. Red fir plots by mean per tree/per plot dwarf mistletoe rating (DMR).

Table 5. Mean ANNUAL basal area m^2/ha growth and mean basal area m^2/ha mortality per plot between measurement 1 and measurement 2 with plots experiencing significant fire in the last 30 years prior to measurement removed (SE = standard error).

	Mean Growth	**SE**	**Mean Mortality**	**SE**	**Net Gain/Loss per Plot**
Red Fir (n = 114)	**1.089**	**0.079**	**-1.531**	**0.291**	**-0.443**
Jeffrey Pine (n = 134)	0.710	0.077	-0.847	0.308	-0.137
White Fir (n = 281)	1.235	0.058	-1.342	0.155	-0.107
Lodgepole Pine (n = 84)	0.467	0.043	-0.983	0.416	-0.516

Plots Experiencing Fire Within 30 Yrs. Removed	**Mean Growth**	**SE**	**Mean Mortality**	**SE**	**Net Gain/Loss per Plot**
Red Fir (n = 105)	**1.110**	**0.082**	**-1.143**	**0.158**	**-0.033**
Jeffrey Pine (n = 101)	0.767	0.089	-0.292	0.089	+0.474
White Fir (n = 239)	1.330	0.064	-1.085	0.150	+0.246
Lodgepole Pine (n = 80)	0.476	0.044	-0.544	0.170	-0.073

Table 6. Red Fir Annual Mortality Rates.

	All Trees	**Trees From Plots Experiencing Fire Within 30 Years Removed**
DBH 2.54-12.69 cm (1-4.9 inches)	3.42%	3.62%
DBH 12.70-60.95 cm (5-23.9 inches)	1.78%	1.15%
DBH ≥ 60.96 cm (24 inches)	1.61%	1.33%
All Size Classes	2.64%	2.48%

Table 7. Percent of standing red fir dead at measurement 1 and measurement 2 by size class with <u>and</u> without plots experiencing significant fire in the last 30 years prior to measurement removed. Dead saplings not measured at initial plot installation.

Trees	**Measurement 1**	**Measurement 2**
DBH 2.54-12.69 cm (1-4.9 inches)	N/A	9.0%
DBH 12.70-60.95 cm (5-23.9 inches)	14.8%	16.8%
DBH ≥ 60.96 cm (24 inches)	16.6%	19.9%

Trees from Plots Experiencing Fire Within 30 Years Removed	**Measurement 1**	**Measurement 2**
DBH 2.54-12.69 cm (1-4.9 inches)	N/A	8.8%
DBH 12.70-60.95 cm (5-23.9 inches)	13.8%	13.9%
DBH ≥ 60.96 cm (24 inches)	15.5%	18.3%

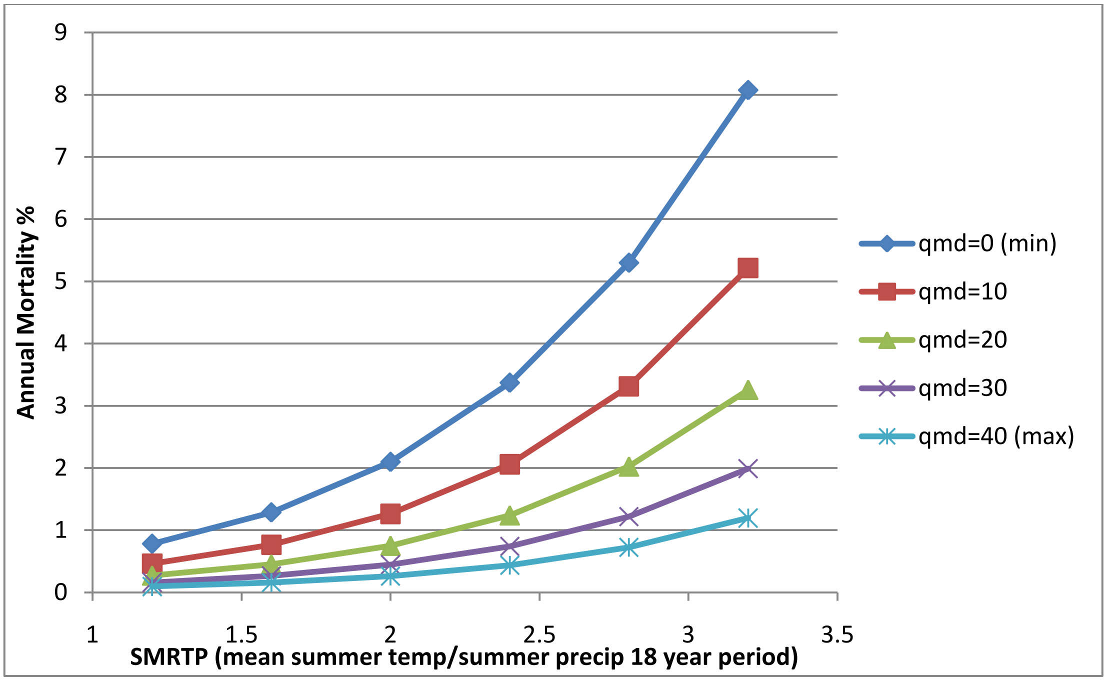

Figure 7. Non-linear mixed model analysis (logit response) results showing effect of SMRTP and QMD in predicting individual tree mortality rates.

Table 8. Non-linear mixed models (logit response) results for the best model fit (AIC value) for predicting individual tree mortality (SE = standard error).

Parameter	**Value**	**SE**	**t**	**Pr(>|t|)**
(intercept)	8.075	1.437	5.618	< 0.001
year	-0.639	0.180	-3.553	< 0.001
QMD	0.053	0.021	2.512	0.014
SMRTP	-1.287	0.429	-2.999	0.003
stem rot	-1.707	0.378	-4.518	< 0.001
top dead	-1.683	0.470	-3.577	< 0.001
foliar damage	-2.624	0.673	-3.896	< 0.001

7 and 104 degrees of freedom

Table 9. Mean red fir and white fir "red flagged" values per tree per plot for annual measurements (SE = standard error).

Species	Measurement 1	SE	Measurement 2	SE	Increase
Red Fir	**0.21769**	**0.033**	**0.37178**	**0.056**	**0.154**
White Fir	0.13448	0.016	0.19032	0.020	0.056

Note: Some of this increase may be due to improved damage coding.

Table 10. Mean elevation by species.

Species	Elevation (m)	Elevation (ft)
Red Fir	**2206**	**7236**
Jeffrey Pine	1944	6377
White Fir	1773	5816
Lodgepole Pine	2544	8345

Table 11. Mean stand age per plot.

Species	Mean	SE
Red Fir	**145**	**4.239**
Jeffrey Pine	113	3.783
White Fir	111	2.338
Lodgepole Pine	157	6.217

Table 12. Percentage of plots containing stumps.

Species	Plots with Stumps
Red Fir	**37%**
Jeffrey Pine	50%
White Fir	61%
Lodgepole Pine	21%

Table 13. Stand condition/stage of development-percent of plots by species.

Description	Red Fir	Jeffrey Pine	White Fir	Lodgepole P.
shrub/grass/forb	**1%**	5%	4%	0%
open sapling-pole timber	**5%**	13%	6%	13%
closed sapling-pole timber	**22%**	20%	36%	25%
open sawtimber	**28%**	43%	27%	38%
large sawtimber	**32%**	15%	21%	13%
old-growth	**12%**	4%	6%	11%

Note: large/old trees (large sawtimber & old-growth) = RF 44%, WF 27%, LP 24%, JP 19%

Table 14. Mean live basal area (m^2/ha) of species by plot with and without plots burned within 30 years of most recent measurement removed (SE = standard error).

	All Plots		SE	With plots burned within 30 years of most recent measurement removed		SE
Red Fir	**93.21**	**(n = 304)**	**4.170**	**95.62**	**(n = 278)**	**4.387**
Jeffrey Pine	46.17	(n = 415)	1.803	48.86	(n = 330)	2.065
White Fir	69.37	(n = 833)	1.953	72.79	(n = 718)	2.114
Lodgepole Pine	73.58	(n = 242)	3.383	75.41	(n = 230)	3.494

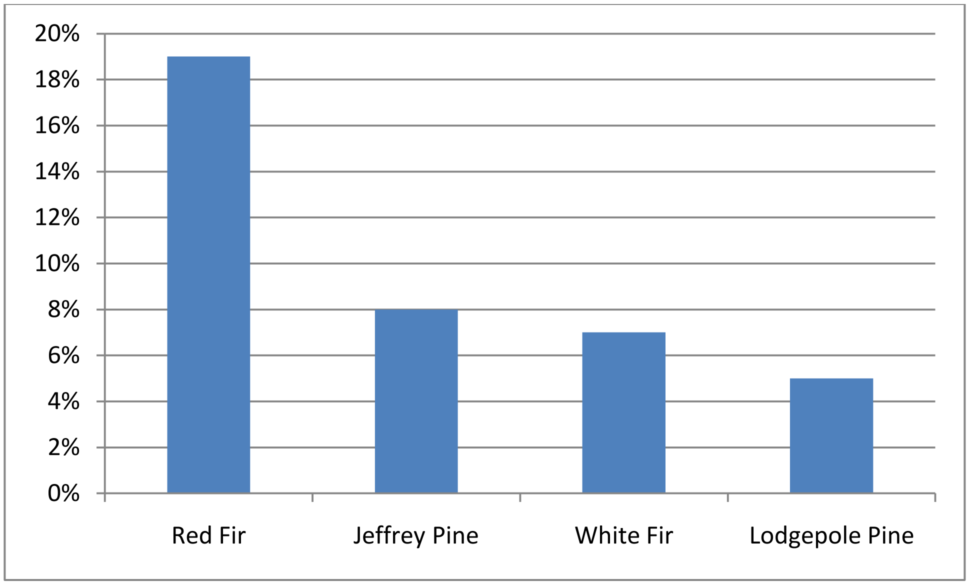

Figure 8. Percentage of total trees containing dwarf mistletoe.

Table 15. Fire coded as a disturbance on red fir plots.

Description	**Percent**
% of plots **<10 years** before most recent (plot) measurement	**5%**
% of plots **10-30 years** before most recent measurement	**3%**
% of plots **>30 years** before most recent measurement	**14%**
% of total RF plots with fire coded as a disturbance	**22%**

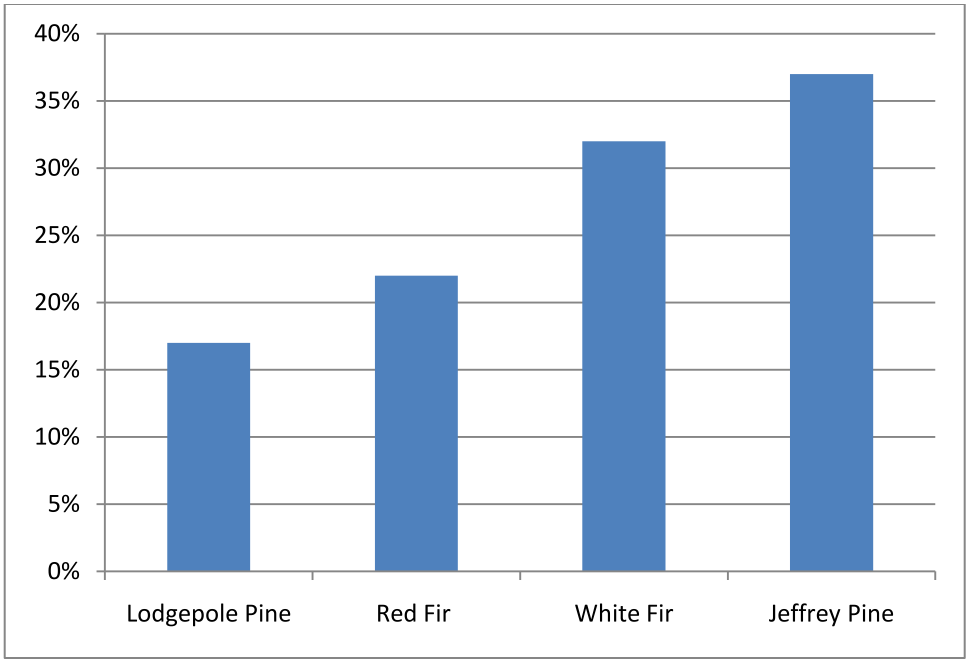

Figure 9. Percentage of total plots with fire coded as a disturbance by species.

Figure 10. Pure red fir stand with (left) and without (right) red fir dwarf mistletoe.

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