EFFECTS OF WILDLAND URBAN INTERFACE FUEL TREATMENTS ON FIRE BEHAVIOR AND ECOSYSTEM SERVICES IN THE KLAMATH MOUNTAINS OF CALIFORNIA

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TITLE: EFFECTS OF WILDLAND URBAN INTERFACE FUEL TREATMENTS ON FIRE BEHAVIOR AND ECOSYSTEM PROCESSES IN THE KLAMATH MOUNTAINS OF CALIFORNIA

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Abstract

EFFECTS OF WILDLAND URBAN INTERFACE FUEL TREATMENTS ON FIRE BEHAVIOR AND ECOSYSTEM PROCESSES IN THE KLAMATH MOUNTAINS OF CALIFORNIA

Jonathan Large

Greater numbers of people are moving into wildland-urban interface (WUI) areas, increasing the number of people at risk to large wildfires. To mitigate the hazard, emphasis is often placed on fuel treatments used to reduce fuel loads and subsequent fire behavior. This approach overlooks the additional benefits provided by vegetation, including carbon storage and sequestration along with air pollutant removal. This study aimed to calculate and compare differences in representative values by examining a study site in the Klamath Mountains of Northern California. Fire behavior simulations were done under various weather scenarios to illustrate both the impact of weather on fire intensity as well as the limitations of various fuel treatments. Ecosystem services were modeled using the I-tree Eco software (formerly the Urban Forest Effects model). Results showed a reduction in surface and an increase in canopy base height from the treatments and subsequent reductions in fire intensity under moderate and high conditions with the largest difference occurring in the Thin + Fire treatment. Under extreme weather conditions, the effectiveness of all fuel treatments was reduced. Ecosystem services showed a reduction of carbon sequestration in the fuel treatments corresponding to the reduction of smaller diameter trees from the fuel treatments. The greatest difference occurred in the Thin + Fire treatment. These results and the methods used to acquire them show the impacts from fuel treatments can be characterized and compared. This information will allow land managers to make decisions that account for a variety of considerations, while also providing them with tools that can facilitate the cooperation and collaboration of multiple stakeholders.

ACKNOWLEDGEMENTS

As my time as a graduate student here at Cal Poly nears an end, I find myself once again sitting in front of a computer monitor with the difference being this time I have a completed document in front of me. The document finally resembles a thesis, broken up into relevant chapters, and discussing methods and results using a past-tense instead of a future one. In essence, it sums up the past two plus years of my life, at least in terms of academics, and I want to take this opportunity to thank the people that helped make this happen.

First off, I must thank my advisor, Dr. Chris Dicus, and not just because I feel that it's a formality to put your advisor's name ahead of all the others. Almost three years ago I responded to an advertisement for a graduate project, showing someone using a terra-torch, and thought "this seems like my kind of project". The next step was to convince him that I was the right kind of student, which can be difficult to do based solely on phone calls from 1,600 km away. However Chris agreed to take me on as a graduate student and patiently helped sort through the paper-trail involved in getting me here.

That brings me to my next acknowledgement, the international student department of the university and notably Susan Tripp. Perhaps one of my future publications will be 'Adventures in Border Crossings', as there were many, but Susan went out of her way to help me navigate through the elaborate process involved and got me here in a timely fashion. Without her help, I'd probably still be sitting in the waiting room of the Coutts / Sweet Grass customs office.

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1.0 Project Overview

1.1 Background Information and Problem Statement

Increasing numbers of people across North America are moving into rural settings to be closer to nature, while at the same time many towns and cities are expanding and encroaching upon wilderness areas. The area where the two meet is known as the wildland urban interface (WUI) zone. There are many potential negative impacts associated with the WUI ranging from environmental concerns such as pollution and exotic pest infestation to safety concerns of residents from wildfire (Alavalapati, 2005).

Wildfire frequency and intensity have shown a dramatic increase over the past few decades, due in part to a combination of forest fuel buildup and climate change (Westerling et al., 2006). Several disastrous fires have resulted in a number of fatalities and a large number of homes being lost, and the traditional reactive approach to suppressing wildfires is proving ineffective.

Efforts are shifting to a proactive management approach, focusing on reducing the potential fire hazard through mitigation actions such as home construction improvements and fuel treatments to establish defensible space around structures. The principle of defensible space is to disrupt the horizontal and vertical continuity of the fuels, slowing or stopping advancing wildfires and making them easier to control (Agee and Skinner, 2005).

Removing trees from forests does not solely affect available fuel levels, but also affects a variety of ecosystem processes ranging from carbon storage and sequestration to air pollution removal. Land managers must begin to understand and consider these values in order to make the best management decisions for both the residents and the environment in the wildland urban interface (Dicus and Zimmerman, 2007).

1.2 Statement of Overall Goal

The overall goal of this project was to assess the effects different fuel treatments have on ecosystem processes and fire behavior, which provides managers with information that can help them make informed and justified decisions that balance ecological values while ensuring the fire hazard reduction targets are met.

1.3 Identification of Subgoals

- Assess the effects fuel treatments have on fire behavior
- Assess the effects fuel treatments have on ecological processes
- Assess computer fire modeling software, compare / contrast different programs
- Assess computer ecological modeling software, compare / contrast different programs
- Assess the effectiveness of fuel treatments on potential wildfire losses
- Assess public perception of fuel treatments
- Determine costs of various fuel treatments

1.4 Statement of Subgoal to be Investigated

This project focused on quantifying the impact of fuel treatments on both potential fire behavior and ecological processes.

1.5 Importance of Project

Knowledge of the full extent of forest management actions is of great importance to land managers, who are increasingly faced with a variety of stakeholders and values affected by their decisions. Current management practices consider forest vegetation as fuel and do not fully consider their ecological value. Thus, by better understanding their actions they can make informed decisions which will benefit both the environment and the people affected directly or indirectly by the ecosystem processes by minimizing the negative costs and maximizing the benefits.

1.6 General Approach

The study focused on empirical observations and measurements taken from a study area in northern California, which were then used to calculate potential fire behavior and ecosystem services.

Data was collected during a single field season from preexisting fuel treatments in an interface area. It was then modeled using various software packages to determine the potential fire behavior and ecosystem services associated with each treatment type.

1.7 Objective(s) / Hypothesis

The project qualified and quantified changes in several ecosystem processes (including carbon sequestration and rates of air pollution removal) and fire behavior (including rates of spread, intensity, and flame length) which may be present in WUI areas. The different values were then compared and contrasted to determine if there was a difference between them.

Null hypothesis	H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5$
Alternative hypothesis	H_A: at least two μ's differ

Where: μ_1 through μ_5 represent the various measured and modeled fire behavior and ecosystem service outputs.

2.0 Review of the Literature

2.1 Wildland urban interface

2.1.1 Definition

The term "urban-wildland interface" has been used as a descriptor since the early 1970s (Butler, 1974 In Cohen, 1999). It signifies an area where wildland vegetation encounters man-made (urban) objects such as buildings and infrastructure (Cohen, 1999; Haight et al., 2004). In this artificial environment trees, shrubs, introduced vegetation and structures can all contribute to fueling an advancing wildfire (Davis, 1990).

The term can be broken down to three sub-levels. The classic interface comprises a distinct boundary and an abrupt change from urban to wildland areas, such as where communities and cities press against the wildland area. The intermix contains single homes and structures or small subdivisions that are scattered throughout an area and are surrounded by wildland fuels. An isolated or occluded interface is comprised of islands of wildland fuels surrounded by urban areas (Davis, 1987; Davis, 1990).

The proximity of human structures and infrastructure to wildfire prone areas creates a mosaic of problems, and indeed it is in these areas that most structures are destroyed by wildfires (Radeloff et al., 2005). The complexity of the fuels and the number of values at risk makes suppression efforts difficult and dangerous in these areas (Davis, 1990).

2.1.2 History / Current status / Importance

The past few decades have witnessed a change in the population dispersion across the United States. The urban expansion of the mid 1900s slowed as people began to actively seek nonmetropolitan areas in which to live (Davis, 1990). Even with this increased rural migration, expanding cities continue to push their boundaries into the surrounding areas and increasing the total interface areas (Nowak et al., 2005).

When considering the WUI, many people envision California (Cortner et al., 1990); however, it is both a national and international issue. In 2003 a survey of the conterminous United States classified 10% of the land base as wildland urban interface zones (Stewart et al., 2003) or 719 156 km^2 that contained 38.5% of all housing units. California may have the greatest number of homes in the WUI with up to 5.1 million across 55 280 km^2, but all of the lower 48 states contain areas classified as WUI. Excluding California, the national WUI proportions display an East – West gradient with areas in northern Florida, the southern Appalachians and Northeastern coastal areas containing the largest expanses (Radeloff et al., 2005). The classic wildland urban interface is a common factor at the edge of major cities including Los Angeles, San Francisco, Seattle, and New York to name a few. It is the intermix that accounts for the largest area nationally at 80.7% (Radeloff et al., 2005).

With one third of housing units located in or near the WUI in the conterminous United States (Radeloff et al., 2005), these areas have the potential to significantly impact the interactions between the populations living there and their surrounding forests. They can have a strong impact on people's attitudes towards forests and forest management, making them some of the most influential forests of the 21st century. Due to the expansion and management issues involved in these areas, urbanization has been considered as one of the greatest factors affecting forests in the 21st century (Nowak et al., 2005).

Populations are moving into these areas for a variety of reasons, including both economical and social ideologies (Davis, 1990). The myriad of people also bring with them a variety of values, beliefs and expectations (Cortner et al., 1990) which increases the difficulty in agreeing on land management options. Many of these people do not want to change their surrounding environment, failing to realize that their presence constitutes a change in itself (Davis, 1990). Frequently the emphasis is placed not on ecological realities but on a false concept of "forest preservation", which often clashes with a foresters or fire managers plans for forest management and conservation (Davis, 1987).

In wildfire terms, interface zones create challenges for state and local agencies tasked to protect them. Although the significant importance of natural resources is recognized, most if not all agencies will prioritize the protection of a threatened structure and allocate suppression resources accordingly. Protecting these structures often results in wildland losses as a result (Davis, 1990). It was this threat to communities that acted as one of the key factors in adopting a new and controversial fuel management approach aimed at reducing hazardous fuel loads on the nation's forests (Radeloff et al., 2005).

2.2 Fuel treatments

2.2.1 Reasoning / goals

The term fuelbreak can be used to describe a wide variety of understory and overstory forest prescriptions, and their common denominator is an area manipulated in a way as to reduce the overall fuel load to reduce the spread of wildland fires (Agee et al., 2000). The method used to reduce the fuels in an area will depend on the present fuel condition of the surface and canopy fuels (Graham et al., 2004).

The concept of reducing fuel accumulation and subsequent fire hazard has been around for decades (Weaver, 1943), and the primary goal is to change the behavior of fire initiating within or entering the fuel altered zone (Agee et al., 2000). The change in fire behavior should result in reduced intensity and severity, which can contribute to defensible conditions and limit the destruction of property and resources (Van Wagtendonk, 1996; Peterson et al., 2005). Wildfire simulations in areas with reduced fuel loads due to treatments have shown a decrease in fire behavior (Van Wagtendonk, 1996), and case studies of the 2002 Rodeo-Chediski fire in Arizona found decreased fire intensities, severity and tree mortality along with lower spread rates in areas that had received fuel reduction treatments before the fire (Strom and Fulé, 2007).

Increased wildfire risk in the WUI exacerbates the need for fuel management solutions (Finney and Cohen, 2003). Managers can attempt to handle the problem reactively, with more initial attack resources, or proactively, by reducing the fuel loads around these areas thereby reducing the potential fire behavior and decreasing the number of structures lost (Dicus and Scott, 2006). Fuel reduced zones in the WUI can not only reduce the fire behavior, but also provide safe areas for suppression resources to work (Martinson and Omi, 2003).

Understanding the effectiveness of fuel reduction treatments stems from the properties of fire spread. Fire does not flow continually across a landscape like water, rather it needs fuel to self-propagate from one combustible material to the next (Cohen, 1999). In the context of a wildfire, both structures and vegetation can contribute to the combustion process. Therefore structure ignition can be reduced by modifying the fuels around them to reduce the fire behavior and limit its spread (Scott, 2003).

Even without a continuous path of combustible material leading from wildland vegetation to a structure it can still ignite due to radiant heat and contact with burning embers. Fuel reduction treatments that lower fire intensity can decrease the amount of radiant heat a structure receives, and structure building materials and design can be chosen to minimize potential firebrand ignition (Cohen, 1999).

Fuel build up in many forests across the country have been documented, and the need for restoration of lower fuel amounts is recognized (Winter et al., 2002; Agee and Skinner, 2005). The cost of fuel reduction treatments is one of the restricting factors, therefore the WUI becomes a priority due to the potential cost-effectiveness of reducing the hazard in these areas (Keeley et al., 2004). Both the necessity of reducing forest fuel levels and the importance of protecting communities played key roles in the establishment of the Healthy Forest Restoration Act (HFRA 2003) that requires at least half of fuel treatment project funding to be used in the WUI (Busby and Albers, 2010). Although well defined policy exists, broad scale implementation methods are not clearly defined (Agee and Skinner, 2005).

Weather plays an important part in the effectiveness of fuel reduced zones in reducing fire behavior to levels where suppression efforts can succeed, as they may be approached by a wildfire burning under normal to extreme weather conditions (Agee et al., 2000). Under extreme weather conditions with low humidity and high winds, wildfires may move around or over top of fuel treatments without hindrance (Finney and Cohen, 2003; Keeley et al., 2004). However, fuel reduced areas are not intended to stop an advancing fire front, rather their role is to reduce fire behavior potentially allowing suppression resources a higher chance of succeeding (Agee et al., 2000; Finney and Cohen, 2003; Graham et al., 2004; Schmidt et al., 2008). On a landscape level, fuel reduction treatments restrict a fires growth by creating a patchwork mosaic of treated areas that can disrupt the horizontal spread (Keeley et al., 2004).

2.2.2 Different methods

Fire behavior is determined in part by different fuel strata in the wildland areas including the amount of live and dead surface fuel and the presence and amount of ladder fuels which allow fire to climb from the surface into the canopies (Graham et al., 2004). Effective fuel treatments affect multiple stand characteristics including reducing surface fuels, canopy cover and stand density while increasing canopy base height (Agee and Skinner, 2005; Schmidt et al., 2008). Fuel reduction treatments are conducted using a variety of methods including prescribed fires, mechanical manipulation, and combinations of both (Graham et al., 1999, 2004; Winter et al., 2002; Hurteau and North, 2009).

Fuel treatment application must contribute to reducing surface fuels, ladder fuels, and crown densities (Agee et al., 2000; Agee and Skinner, 2005). Through a reduction in surface fuels and an increase in canopy base height crown fire initiation will be minimized by decreasing flame heights and eliminating a combustible path for a fire to follow from the surface to the canopy (Graham et al, 2004; Agee and Skinner, 2005). This pathway is important to control as it can allow a surface fire to intensify and begin burning in the canopy creating a crown fire. Crown fires pose a significant risk to communities and fire suppression resources due to their intensity, and fuel treatments can be used to reduce the likelihood of crown fire initiation (Graham et al., 2004). Two important canopy characteristics that must be manipulated include canopy bulk density (CBD) and canopy base height (CBH). Canopy base height contributes to crown fire initiation through the presence / absence of ladder fuels, while canopy bulk density is a measure of the available canopy fuel per unit of volume and contributes to the crown fire propagation (Graham et al., 1999; Scott and Reinhardt, 2001; Scott, 2003; Agee and Skinner, 2005).

Canopy bulk density is difficult to measure in the field, currently the best estimations use modified allometric equations based on tree species and crown size (Scott, 2003). Continuous crown fire spread requires a certain amount of fuel to propagate, below which spread will not be constant. Scott (2003) found that summer drought moisture conditions with a 25 mph (40 km/h) open windspeed required a CBD above 0.10 kg/m^3, whereas Agee (1996) reported a range of 0.074 to 0.125 kg/m^3. Specific CBD values are likely to be site specific and variable depending on additional stand criteria (Agee et al., 2000).

To determine the effectiveness or write a prescription to reduce the fuels in an area, the desired outcome must be considered including the environmental conditions an area must resist. The two important environmental factors are the fine dead fuel moisture content and the 10 meter windspeed. Extreme weather is characterized by the percentage of time during which it occurs, and as such the 50^{th} percentile demarks average weather while the 97^{th} percentile demarks weather that occurs 3% of the time. Windspeeds are difficult to obtain from recording stations as the 10-minute average commonly collected can mask significant variability that can drastically affect fire behavior (Scott, 2003). Scott (2003) uses an extreme windspeed of between 20 (32 km/h) and 40 (64 km/h) mph, with 25 mph (40 km/h) as the default.

Different areas rely on a variety of tools and equipment to reduce fuel loads in an area. Many land-management agencies prefer prescribed fire due to its low cost per hectare, while industry groups prefer thinning as a way to capture the tree volume removed (Van Wagtendonk, 1996).

2.2.3 Prescribed fire

Prescribed fires can be described as "the deliberate application of fire to forest fuels under specified conditions such that well-defined management goals are attained" (Wade and Lunsford 1989 In Fernandes and Botelho, 2003) and have been used for decades to reduce surface fuels in Western forests (Biswell, 1989 In Schmidt et al., 2008). Although the ecosystem benefits of a reintroduction of fire are known (Arno, 1996) it is the hazard reduction and subsequent effects on human safety that remain the main motivation for most prescribed fires (Haines et al., 1998).

Prescribed fire as a tool can affect multiple fuelbed characteristics in the forest as it can consume lower ladder fuels and kill lower branches on a tree thereby raising the canopy base height (Graham et al., 2004) although it is most effective at reducing surface fuel loads (Van Wagtendonk, 1996; Schmidt et al., 2008). The effectiveness of a prescribed burn is dependent on a variety of conditions including weather and fuel moisture levels (Peterson et al., 2005). The resulting reduction in fuel loads both on the surface and in the canopy disrupts the horizontal and vertical continuity of the fuel complex. This can be measured qualitatively or quantitatively using variables such as depth of burn, scorch height, and diameter of remaining surface fuels to determine consumption and intensity (Fernandes and Botelho, 2003)

Although post-fire surface fuel loads will be decreased, the overstory vegetation killed but not consumed will accumulate on the surface contributing to a new layer of fuel; however, the canopy base height will be increased (Agee, 2003; Agee and Skinner, 2005). The overall longevity of a prescribed fires effect will be determined by the pre-fire stand conditions and vegetation characteristics (Fernandes and Botelho, 2003), and a range between 2 – 5 years before litter levels return to pre-fire levels is commonly accepted (Van Wagtendonk and Sydoriak, 1987)

Although economically feasible over large areas, prescribed burn programs are constrained by a number of factors including fuel conditions, weather limitations, air quality regulations and inadequate funding (Fernandes and Botelho, 2003). Smoke emissions can be an important consideration due to their impacts on local and regional air quality (Peterson et al., 2005).

Pile and burn treatments are an option where broad prescribed burn treatments are not favorable. In this treatment materials such as understory vegetation are cut and piled but can be burned at a later date (Stephens, 1997). This decreases the dependency on favorable burning conditions, and gives managers more control over the amount of material burning and subsequent emission at a given time.

2.2.4 Thinning

From a silvicultural perspective thinning operations were meant to redistribute the growth potential on a site to fewer trees, however many different partial cutting methods get grouped into the thinning category (Graham et al., 1999; 2004). Although timber management thinning prescriptions are well defined, fuel hazard reduction and ecological restoration thinning operations are less clear (Omi and Martinson, 2004).

Mechanical thinning operations are often precise at meeting objectives as they can target and avoid specific stand characteristics (Van Wagtendonk, 1996; Agee et al., 2000; Graham et al., 2004). Many of the different types of thinning commonly used can reduce stand density, ladder fuels and canopy base height, and average canopy bulk density (Graham et al., 1999; 2004; Agee and Skinner, 2005) Thinning is therefore an effective method at decreasing the probability of crown-fire spread if canopy bulk densities are reduced.

Thinning operations alone do not focus on the surface fuels with the exception of isolated compaction resulting from the use of equipment, and can result in a surface fuel increase depending on the method of tree removal (Graham et al., 2004; Agee and Skinner, 2005) which can contribute to an increase in surface fire behavior (Graham et al., 1999). Management of thinning residues is an important consideration in prescription planning, with methods that chip or burn tree tops and branches shown to be the most effective at reducing surface fire spread (Graham et al., 1999; 2004; Agee and Skinner, 2005; Peterson et al., 2005).

Post-treatment wildfire intensity and severity in thinned stands will be most effective if surface fuels are reduced, including both the pre-treatment fuels (Graham et al., 2004) and the residue resulting from the treatments themselves (Graham et al., 1999). An effective strategy is to thin the understory vegetation thereby removing ladder fuels and decreasing canopy bulk density and increasing canopy base height, followed by a method to reduce surface fuels such as prescribed fire, piling and burning or mastication (Graham et al., 2004). Due to tree branch mortality from surface fire scorching subsequent burns may be necessary to reduce fuel accumulation after the initial treatment (Stephens and Moghaddas, 2005).

2.2.5 Limitations

Fuel treatments are gaining popularity, but there are still limitations and issues that arise with their planning, implementation, and effectiveness.

The effectiveness of fuel treatments is related both to the resulting fuel complex and the weather conditions under which an advancing fire is burning. Under extreme weather conditions, characterized by high winds and low humiditys, it is unlikely that the reduced fuel loads will affect a fire (Fernandes and Botelho, 2003). This is due to a fires spread characteristics, as the high winds can push flaming embers from the fire front over a treated area igniting more fires that continue to spread (Keeley et al., 2004). Fuel treatments are not intended to stop wildfires under extreme weather scenarios (Omi and Martinson, 2004) rather they are meant to reduce fire intensity and increase suppression success (Keeley et al., 2004). Treated areas can slow a fire advancing from an untreated area by inhibiting crown fire spread (Omi and Martinson, 2004).

Social and political factors affect the viability of fuel treatments (Dicus and Scott, 2006) as the complexity of land ownership and different management goals can create conflicting opinions over decisions (Winter et al., 2002; Keeley et al., 2004). Fuel treatment support is shown to be tied to perceived outcomes, with “bad” actions including escaped fires, intense smoke emissions or negative aesthetic impacts. Residents in WUI areas generally understand the goals behind fuel treatments and will support a strategy if it is thought to be well-planned and implemented. Due to concerns of prescribed fires escaping, mechanical treatments are often preferred around developed areas (Winter et al., 2002; Graham et al., 2004).

Mechanical fuel treatments may be popular in the WUI, but they are expensive and limited by machine operability constraints (Agee et al., 2000). One way to overcome the expense is to remove some commercially valuable timber to offset the costs (Keeley et al., 2004); however, this generates concerns that thinning prescriptions will be used to as an excuse to justify logging operations (Omi and Martinson, 2004).

Fuel treatment effectiveness is largely dependent on age, and treatments that affected both surface and canopy fuels were found to be effective for up to a decade (Agee and Skinner, 2005; Omi and Martinson, 2006)

Fuel reduction treatments may modify understory conditions to create conditions leading to an increase in fire intensity and severity (Graham et al., 1999; Agee et al., 2000; Scott, 2003). Reducing canopies can allow higher winds to reach the surface where they can influence fire spread (Van Wagtendonk, 1996; Agee et al, 2000; Scott, 2003; Agee and Skinner, 2005). Reduced canopy cover can increase surface solar radiation, increasing surface temperatures and decreasing fuel moisture levels and humidity (Van Wagtendonk, 1996; Scott, 2003; Graham et al., 2004, Agee and Skinner, 2005). Increased solar radiation can also result in a higher biomass of fine fuels such as grasses that can contribute to spread rates (Omi and Martinson, 2004). The potential increases in surface fire intensity are often outweighed by the reduced potential for crown fire initiation and spread (Weatherspoon, 1996; Scott, 2003; Agee and Skinner, 2005) as surface fires are easier for suppression resources to control (Scott, 2003).

Fuel reduction treatments using fire must contend with smoke emissions that generate controversy due to the vast dispersal areas (Winter et al., 2002). Although people understand the relationship between fire and air quality and have various degrees of smoke tolerance (Winter et al., 2002), smoke management and air pollution concerns were the second largest reason for prescribed burn cancelation in the US (Barrett et al., 2000; Fernandes and Botelho, 2003).

2.3 Ecological Processes in the Interface Zone

Increased interface zones result in increased interactions and conflicts between the established wildland areas and the artificial environment created by humans. These areas can have significant effects on biodiversity and ecosystems, many of them in a negative context (McKinney, 2002; Radeloff et al., 2005). The encroachment of development on wildland areas often results in habitat loss and fragmentation (Theobald et al., 1997) and declines in biodiversity (McKinney, 2002). However not all species will suffer, as during construction habitat conditions may favor exotic species introduction. The introduction of exotic species is one of the major impacts humans have had on surrounding ecosystems (Vitousek et al., 1997), as they can impact native vegetation and alter habitat conditions (Radeloff et al., 2005).

Interface forests are not only subjected to natural processes such as wildfire, insects and disease, but are also threatened by the effects of urbanization. Construction during community development may affect the roots of surrounding trees by cutting them or compacting the soil, and natural soil percolation may be halted or changed. Changes such as these can decrease the overall health of the forest, making them more susceptible to the natural processes (Davis, 1990). The transition of land use in the interface zone from forestry or agricultural land to urban areas raises a number of environmental concerns (Alavalapati et al., 2005). Trees in the WUI provide a variety of social and ecological services that can improve human health and well being due to their proximity to a large proportion of the United States population (Nowak et al., 2005; Nowak and Dwyer, 2007). The expansion of communities and increase in wildland urban interface areas alters and displaces forests, agricultural fields and other open spaces (Nowak et al., 2005). The trees and associated resources in these areas are often in close proximity to large populations, meaning they can greatly influence the health of one another (Alavalapati et al., 2005; Nowak et al., 2005). Since they are frequently close to populations management within them is viewed by a large number of people (Nowak et al., 2005), and new neighbors can mean new or different values, lifestyles, and ethics which may lead to tension and conflicts regarding management of these areas (Alavalapati et al., 2005).

Some of the affected characteristics in the WUI include ecosystem fragmentation, increased potential for invasive species invasion, pollution concerns, and wildfire (Nowak et al., 2005). Wildfire is of great importance due to the often high social and economic costs associated with interface fires, making the protection of homes in the interface a primary concern (Cohen, 2001). Emphasis is often placed on fuel management around homes through the manipulation of flammable biomass by reducing, removing, or rearranging the surrounding forest fuels (Omi, 2007). This focus on forests as fuel often overlooks additional benefits provided by trees. Some examples are carbon cycles, reduced energy-use and subsequent power plant emissions, improved air quality, and hydrology (Nowak and Dwyer, 2007).

2.3.1 Wildfire effects

The severity of wildfire effects depends on two characteristics: intensity, or the rate at which thermal energy is produced and released, and duration of the event. These characteristics are controlled by different environmental factors that affect the combustion process including fuel variables (moisture, amount, arrangement, size, etc.), weather variables (air temperature, relative humidity, wind) and site characteristics (slope, aspect) (Certini, 2005).

The combustion process occurs in different phases: ignition, flaming, glowing and smoldering (Lobard and Warnatz, 1993). It is extended periods of glowing combustion from larger fuels that can lead to greater soil heating and consumption of soil (Moghaddas and Stephens, 2007). Soil may experience fire-induced changes on different time scales depending on variables such as fire severity and frequency, as well as post-fire climatic conditions (Certini, 2005).

Although soil surface temperatures can approach 900 °C during a fire event, high temperatures do not penetrate deep within the soil as dry soil is a poor conductor of heat (Ice et al., 2004). Duration is more influential than surface temperatures, as heat penetration into the soil may be shallow but can persist from a few minutes to several days (Certini, 2005).

The visually obvious post-fire change is the loss of organic matter consumed during the combustion process. Surface layer organic matter may be mineralized or volatized, depending on burn temperatures (Ice et al., 2004). The vaporization of organic matter can create hydrophobic substances which are then driven further into the soil depending on the temperature gradient created from the fire on the surface. These vapors cool in the soil and coat mineral soil particles and can form a hydrophobic layer (Debano and Krammes, 1966; Debano, 1981) that can reduce infiltration and percolation (Ice et al., 2004).

Fuels such as coarse woody debris (CWD) or standing dead trees (snags) may also be consumed during a fire event. These characteristics provide important habitat to a variety of birds, mammals and insects (Stephens and Moghaddas, 2005).

Soil pH increases following a fire can result due to the creation of organic acids; however, significant increases only occur above high temperatures (greater than 450 – 500 °C) (Certini, 2005).

2.4 Ecological Characteristics of Forests

2.4.1 Carbon

As trees grow, they sequester carbon from the atmosphere and store it in their tissues. The amount of carbon trees can store is directly related to their size, with larger trees estimated to store 1000 times more carbon than smaller trees. Across the continental United States, the amount of carbon stored in urban forests is estimated to be equivalent to the amount of carbon emitted by the total population in 5.5 months (Nowak and Dwyer, 2007), while the current forest was estimated to store 800 million tons of carbon at the end of the last century (Rowntree and Nowak, 1991).

Carbon is sequestered through an uptake of carbon monoxide that is then stored in tissues, which occurs both day and night during the in-leaf season for trees (Nowak et al., 2006). Sequestration is based on tree size with larger healthy trees estimated to sequester around 93 kilograms of carbon per year versus 1 kilogram of carbon per year for smaller trees. This total rate of sequestration from trees in urban areas across the United States is equivalent to the total emissions from the total population over a five day period (Nowak and Dwyer, 2007).

Carbon in the forest is reduced during a fire event through consumption of forest materials including live and dead vegetation and a release into the atmosphere as carbon dioxide

(Stephens et al., 2007). Forest carbon storage and sequestration is generating interest due to its potential to offset current anthropogenic carbon dioxide (CO_2) emission (Woodbury et al., 2007).

2.4.2 Energy savings

Trees surrounding structures can directly and indirectly affect their energy consumption from heating and cooling through effects of transpiration, altered wind speeds, and localized shading. Blocked solar radiation combined with evapo-transpiration can cool the surrounding air in the summer, and blocking the wind can help conserve heat during the winter (Nowak and Dwyer, 2007). Estimations on a national scale indicate that United States residents could save approximately $2 billion dollars annually if 100 million mature trees were established around their homes (Akbari et al., 1988 In Nowak and Dwyer, 2007).

Energy conservation from trees in the interface zone varies greatly depending on regional climate, foliage characteristics, and location with respect to the building. Tree placement has been shown to have the greatest effect, as improper placement can actually increase costs relative to no trees present (McPherson, 1987).

2.4.3 Air Quality

Air pollutants are a concern in many urban centers, and urban vegetation is being researched as a way to reduce pollution levels through the ability of trees to improve air quality (Nowak et al., 2006). Models have shown ozone (O_3) to have the greatest amounts removed by trees, followed by particulate matter less than ten microns (PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO) (Nowak et al., 2006). Although the effect on O_3, SO_2 and NO_2 is greatest during daytime of the in-leaf season when water is being transpired, PM_{10} removal occurs both day and night throughout the year (Nowak et al., 2006).

Trees can remove pollutants in the air either through interception and deposition on their surface areas (such as bark or branches) or by direct absorption through the stomata where they are diffused into intercellular spaces (Nowak et al., 2006; Smith, 1990 in Nowak and Dwyer, 2007). The amount of pollution removed from the surrounding air is directly influenced by the amount of healthy leaf surface area, local air pollutant concentration, and local meteorology (Nowak and Dwyer, 2007).

When considering the ability of trees to mitigate air pollution it is important for land managers to take into account the emissions resulting from maintenance vehicles and equipment. The greater the maintenance emissions (from work vehicles traveling to the site, chainsaw usage, etc.) the longer the trees must live and function to offset these costs (Nowak and Dwyer, 2007). This emphasizes that species selection in interface areas is very important due to the potential maintenance requirements over a desired length of time.

2.4.4 Hydrology

Trees impact local hydrology by intercepting and retaining or slowing precipitation which can reduce the rate and volume of stormwater runoff (Nowak and Dwyer, 2007). This can contribute to flood control and improved water quality in surrounding areas.

2.4.5 Impacts of fuel treatments

Studies of greenhouse gas emissions from wildfires show fuel reduction treatments can be used to lower these by reducing the amount of biomass consumed (Bonnicksen, 2008). Creating forests resistant to intense fire events can decrease the combustibility of the remaining fuels. Tree removal through thinning operations may also create consumer wood products that store carbon for long time periods (Bonnicksen, 2008; Hurteau et al., 2008).

Fuel reduction treatments have a potential effect on carbon storage in forests where fuel accumulation increases the risk of stand replacing fires and their subsequent emissions. Current carbon accounting measures do not account for this potential benefit, and consider fuel reduction treatments as an immediate carbon source due to their reduction of stand carbon levels (Hurteau et al., 2008). Long term carbon management studies have shown that an initial carbon removal through treatments will increase fire resistance and carbon storage (Stephens et al., 2009). Mechanical equipment used during fuel reduction treatments have raised concerns over potential soil compaction, however studies have shown no significant treatment effect on soil bulk density (Moghaddas and Stephens, 2007).

Fuel reduction projects may contribute to an increase in nonnative invasive plants and insects by creating conditions suitable for their establishment. This can contribute to competition and a potential decrease in native species (Merriam et al., 2007) although Omi et al. (2006) concluded that a reduction in severe fire events was more significant and that effective fuel treatments may help increase native plant richness while inhibiting post-fire non-native species establishment.

2.5 Klamath Mountain Fire Ecology

The Klamath mountain region includes land in northern California and southern Oregon. The area within the state of California encompasses 22,500 km^2 (8,690 mi^2) and accounts for six percent of the overall land mass of the state (Skinner et al., 2006). In addition to the large area contained within, the deeply incised and highly complex terrain (Taylor and Skinner, 2003) covers a range of elevations from 30 meters (100 ft) to 2,755 meters (9,038 ft) (Skinner et al., 2006). This highly variable topography has contributed to the complex fire regime of the area (Taylor and Skinner, 2003; Skinner et al., 2006).

A variety of factors combine to create what can be considered as a classic fire environment in the Klamath mountains, with a long history of natural and anthropogenic caused fires. The environmental conditions in the area, characterized by a prolonged dry summer reducing fuel moisture contents in both live and dead fuels, are well suited to supporting a variety of fire activity. Depending on the seasonal weather patterns, fires can occur from May to November, and historic records show that fires often did burn for prolonged periods during these times (Agee, 2007).

2.5.1 Climate

The Klamath region is characterized by a Mediterranean climate, typically having wet and cool winters followed by warm and dry summers (Skinner et al., 2006). The pronounced annual summer drought typical of this climate ensures that much of the landscape is dry enough to support fire by late summer despite micro-environmental influences (Taylor and Skinner, 1998; Skinner, 2003).

Temperatures in the region vary and are subject to a strong moisture and temperature gradient emanating west to east from the Pacific coast (Skinner et al., 2006). This gradient results in cooler and wetter areas close to the coast with annual precipitation levels generally declining as one moves inland (Agee, 2007). The majority of precipitation the area receives occurs between the months of October and April with thunderstorm occurrence common in the summer months (Skinner et al., 2006).

Fire events are common under a variety of weather patterns, and critical fire weather is considered to be any associated with sustained periods of high winds and low humidity's (Skinner et al., 2006). Three distinct weather patterns are recognized as having contributed to large historical fire events (Hull, in Skinner et al., 2006; Agee, 2007). Pacific High-Post-Frontal or postfrontal conditions are created when a high pressure system follows behind a cold front. This condition is characterized by strong north and northeasterly winds, increased temperatures and lower humidity's. Pacific High-Pre-Frontal or prefrontal conditions are found along the tail of a rapidly moving cold front. This condition is characterized by strong south to westerly winds, with decreasing temperatures and increasing humidity's as the cold front approaches. It is the strong winds from this event, followed by their change in direction following the frontal passage, that are of concern in the area. Subtropical High conditions are the result of a high pressure system stalling over the area, causing the air aloft to sink and warm adiabatically and resulting in warm, dry air at the surface. Although fires burning under this condition are generally low to moderate severity, there are very poor atmospheric mixing conditions and the formation of inversions is common.

As previously mentioned, thunderstorm occurrence is common during the summer months, generally peaking during July and August (Taylor and Skinner, 2003). There is a gradient in the incidence of lightning, increasing from the coast inland and from low to high elevation. Lightning in the Klamath region has a 33% chance of striking any square mile during a given year (Agee, 2007), and lightning fires commonly account for the greatest amount of area burned (Skinner et al., 2006).

2.5.2 Vegetation

The complexity of the area's geology and terrain interactions have resulted in the establishment of a diverse forest structure labeled by some as the most diverse conifer forests in North America (Cheng, in Skinner et al., 2006). The Klamath region supports a high level of temperate biodiversity (Odion et al., 2004), and the alpine, subalpine and montane forests of the region have been noted for their high floristic diversity (Whittaker, in Mohr et al., 2000).

The vegetation in the Klamath Mountains reflects the gradients in topography (and associated temperature variations) and precipitation and shows signs of the historic regularity of fire (Mohr et al., 2000). The widespread occurrence of species with fire resistance and persistence mechanism illustrates the species familiarity with fires over the past centuries (Agee, 2007), although the influence of other natural disturbances such as wind and pests are also apparent in their effects on the landscape (Taylor and Skinner, 1998).

Vegetation gradients in the Klamath region create a heterogeneous pattern (Skinner et al., 2006), with elevation (and its respective temperature differences) and soil moisture being recognized as the primary landscape level controls on species distributions (Taylor and Skinner, 1998; Taylor and Skinner, 2003).

The mixed-conifer or mixed-evergreen forests of the area contain a wide variety of coniferous and hardwood tree species (Agee, 1993). The multilayered, multi-aged structure contain a mix of Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) as the most widely distributed conifers with a variety of other species present in their understory (Agee, 1993) and it is the prevalence of Douglas-fir and the diversity of understory hardwoods that distinguishes Klamath mixed-conifers from other mixed-conifer forests in the Pacific Northwest (Taylor and Skinner, 2003). The composition of these species varies with elevation and aspect; generally lower elevations comprise a mix of Douglas-fir, ponderosa pine and sugar pine (*Pinus lambertiana*) while higher elevations comprise a mix of Douglas-fir, white fir (*Abies procera*), and sugar pine (Taylor and Skinner, 1998).

The elevation gradient has been grouped into three general zones: the lower montane, the mid to upper montane and the sub-alpine (Skinner et al., 2006)

The lower montane area comprises a complex and diverse mix of vegetation across various topography and fire regimes. There are a variety of grasslands, shrublands, and Douglas-fir stands, with various mixtures and abundances. Many of the dominant species such as Douglas-fir and ponderosa pine have fire resistant characteristics such as thick bark, deep roots and high crowns. Douglas-fir is considered one of the most fire resistant tree species in the Klamath region.

The mid to upper montane elevations contain the highest diversity in forest types, ranging from grasses to mixed-conifers containing pines, firs and oaks in various abundances. It is differentiated from the lower montane areas by the increased abundance of white fir and Shasta red fir (*Abies x shastensis*) and the decreasing appearance of hardwoods.

The sub-alpine zones are the highest in the area, and the shallow soils commonly found there limit the species that can grow in the area.

Although the mixed-conifer forests of the Klamath region differ from those further to the north, they have several features in common including overlapping ranges in historical fire-return intervals, significant forest structure changes from the fire protection era and similar challenges to living with fire in the future (Agee, 1993).

2.5.3 Fire Regime

There are few other forested regions that have experienced fires as frequently and with as much variability in severity as the Klamath Mountains (Taylor and Skinner, 1998). Although this is recognized as contributing to the overall landscape diversity, grouped together with the complex geology, land use history and steep environmental gradients it has prevented broad generalizations about fire and its ecological effects (Agee, 1993; Taylor and Skinner, 1998; Odion et al., 2004).

Variations in fuels based on topography and elevation play a key role in characterizing fire behavior and regimes, and often result in diversity on the local slopes of individual mountains (Agee, 2007). This variation makes it difficult to separate fire regimes by ecological zones (Skinner et al., 2006). Generally there is a negative correlation between elevation and fire frequency, with the lower elevations burning more often due to the warmer temperatures and longer fire seasons (Taylor and Skinner, 2003). Severity has also been shown to vary with aspect and elevation, with the upper third or south/west aspects burning with higher severities than the lower third or north/east slopes (Taylor and Skinner, 1998; Skinner et al., 2006).

Average fire intensities have been studied in various areas throughout the Klamath Mountains, and indications are that the mixed-conifer forest historically burned with low to moderate severity fires (Agee, 1993; Taylor and Skinner, 1998; Mohr et al., 2000; Taylor and Skinner, 2003). The mixed severity has created a complex mix of underburned forests with little overstory mortality, thereby thinning the stands but maintaining a dominant tree cover (Agee, 2007). One study estimated the overall severities as 59% low, 29% moderate and 12% high (Odion et al., 2004).

The litter composition in the region consists of continuous beds of dry forbs, grasses, hardwood leaves and conifer needles that can support frequent surface fires (Taylor and Skinner, 1998), and return intervals have been shown to be shorter in Klamath mixed conifer forests than in those further north (Agee, 2007). Median fire return intervals were similar among species composition groups (12 – 19 years), although they were shorter on south and west slopes than north and east slopes. As well, fire suppression policies have increased the fire return intervals (Taylor and Skinner, 1998).

Numerous fire history studies have focused on the Klamath region using dendrochronologic records to estimate fire frequencies (Mohr et al., 2000). Of all the natural disturbances that have occurred in the area, fires have had the greatest frequency and the numerous and less severe fires meant that large severe fires were uncommon in the area. The higher fire frequencies of the Klamath mixed-conifer forests compared to those in Oregon / Washington forests contributed to its forest structure, creating finer scale canopy openings (Taylor and Skinner, 1998; Mohr et al., 2000). Although dominated by frequent low intensity fires, there are indications that several large, high severity fires played an integral role in shaping the landscape level forest structures, although these were more common on the upper slopes (Taylor and Skinner, 2003).

2.5.4 Fire History

Fire ignition in the area is a result of both lightning and human activities. Lightning occurs frequently in July and August, giving these months the highest incidence of ignitions while their extent varies with climatic changes (Agee, 1993). Human activities in the area have been divided into three distinct periods, the era of Native American activities, the Euro-American settlement era and the era of fire suppression policies (Agee, 1993; Skinner et al., 2006). Like most of the drier forest types in the western United States, the Klamath Mountains have had a significant component of their landscape shaped by Native American burning for centuries (Agee, 1993). Local Klamath tribes used fire as their main resource management tool, lighting fires to promote plant production for food and fiber, to improve hunting grounds and for ceremonial purposes (Agee, 1993; Taylor and Skinner, 1998; Taylor and Skinner, 2003; Agee, 2007).

Following the discovery of gold in the Trinity River in 1848, many Euro-Americans began settling in the area (Taylor and Skinner, 2003; Skinner et al., 2006). They continued to use fire on the landscape to facilitate travel, clear ground and expose rock outcrops, and their usage is thought to mimic the traditional fire frequency common from the previous fires used by the Native American tribes (Taylor and Skinner, 1998).

Fire occurrence and burned area did not decline until after 1905, when the area became part of the National Forest System and a policy of fire suppression was introduced (Taylor and Skinner, 1998; Taylor and Skinner, 2003). However, the effectiveness of the fire suppression policy was not seen until the 1920s in accessible areas and many remote areas did not see a reduction until after World War II with the improvement in fire fighting strategies and techniques (Taylor and Skinner, 2003; Skinner et al., 2006).

2.5.5 Current Situation

Although the Klamath Mountains have been subjected to a variety of management activities, fire exclusion has had the most pervasive effect since it is the only activity that has been universally applied across the landscape. A century of fire exclusion policies affecting the region have resulted in a reduction in spatial complexity and the creation of homogeneous and abundant fuel conditions over the entire area (Agee, 1993; Taylor and Skinner, 1998). Selective logging practices in the late 1900s have further accelerated the successional processes in the forests (Agee, 1993; Taylor and Skinner, 1998).

As a result of the increased fuel loading, wildfires that occur are likely to be of greater intensity and present greater control difficulties (Agee, 1993; Skinner et al., 2006). This trend has been evident in recent decades (Odion et al., 2004). One study compared fire exclusion to "saving" biomass on the sites, indicating that although the balance of the savings account is growing the risk of bankruptcy is inevitable (Agee, 1993).

Forest management in the Pacific Northwest presents significant fire management challenges, particularly in the Klamath region (Agee, 1993). In addition to issues such as smoke management and fuel accumulation, area managers must balance wildlife habitat concerns and the risks associated with the wildland urban interface. With an average of less than 1.2 people per km^2 (3 people / mi^2) the area is less populated than the state average; however, a large portion of these people live in scattered dwellings and communities in vulnerable areas (Skinner et al., 2006). These areas pose unique management concerns and often have an increased number of stakeholders with a variety of opinions on management activities in their area.

Future management decisions will likely be driven more by specific management objectives and a breakdown of current fire suppression policies as larger wildfires escape and suppression costs escalate (Agee, 1993). Although reintroduction of fires to the area will take time and money, the Klamath area is fortunate that changes have not been quite as significant as the ponderosa pine forests in other parts of the western United States. One thing is certain, and that is the exclusion of fire from environments such as these cannot continue (Agee, 2007). Although the immediate reintroduction of fire on the landscape may not be feasible or even desirable, with a better understanding of the important role fire plays in the ecosystem managers can begin to correct the mistakes made over the past century, and restore the unique ecosystems of the Klamath mountains to their historic health and diversity.

2.6 Computer models

Technological advances in both hardware and software over the past decades have ushered in a new spectrum of tools available for land managers. New computer models running on advanced systems can help with the prediction and communication of different available management options (Andrews and Queen, 2001).

2.6.1 Fire behavior

Computer models play an important part in fire management and are used to predict various effects and outcomes of different actions. They can be used to assess how a fire may burn under a given set of conditions, or to evaluate the long-term response of an area post-fire. Many of the current models use the same basic surface spread calculations based on Rothermel's 1972 model, including BEHAVE, the FARSITE fire area simulator, and the National Fire Danger Rating System (NFDRS) to name a few (Andrews and Queen, 2001).

Fire behavior models play an integral role in management decision making due to the nature of fire and its response to variable burning conditions (Cruz et al., 2005). Managers must be able to effectively evaluate, compare and contrast different options such as various fuel reduction treatments and assess their respective outcomes. Computer modeling can help assess short and long term impacts that may be encountered by considering changes in both fuel and fire potential over determined time horizons (Andrews and Queen, 2001).

Models can be divided into several categories based on both their required inputs and their outcomes. For example, empirical models are created from field observations and data, while physically based models are based on principles and laboratory data (Andrews and Queen, 2001). The inputs a required for Rothermel's 1972 spread model were divided into environmental parameters such as slope, wind speed and fuel moisture content, and fuel parameters such as fuel loads by different size class (Andrews and Queen, 2001).

To facilitate the use of computer simulations, standard fuel models were developed to represent the major fuel types commonly found around the country. These standard fuel models have associated pre-determined fuel parameters, which can be manipulated to create custom fuel models if needed (Andrews and Queen, 2001).

The predicted effects of a fire from a model were classified based on the time between the fire and the emergence of the effect as well as distance between the fire and the effect (Albini and Brown, 1996 In Andrews and Queen, 2001). Their taxonomy described first-order fire effects and secondary effects. First order effects include prompt results occurring no later than a few days after the fire and are restricted to localities within the burned area. Fuel consumption and smoke emissions are examples of a first order fire effect (Andrews and Queen, 2001). Secondary effects are those that result from the fire environment, fire characteristics and first-order fire effects. They are usually either removed from the fire or become evident after a time period. Smoke transport and dispersion along with their effect on distant air quality are an example of secondary effects, as they can occur over a distance from the fire and is based upon smoke emissions. Erosion and water quality changes also examples of secondary effects (Andrews and Queen, 2001).

Fire behavior modeling and prediction is both an art and a science, and as such computer simulations and outputs need to be compared to field observations in order to validate them. Differences can occur between the predicted and observed values based on a variety of reasons, including weaknesses in the model itself, micro-climatic conditions, and variability in the fuels matrix or problems with the observed fire behavior (Andrews and Queen, 2001).

2.6.2 FVS - FFE

The Forest Vegetation Simulator (FVS) includes several submodels, such as the Fire and Fuels Extension (FVS-FFE) available from the United States Forest Service. This extension uses the tree data generated in the FVS model to perform various calculations of both fire intensity and fire effects. The required inputs include moisture, windspeed, and the fuel load characteristics (Beukema et al., 2003).

One assumption in the FFE program is that the live herbs and shrubs are based on the dominant species in the stand and are therefore not modeled explicitly. Their contribution to fire behavior is limited to smoke emissions, and it is assumed that they grow back within one year of the fire event (Beukema et al., 2003).

2.6.3 UFORE / I-tree

The Urban Forest Effects (UFORE) model is a computer simulation used to calculate the structure, environmental effects and values of urban forests (Nowak and Crane, 1998). It was developed through funding from the United States Department of Agriculture Forest Service Northeastern Research Station. It has since been incorporated into the I-tree suite of urban forest management software as the I-tree Eco application. The model reports on a variety of forest characteristics including carbon storage, carbon sequestration, and air pollution removal. Carbon storage is based upon the total biomass for each tree, which is calculated based on equations from the literature to obtain values for whole-tree biomass using tree species, height and diameter. Carbon sequestration is based upon the storage potential of annual average biomass growth (Nowak and Crane, 1998).

Air pollution removal is calculated based upon deposition rates of ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO) on the surface of the tree leaves. It is based on total leaf area determined from tree species and size, and correlated with hourly pollution-concentration data (Nowak and Crane, 1998).

3.0 Fuels and Fire Behavior

3.1 Introduction

Increasing numbers of people across North America are moving into fire prone environments (Davis, 1990). Simultaneously wildfire frequency and severity have shown a dramatic increase over the past few decades due in part to a combination of forest fuel buildup (Minnich et al. 1995; Winter et al., 2002; Agee and Skinner, 2005) and climate change (Westerling et al., 2006). Even with increased suppression resources and technology, several disastrous fires have resulted in multiple fatalities and a substantial loss of homes and infrastructure (e.g., 2003 and 2007 California Fire Sieges). The traditional reactive priority of wildfire suppression is inefficient and often ineffective.

Efforts are shifting towards a proactive management approach focused on reducing the potential fire hazard through mitigation actions such as home building improvements, land use planning, and fuel treatments. The concept of reducing fuel accumulation and subsequent fire hazard has existed for decades (Weaver, 1943), with the goal of changing the behavior of fire initiating within or entering the fuel altered zone (Agee et al., 2000) by manipulating the horizontal and vertical continuity of the fuels complex, thereby slowing or stopping advancing wildfires and making them easier to control (Agee and Skinner, 2005).

Fire behavior is determined in part by different fuel strata in wildland areas including the amount of live and dead surface fuels and the presence and amount of ladder fuels, which facilitate the transition from surface fires to crown fires (Graham et al., 2004). Effective fuel treatments affect multiple stand characteristics including surface fuels, canopy cover and stand density and canopy base height (Agee and Skinner, 2005; Schmidt et al., 2008).

Crown fires pose a significant risk to communities and fire suppression resources due to their intensity, and fuel treatments can be used to reduce the likelihood of crown fire initiation (Graham et al., 2004). Two important canopy characteristics that must be manipulated include canopy bulk density (CBD) and canopy base height (CBH). Canopy base height contributes to crown fire initiation through the presence / absence of ladder fuels, while canopy bulk density is a measure of the available canopy fuel per unit of volume, which contributes to crown fire propagation (Graham et al., 1999; Scott and Reinhardt, 2001; Scott, 2003; Agee and Skinner, 2005).

There are a variety of techniques available to land managers to achieve fuel reduction goals, most of which include prescribed fire, mechanical fuels manipulation, or a combination of the two (Graham et al., 1999, 2004; Winter et al., 2002; Hurteau and North, 2008). Their primary goal is to change the behavior of fire initiating within or entering the fuel altered zone (Agee et al., 2000), thereby reducing fire intensity and severity, and contributing to defensible conditions that limit the destruction of property and resources (Van Wagtendonk, 1996; Peterson et al., 2005). Effective fuel treatments affect multiple stand characteristics, including reducing surface fuels, canopy cover and stand density while increasing canopy base height (Agee and Skinner, 2005; Schmidt et al., 2008).

The overall objective of this study was to determine how common fuel treatments in the Klamath mountains of northern California impact fuel loading and subsequent fire behavior. The first specific objective was to determine how surface and canopy fuel parameters changed following four fuel treatments, including prescribed fire, mechanical thinning from below, thinning followed by prescribed broadcast fire, and thinning followed by piling and burning of coarse surface fuels. The second specific objective was to determine if and how fire behavior varied following the different treatments under different weather scenarios characteristic of the region.

3.2 Methods

3.2.1 Site Description

The study site is located in the western Klamath Mountains of northern California, USA (latitude: 41.1, longitude: -123.1). The terrain is highly variable, ranging between 30 m and 2,755 m elevation and is deeply incised. The climate is Mediterranean, typified by wet and cool winters followed by warm and dry summers (Skinner et al., 2006). The majority of precipitation occurs between the months of October and April, often occurring in the winter as snow although thunderstorm occurrence is common in the summer months (Skinner et al., 2006). A strong temperature and moisture gradient results in cooler and wetter areas in the western portion of the region, becoming hotter and drier in the east (Skinner et al., 2006; Agee, 2007).

Vegetation in the Klamath Mountains similarly reflects gradients in topography and precipitation, which create a heterogeneous species distribution (Skinner et al., 2006) that is controlled largely by elevation and soil moisture (Taylor and Skinner, 1998; Taylor and Skinner, 2003). Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) are the most widely distributed conifers in the region (Agee, 1993), but the prevalence of Douglas-fir and the diversity of understory hardwoods distinguish Klamath mixed-conifer forests from other forest types in the Pacific Northwest (Taylor and Skinner, 2003). In general, lower elevation sites are comprised of a mixture of Douglas-fir, ponderosa pine, and sugar pine (*Pinus lambertiana*), while higher elevation sites are characterized by a mixture of Douglas-fir, sugar pine, and white fir (*Abies concolor*) (Taylor and Skinner, 1998).

Signs of historic fire occurrence are prevalent throughout the Klamath Mountains (Mohr et al., 2000). The area has a long history of both lighting and anthropogenic ignitions (Taylor and Skinner, 2003; Skinner et al., 2006). Widespread occurrence of species with fire resistance and persistence mechanisms illustrates fire's selective forces (Agee, 2007), although wind events, insects, and disease also help shape vegetation across the landscape (Taylor and Skinner, 1998).

Fires generally occur from May to November and often burn for prolonged periods (Agee, 2007). A pronounced annual summer drought ensures that much of the landscape supports fire by late summer despite micro-environmental influences (Taylor and Skinner, 1998; Skinner, 2003) . Fire events are common under a variety of weather patterns, but critical fire weather is considered to be any associated with sustained periods of high winds and low relative humidity (Skinner et al., 2006). Thunderstorms are common during the summer months, generally peaking during July and August (Taylor and Skinner, 2003) with an increasing gradient in the incidence of lightning from west to east and from low to high elevation. Lightning in the Klamath region has a 33% chance of striking any square mile during a given year (Agee, 2007) and lightning fires commonly account for the greatest amount of area burned in the region (Skinner et al., 2006).

Variation in fuels, based on topography and elevation, strongly influences fire behavior and regimes in the area, and regularly result in significant diversity on individual mountains (Agee, 2007). Several studies have indicated that the mixed-conifer forest historically burned with low to moderate severity (Agee, 1993; Taylor and Skinner, 1998; Mohr et al., 2000; Taylor and Skinner, 2003). These mixed-severity fires created a complex mixture of underburned forest with little overstory mortality, subsequently thinning the stands but maintaining a dominant tree cover (Agee, 2007).

Surface fuels regularly consist of continuous beds of dry forbs, grasses, hardwood leaves and conifer needles, which support frequent, low-intensity surface fires (Taylor and Skinner, 1998). Median fire return intervals were historically 12 – 19 years (shorter on south and west slopes than north and east slopes), which are generally shorter than in mixed-conifer forests found further north (Agee, 2007). Fire exclusion in the last century has increased fire return intervals beyond the historic range of variability (Taylor and Skinner, 1998).

3.2.2 Field Measurements

Vegetation and fuels data were collected at three distinct sites, which were in the same watershed and separated by less than 20 km. At each site, data were collected in four different fuel treatments commonly utilized on the Klamath National Forest and in an adjacent untreated stand, which was used as a control. All fuel treatments were completed within three years of data collection so as to minimize temporal variation following treatment.

Treatments at each site included

1. Fire-only: broadcast prescribed fire with no pre-fire mechanical treatment.
2. Thin-only: mechanical thinning-from-below where cut vegetation was transported to the nearest road and subsequently chipped or burned.
3. Thin+Fire: mechanical thinning-from-below where cut vegetation was removed from the site, and then followed by a broadcast prescribed fire.
4. Thin+Pile&Burn: Mechanical thinning-from-below where cut vegetation was piled on-site, and then subsequently burned.

For each Site×Treatment combination, data were collected in three 0.08 ha plots. Thus, data were collected in 12 treated plots per site, or 36 treated plots over all 3 sites. Data were also collected in two adjacent, untreated 0.08 ha plots for each Site×Treatment combination. However, due to the close proximity of some treated areas, untreated control plots were shared for a Site×Treatment combination at two sites. Thus, data were collected in 20 untreated control plots over all 3 sites (8+6+6).

At each 0.08 ha plot, species and diameter at breast height (1.37 m), total height, and height-to-live crown were measured on all trees > 1.37 m in height. Also at each plot, surface fuel measurements were collected per Brown (1981) on three 18.3 m transects, which were established at azimuths of 0^{o}, 120^{o}, and 240^{o} from plot center. Dead and down surface fuels were characterized per standard time-lag classifications (1-hr < 0.64 cm, 10-hr = 0.64 – 2.54 cm, 100-hr = 2.55 – 7.62 cm, 1000-hr > 7.62 cm). Individual 1000-hr fuels were recorded for diameter and categorized based on a soundness scale from 1-5 (where one equals sound and five equals fully rotten), which was used in their fuel load calculations. Herbaceous height, fuelbed depth, litter depth, and duff depth were recorded in 1 m subplots at 9.15 m and 18.3 m on each transect.

3.2.3 Fuel and Fire Behavior Calculations

The Fire Effects Monitoring and Inventory Protocol (FIREMON) (Lutes et al., 2006) was utilized to calculate loading for each time-lag surface fuel class for each transect. Canopy fuel parameters (available canopy bulk density, canopy base height, available canopy fuel load) were calculated with FuelCalc (Version 0.52, Larry Gangi; Reinhardt et al., 2006) based on tree data collected in the 0.08 ha plots. All values were converted to a per-hectare base. The values of individual surface and canopy fuel parameters for each Site×Treatment combination (n=3 per combination) was the mean of all 9 transects for a given combination in treated areas (3 transects

× 3 plots) and the mean of all 6 transects for a given combination in untreated areas (3 transects × 2 plots).

Custom surface fuel models were created for each Site×Treatment combination. Using tree data, the Fire and Fuels Extension (Reinhardt and Crookston, 2003) of the Forest Vegetation Simulator (Dixon, 2003) assigned a standard fuel model (Anderson, 1982) to each Site×Treatment combination. Using the FVS-assigned fuel model as the initial base model, custom surface fuel models were then developed for each Site×Treatment combination with BehavePlus (v. 4.0; Andrews et al., 2008), adjusting fuel components based on the mean of FIREMON-calculated surface fuel loadings. In the custom fuel models, litter loads were added to the 1-hr fuel loading to create a more realistic fuel model per methodology on the Klamath National Forest (Personnel communication, C. Isbell, Klamath National Forest).

FireFamily Plus (version 3.05) (Rocky Mountain Research Station Fire Lab and Systems for Environmental Management, 2002) was used to calculate weather variables for the 50^{th}, 90^{th}, and 97^{th} percentile conditions (those encountered 50%, 10%, and 3% of the time, respectively), which were subsequently used in fire behavior simulations. Historic weather data from the nearby Sawyers Bar remote automated weather station (RAWS) were obtained for the fire season (May 1, 1961 – October 31, 2008). While extreme fire behavior is commonly associated with high winds, winds recorded at weather stations that collect ten minute averages (e.g., the Sawyers Bar RAWS) are often not useful for predictions due to their inability to record significant variation (Scott, 2003). Thus, higher windspeeds were used for fire behavior simulations (Scott 2003; Schmidt et al., 2008)as well as per Klamath National Forest staff (C. Isbell, personal communication). Weather parameters utilized in fire behavior simulations (described below) are displayed in Table 1.

Table 1. Wind speed (km/hr) and fuel moisture (%) values utilized in NEXUS fire behavior simulations for three weather conditions.

Input	Percentile Condition		
	50th	90th	97th
Wind speed (km/h)	16	24	32
Temperature (‘C)	31	38	40
Fuel moisture			
1 –hr	4	3	2
10 –hr	5	4	3
100 –hr	10	6	5
Live woody	77	70	70
Live foliage	100	100	80

NEXUS (version. 2.0; Scott and Reinhardt 2001) was used to simulate fire behavior for each Site×Treatment combination based on the derived custom surface fuel models and the mean canopy characteristics for each Site×Treatment combination and on weather parameters in Table 1. A wind reduction factor of 0.3 was used for control and prescribed burn plots and 0.4 was used for all other treatments (Schmidt et al., 2008). Slope and wind direction were set to 0% to eliminate them as variables.

3.2.4 Statistical Analysis

For statistical testing, the experimental unit for a given parameter was a Site×Treatment combination. Thus, n=3 replicates for each Site×Treatment combination, or total n=15 replicates (3 sites, each with 4 treatments and 1 untreated control). For treated replicates, the value for each Site×Treatment combination was the mean of 3 plots sampled for given combination. For untreated control replicates, the value for each Site×Treatment combination was the mean of 8 (or 6) control plots sampled at a given site. Means for untreated controls at a given site were utilized only after it was verified that the 8 (or 6) plots did not significantly vary ($\alpha = 0.10$). A general linear model was utilized to test if a given parameter varied among all treatments ($\alpha =$

0.10; Minitab v.15.1.30.0); if so, then Tukey's multiple comparison tests were subsequently utilized to identify specific differences between treatments and control.

Datasets were tested against the two assumptions of the general linear model for normality of the residuals and equal variance. All datasets met these requirements unless otherwise noted.

3.3 Results

Surface fuel loads significantly varied between treatments for multiple categories (Table 2), including 10-hr and 1000-hr dead fuels and litter (Figure 1).

Table 2. Mean surface fuel loads (Mg/ha) for treated and control areas in the Klamath Mountains as calculated with the FIREMON software (n=3 per treatment). Numbers in parentheses represent standard deviation of the mean.

Surface Fuel Parameter	Treatment: Control	Fire Only	Thin Only	Thin + Fire	Thin + Pile & Burn	P-value
1-hr	0.36	0.18	0.34	0.13	0.35	0.15
	(0.77)	(0.17)	(0.12)	(0.12)	(0.13)	
10-hr	1.09	0.25	1.19	0.20	0.65	0.00
	(0.22)	(0.22)	(0.29)	(0.16)	(0.14)	
100-hr	1.32	0.73	1.77	0.74	0.74	0.27
	(0.62)	(0.20)	(1.07)	(0.48)	(0.36)	
1000-hr	2.77	1.16	3.31	1.07	1.74	0.03
	(0.48)	(0.26)	(1.42)	(0.66)	(0.54)	
Duff load	2.35	2.29	0.68	0.51	1.48	0.23
	(1.35)	(1.89)	(0.75)	(0.30)	(1.56)	
Litter load	4.88	2.13	4.42	2.31	4.00	0.01
	(1.42)	(1.34)	(1.42)	(1.77)	(0.65)	

When compared to the untreated control, patterns of changes in fuel loading were similar across the four treatments (Figure 1). Surface fuel load reductions were greatest in the Thin+Fire and the Fire-Only treatments, while Thin+Pile&Burn showed only a slight decrease. Thin Only showed an increase in several categories, including the 1000 hour fuels.

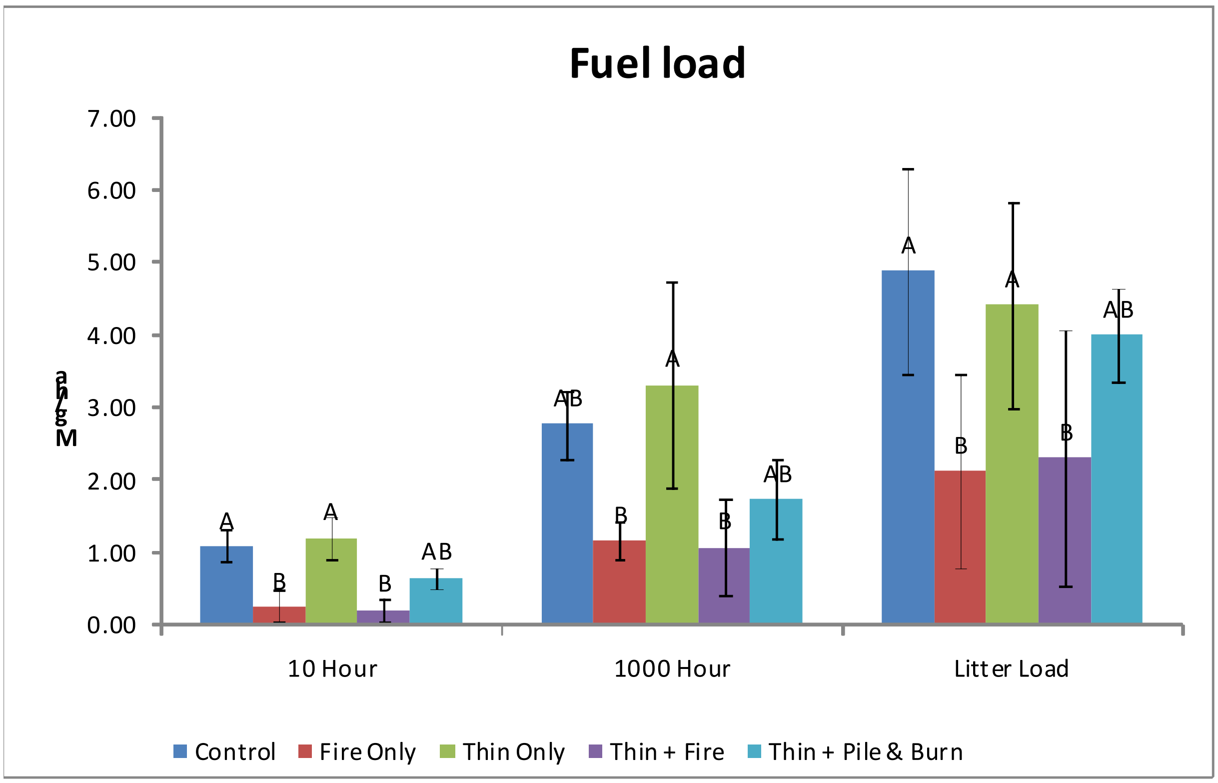

Figure 1. Mean fuel loads (with standard deviations) for 10-hr, 1000-hr, and litter on treated and control areas in the Klamath Mountains. Bars represent standard deviation of the mean (n=3 per treatment). Differing letters represent significant differences between means (α = 0.10) for each given fuel category.

Canopy properties are shown in Table 3. Canopy base height was raised under the four treatments, with the Thin+Fire treatment significantly higher than the untreated control ($\alpha = 0.10$, Figure 2). Canopy bulk density and Available Canopy Fuel Load did not vary significantly between treatments.

Table 3. Mean canopy fuel parameters for treated and control areas in the Klamath Mountains as calculated with FuelCalc software (n=3 per treatment). Numbers in parentheses are standard deviation of the mean.

Canopy Parameter		Treatment Control	Fire Only	Thin Only	Thin + Fire	Thin + Pile & Burn	P-value
Canopy Bulk Density	(kg/m^3)	0.110 (0.037)	0.108 (0.023)	0.131 (0.028)	0.099 (0.014)	0.083 (0.003)	*0.22*
Canopy Base Height	(m)	4.36 (0.48)	11.32 (2.97)	10.88 (5.33)	13.17 (1.23)	7.50 (0.18)	*0.04*
Available Canopy Fuel Load	(Mg/ha)	3.60 (1.07)	2.94 (0.96)	3.52 (0.85)	2.69 (0.27)	2.71 (0.73)	*0.60*

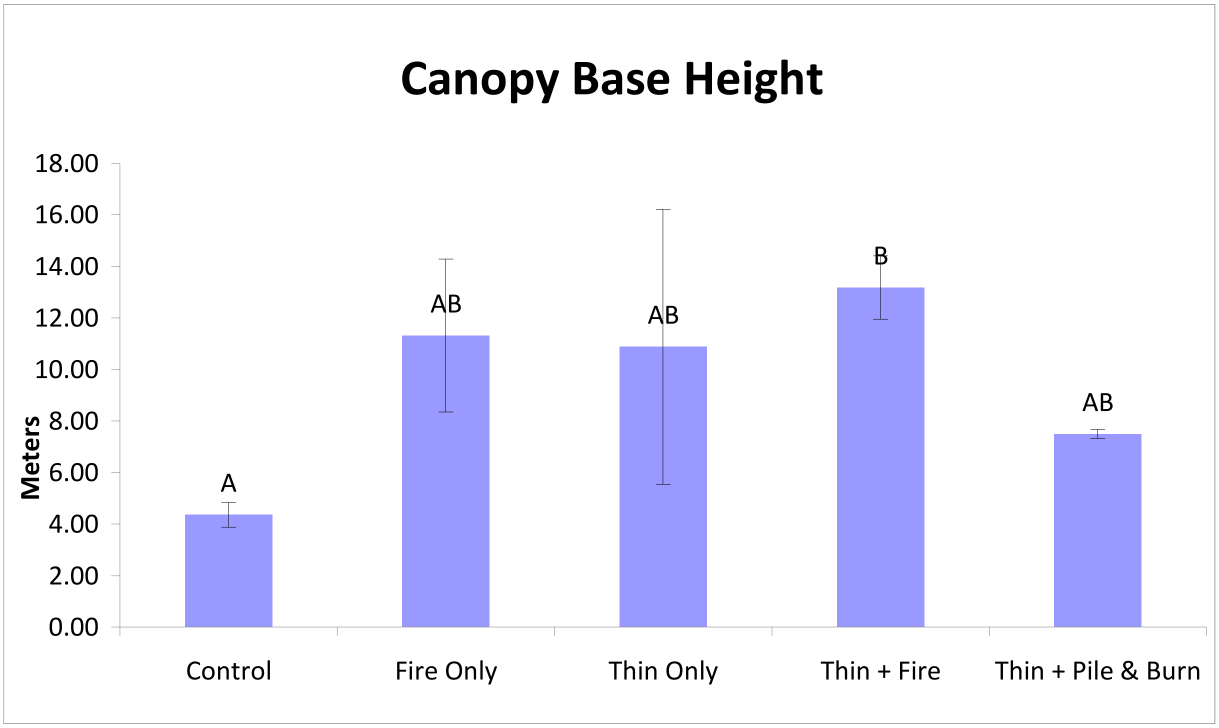

Figure 2. Mean canopy base heights (with standard deviations) for treated and control areas in the Klamath Mountains. Bars represent standard deviation of the mean (n=3 per treatment). Differing letters represent significant differences between treatments (α = 0.10) comparison between the four treatment types in the Klamath mountains.

Fire behavior is strongly affected by weather characteristics, exhibiting higher intensities and spread rates under more extreme weather conditions (table 4). Fuel treatments showed a general decrease in fire behavior indices.

Table 4. Mean simulated fire behavior from NEXUS under 50th, 90th, and 97th percentile weather conditions in the Klamath Mountains. Numbers in parentheses are standard deviation of the mean.

		Control	Fire Only	Thin Only	Thin + Fire	Thin + Pile & Burn	p-value
50th percentile							
Crown Fraction Burned	%	0.22 (0.04)	0.00 (0.00)	0.00 (0.01)	0.00 (0.00)	0.03 (0.05)	0.00
Rate of Spread	m/min	7.77 (3.57)	3.86 (2.50)	5.63 (1.79)	1.38 (0.45)	5.49 (4.27)	0.17
Heat Release	kJ/m2	46189 (16257)	18911 (14441)	27412 (4490)	1503 (262)	22282 (18269)	0.02
Fireline Intensity	kW/m	8114 (7590)	1619 (1489)	2652 (1279)	36 (18)	2908 (2675)	0.15
Flame Length	m	5.63 (2.61)	2.00 (1.35)	2.87 (0.64)	0.37 (0.12)	2.67 (2.12)	0.03
Torching Index	km/hr	10.22 (1.71)	154.87	40.57 (35.54)	466.00	209.50	0.14
Crowning Index	km/hr	40.91 (14.54)	35.40 (7.03)	31.83 (4.82)	38.93 (4.65)	43.90 (1.06)	0.41
90th percentile							
Crown Fraction Burned	%	0.64 (0.20)	0.24 (0.42)	0.57 (0.51)	0.00 (0.00)	0.28 (0.25)	0.27
Rate of Spread	m/min	18.61 (2.10)	9.74 (7.57)	15.57 (6.23)	3.19 (1.10)	12.30 (9.50)	0.14
Heat Release	kJ/m2	67537 (11076)	29223 (27695)	52395 (18281)	1765 (308)	32028 (26311)	0.04
Fireline Intensity	kW/m	24008 (10392)	7065 (8842)	14858 (9109)	98 (51)	9342 (8226)	0.07
Flame Length	m	16.47 (1.12)	6.27 (7.35)	13.20 (8.53)	0.60 (0.17)	6.93 (5.75)	0.08
Torching Index	km/hr	7.19 (0.74)	122.30	28.87 (23.69)	369.40	164.67	0.14
Crowning Index	km/hr	35.48 (12.75)	30.73 (6.13)	27.57 (4.21)	33.80 (4.07)	38.17 (0.91)	0.41
97th percentile							
Crown Fraction Burned	%	0.86 (0.20)	0.67 (0.58)	1.00 (0.00)	0.67 (0.58)	0.51 (0.44)	0.75
Rate of Spread	m/min	28.37 (0.24)	20.40 (14.56)	28.81 (0.00)	20.59 (14.24)	19.17 (14.83)	0.79
Heat Release	kJ/m2	74822 (9901)	41700 (33824)	64062 (8780)	16563 (13191)	38056 (31438)	0.11
Fireline Intensity	kW/m	33053 (2749)	29211 (4651)	30766 (4216)	11557 (1540)	25985 (1885)	0.03
Flame Length	m	26.85 (1.21)	17.10 (14.16)	26.13 (2.40)	9.33 (7.52)	13.40 (11.20)	0.21
Torching Index	km/hr	5.33 (0.15)	102.97	22.83 (18.92)	313.80 (99.73)	136.43	0.13
Crowning Index	km/hr	35.48 (12.75)	30.67 (6.19)	27.57 (4.21)	33.73 (4.04)	38.13 (0.95)	0.42

Several treatment effects on fire behavior differed significantly under the three weather scenarios examined. Although the fire behavior variables that differed were not the same for each weather scenario (table 5), the same pattern was observed in all cases where the Thin+Fire treatment showed the statistical difference from the Control ($\alpha = 0.10$).

Table 5. Significant differences ($\alpha = 0.10$) between fire behavior variables and corresponding percentile weather conditions. Differing letters indicate differences found using Tukeys comparison.

		Control		Fire Only		Thin Only		Thin + Fire		Thin + Pile & Burn		P-value
50^{th}												
CFB	%	0.22 (0.04)	A	0.00 (0.00)	B	0.00 (0.00)	B	0.00 (0.00)	B	0.03 (0.05)	B	0
HPUA	kJ/m^2	46189 (16257)	A	18911 (14441)	AB	27412 (4490)	AB	1503 (262)	B	22282 (18269)	AB	0.02
FLML	m	5.63 (2.61)	A	2.00 (1.35)	AB	2.87 (0.64)	AB	0.37 (0.12)	B	2.67 (2.12)	AB	0.03
90^{th}												
HPUA	kJ/m^2	67537 (11076)	A	29223 (27695)	AB	52395 (18281)	A	1765 (308)	B	32028 (26311)	AB	0.04
FLIN	kW/m	24008 (10392)	A	7065 (8842)	AB	14858 (9109)	AB	98 (51)	B	9342 (8226)	AB	0.07
FLML	m	16.47 (1.12)	A	6.27 (7.35)	AB	13.20 (8.53)	AB	0.60 (0.17)	B	6.93 (5.75)	AB	0.08
97^{th}												
FLIN	Kw/m	38125 (8997)	A	29211 (4651)	A	30766 (4216)	A	11557 (1540)	B	25985 (1885)	AB	0.05

Fireline intensity under the 97^{th} percentile conditions was the only dataset that did not meet the normality assumption of the general linear model. Various transformations of the data were attempted (Log10, LogN, Square root, Cubed rood) however there were no improvements on the normality results. Further examination identified three values (one each for the Fire Only, Thin + Fire, and Thin + Pile & Burn treatments) that were much lower than the remaining values which were contributing to an abnormal distribution of the residuals. Further investigation into these values showed unusually low surface fuel levels when compared to the remaining samples, due to the recent nature of those particular fuel treatments (within two months rather than 1 – 3 years for the remaining samples). As these were not considered representative replications of the remaining samples, these values were dropped from the statistical evaluation. Once dropped, further statistical tests met the normality assumption of the model.

Fire behavior under the 97^{th} percentile conditions exhibited greater intensities and spread rates than either the 50^{th} or 90^{th}. Fire intensity was the only value that differed significantly under the 97^{th} percentile conditions, though it was highest in the Control under all weather scenarios (Figures 3, 4, 5).

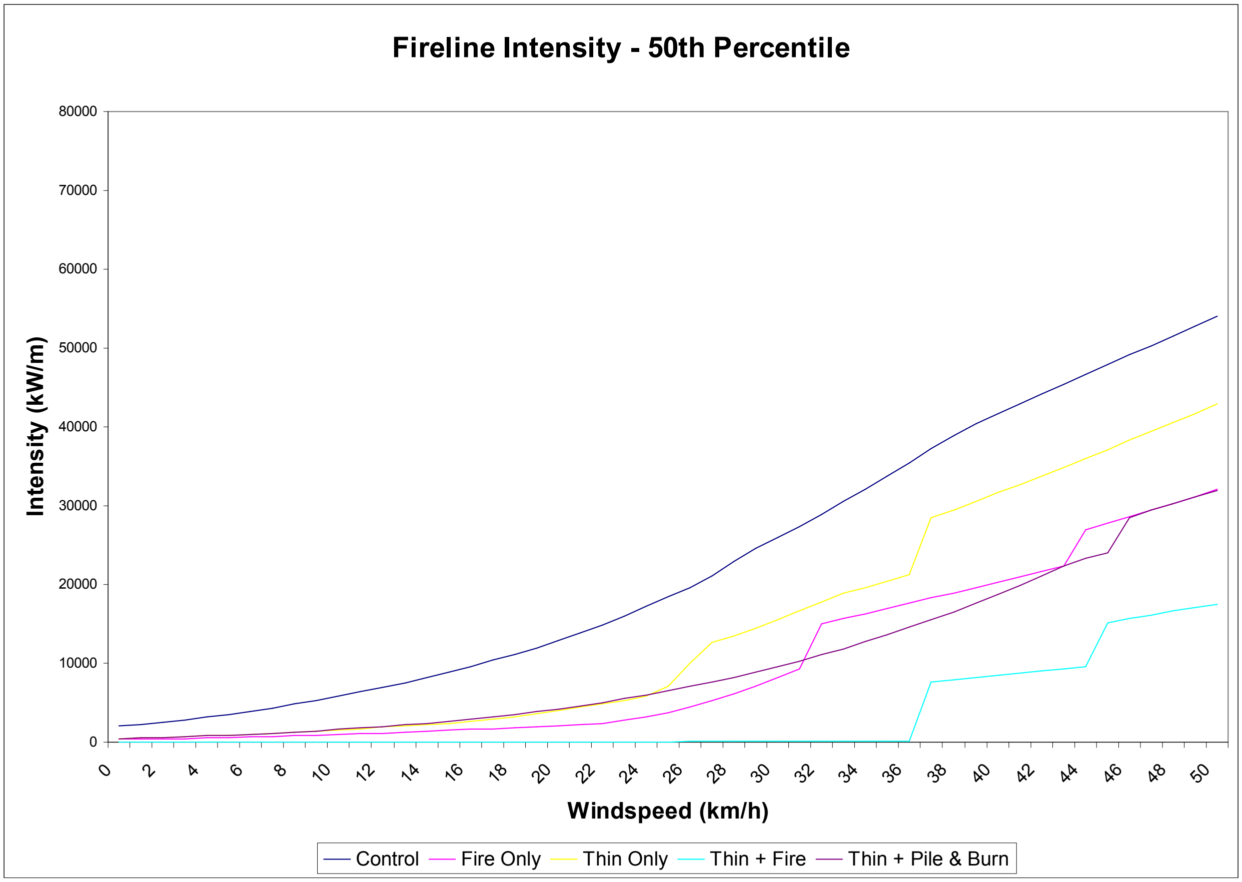

Figure 3. Calculated fireline intensity outputs from NEXUS for the Klamath Mountain study site illustrating changes resulting from increased windspeeds under 50th percentile weather conditions.

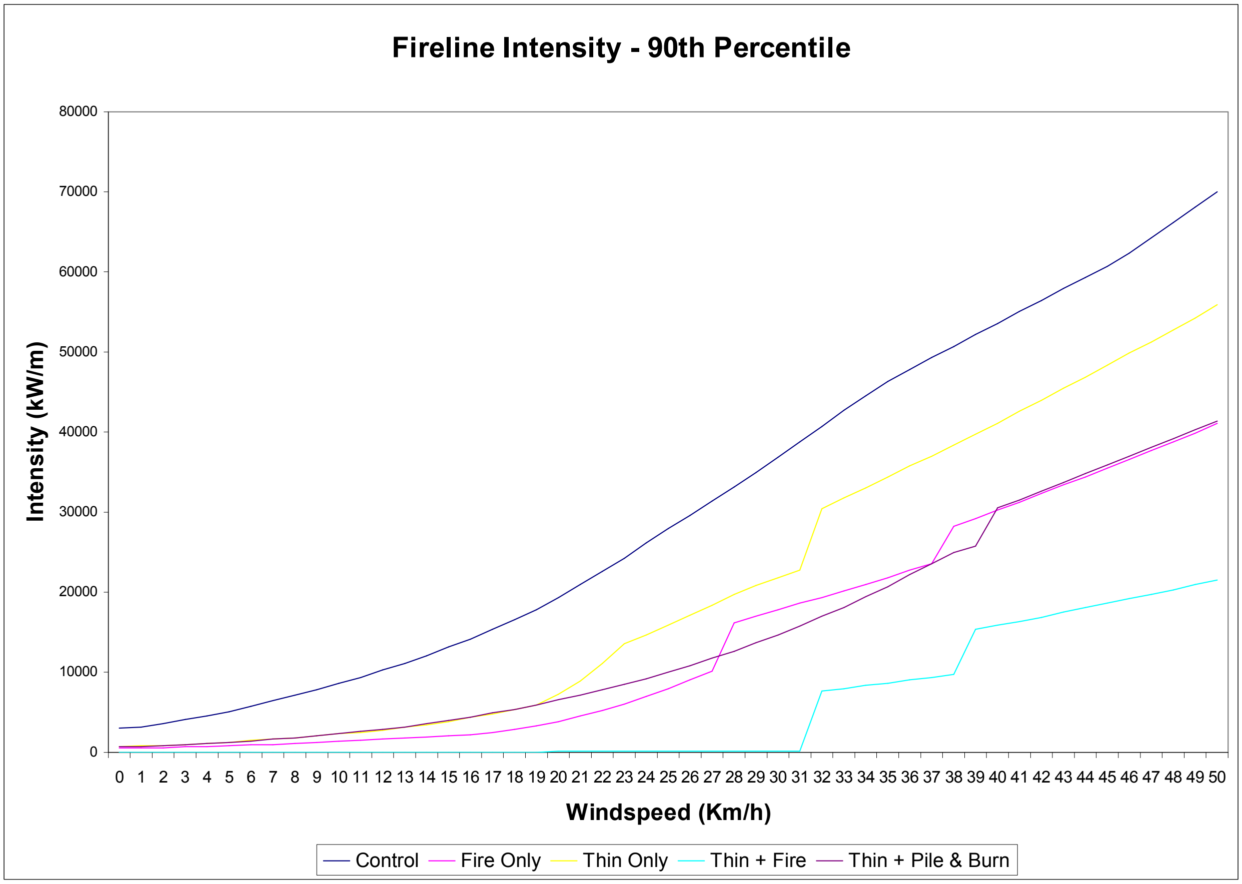

Figure 4. Calculated fireline intensity outputs from NEXUS for the Klamath Mountain study site illustrating changes resulting from increased windspeeds under 90th percentile weather conditions.

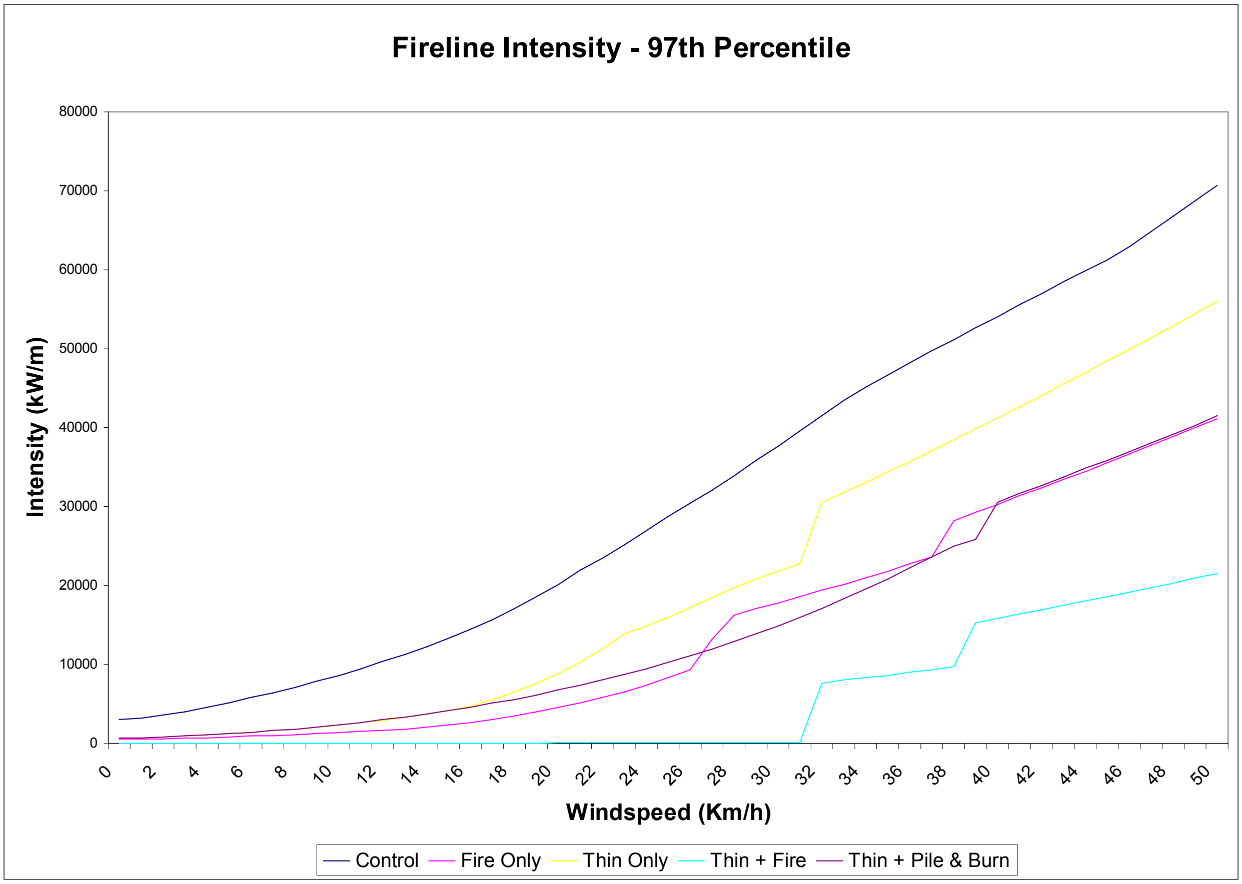

Figure 5. Calculated fireline intensity outputs from NEXUS for the Klamath Mountain study site illustrating changes resulting from increased windspeeds under 97th percentile weather conditions.

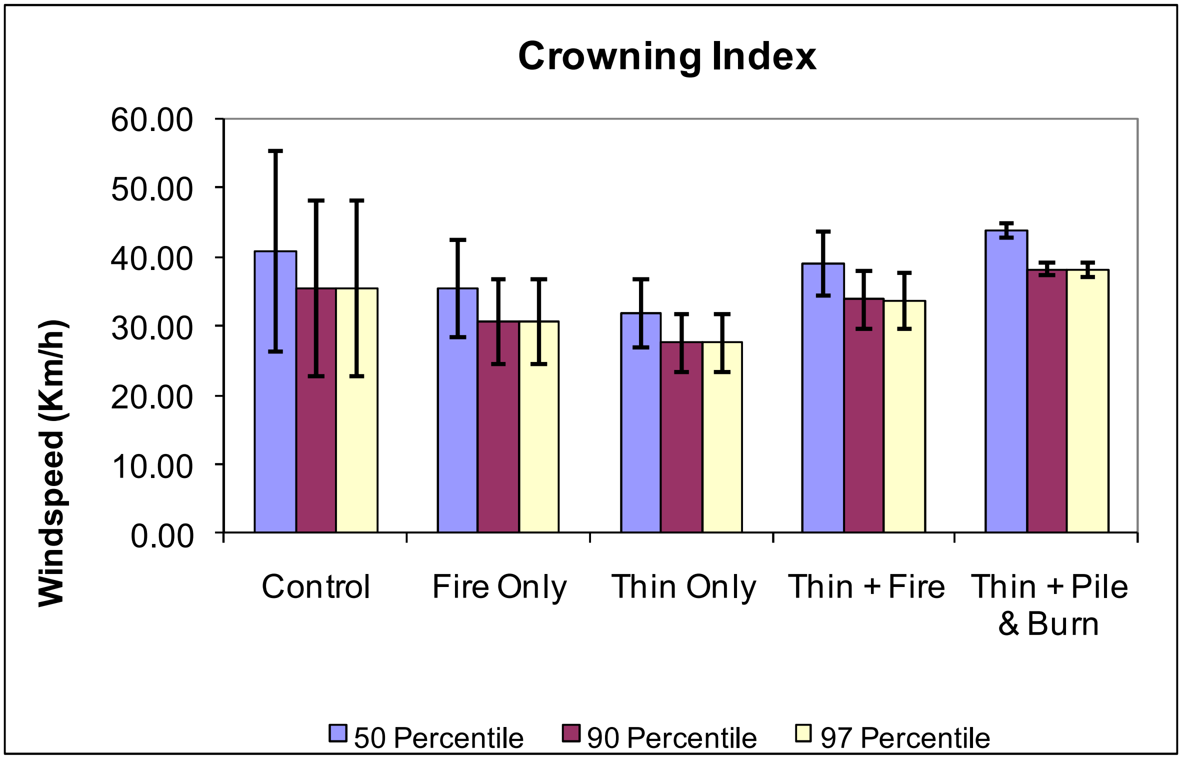

Figure 6. Mean crowning index (CI) for the various fuel treatments under 50th/90th/97th percentile weather conditions in the Klamath Mountains (n = 3 per treatment). No statistical difference was observed (α = 0.10)

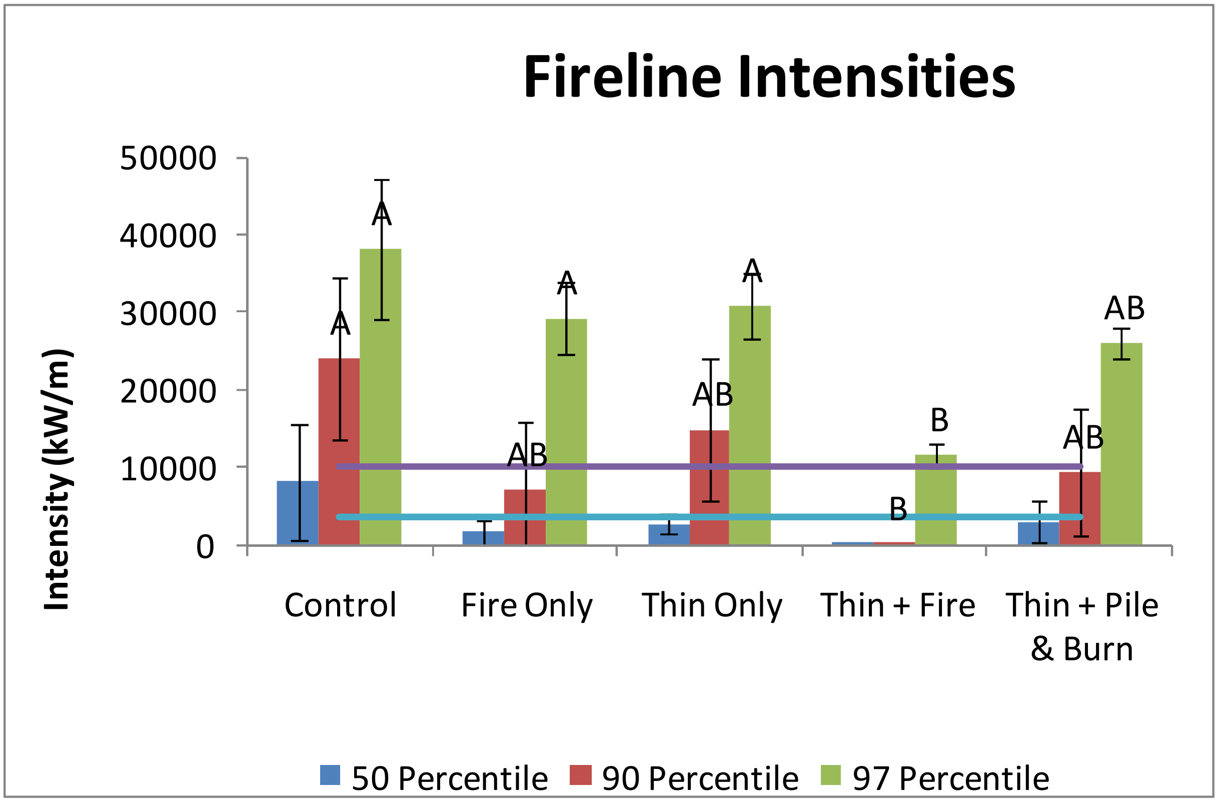

Figure 7. Mean fireline intensities (with standard deviations) under 50th/90th/97th weather scenarios for different fuel treatments (n = 3 per treatment). Lower line (3,500 kW/m) indicates suppression capabilities of ground crews, upper line (10,000 kW/m) indicates overall upper suppression capabilities. Differing letters illustrate Tukeys statistical differences (α = 0.10).

3.4 Discussion

For maximum efficacy, fuel treatments should reduce surface fuels, ladder fuels, and crown densities (Agee and Skinner, 2005; Agee et al, 2000). In general, reducing surface fuels lowers surface fire intensity, raising canopy base height increases the threshold fireline intensity necessary to transition from a surface fire to a crown fire, and reducing crown bulk density increases the rate of spread that is required to sustain an active crown fire (Scott & Reinhart, 2001; Agee and Skinner, 2005; Graham et al, 2004).

In the present study fuel treatments that did not specifically target surface fuels (i.e., Thin Only) had higher remaining fuel loads than the Fire Only and Thin + Fire options which consumed the surface fuels during their burning component (figure 1) . The Thin Only treatment fuel loads were similar and slightly higher in the 10 hour and 1000 hour fuels, likely due to an increase in slash from the mechanical operations as seen in other studies (Agee and Skinner, 2005; Graham et al., 2004). Similar results were shown in Schmidt et al (2008) where thinning treatments contributed to a 67 % increase in 100 hour fuels (versus 72 % in this study), while burn treatments had lower fuel loads than the control or thinned stands. The Thin + Pile & Burn treatment slightly reduced the 10 hour and 1000 hour fuels, however its effect on litter load was negligible likely due to the scattered and localized location of burn piles.

Treatment effects on canopy base height differed significantly in this study, with the Thin + Fire treatment having the greatest change (280 % increase). Similar results were found in Schmidt et al. (2008) where thin and burn had a substantial impact on canopy base height (430 % increase). The combined Thin + Fire treatment reduced canopy base height and canopy bulk density via thinning, while the broadcast fire further increased canopy base height and reduced surface fuel loads (Graham et al, 2004). This is important to affecting fire behavior because it reduces surface fire intensities and the subsequent energy released which contributes to initial canopy combustion. The simultaneous decrease in canopy bulk density and increase in canopy base height results in an increased energy requirement to initiate and sustain canopy fuel combustion. Together, these decrease the risk of a crown fire developing.

Canopy bulk density effects did not differ significantly between the treatments, ($p = 0.21$) and ranged between 0.08 (Thin + Pile & Burn) to 0.13 (Thin Only). Similar studies identified continuous crown fire threshold CBD values of 0.074 – 0.125 kg/m3 (Agee, 1996) and 0.10 kg/m3 (Scott, 2003). The low thinning methods used in this study did not reduce the canopy bulk density to a point where active crown fire spread was not possible (table 3), minimizing differences in crowning index between the treatments (figure 6).

The lack of treatment effect on canopy bulk density is also evident in considering fireline intensity outputs (figures 3, 4 5). The fuel treatments reduced the initial intensity for varying lengths of time, until enough energy was produced to sustain an active crown fire. After this point, all treatments followed a similar pattern of increased intensity with increased windspeed. Under all three weather scenarios, the Thin + Burn treatment proved the most effective at minimizing intensity.

The effectiveness of fuel treatments is related both to the resulting fuel complex and the weather conditions under which an advancing fire is burning. Under extreme weather conditions, characterized by high winds and low relative humidity, it is unlikely that the reduced fuel loads will stop a fire (Fernandes and Botelho, 2003) due to fire spread characteristics. The high winds can push flaming embers from the fire front over a treated area igniting more fires that continue to spread (Keeley et al., 2004). However, fuel treated areas are not intended to stop an advancing fire front, but rather is to reduce fire behavior and subsequent fire severity

(Reinhardt et al., 2008) and also to potentially allow suppression resources a higher chance of success (Agee et al, 2000; Finney and Cohen, 2003; Graham et al., 2004; Schmidt et al, 2008).

Fire behavior in this study showed a strong response to the weather scenarios, with increases observed under all treatments as the weather trended towards extreme values. Fireline intensity is a determining factor in suppression success or failure, with 3,000 – 4,000 kW/m commonly recognized as the limit for ground force suppression and 10,000 kW/m as a level above which all suppression efforts will fail (Hirsch and Martell, 1996).

The four treatments examined in this study were successful at reducing fireline intensities to a level where ground suppression forces could contain them, but only under the 50^{th} percentile weather conditions. Under more extreme fire weather scenarios, even the treated stands were burning at levels near or beyond suppression capabilities. The Thin + Fire treatment was the only simulation that kept fireline intensity near the 10,000 kW/m threshold under the most extreme (97^{th} percentile) weather conditions considered (figure 7).

3.5 Conclusions

Treatments to reduce potential fire behavior must follow address three important criteria: a reduction in surface fuels, an increase in canopy base height, and a reduction in crown density (Agee and Skinner, 2005). Combinations of these objectives will affect surface fire, crown fire initiation (torching) and active crown fire spread. The four treatments considered in the present study used different methods to affect the fuels complex to various degrees, with reductions in fire behavior reflected in their overall impact on different components of the fuel complex.

Thin Only treatments do not greatly affect surface fuels with the exception of compaction resulting from the use of equipment, and can potentially contribute to an increase in fuel loads depending on the method of tree removal (Agee and Skinner, 2005; Graham et al., 2004) which can result in an increase in surface fire behavior (Graham et al., 1999). Fire Only treatments can affect multiple fuelbed characteristics by consuming lower ladder fuels and killing lower branches on trees thereby raising the canopy base height (Graham et al, 2004); however, it has the greatest impact on reducing surface fuel loads (Van Wagtendonk, 1996; Schmidt et al, 2008). Thin + Pile & Burn treatments do not treat surface fuels over the entire site, rather they only reduce those in the vicinity of the burn piles.

Post-treatment wildfire intensity and severity in thinned stands will be most effective when surface fuels also reduced (Graham et al., 1999, 2004). The most effective fuel treatment strategy is to thin the understory vegetation, which decreases canopy bulk density and increases canopy base height, followed by a method to reduce surface fuels such as prescribed fire, piling and burning coarse surface fuels, or mastication (Graham et al, 2004) as was found in this study.

Statistical differences between the four treatments and the untreated control were significant in only a few of the calculated variables. However this does not indicate the absence of an effect. This study was limited to a small sample size (n = 15), and due to time constraints treatment age ranged between 1 – 3 years. The varied time since treatments occurred introduced a large amount of variability into the small sample size (as evidenced by several large standard deviations) which may mask true treatment differences.

Data from this study indicate that the Thin + Burn treatment had the greatest reduction in potential fire behavior under the three weather scenarios due to its effect on canopy base height from the mechanical component and its reduction of surface fuels through the burn component. Although the other treatment options considered resulted in a noticeable reduction in fire behavior, their impacts were lessened due in part to the remaining canopy and surface fuel loads. This illustrates the effect different levels of the fuel complex (surface, ladder, and canopy) have on fire behavior and the importance of choosing treatment options that manipulate the entire complex to achieve fire behavior reduction goals under various weather components.

It is important to consider the overall goal of any fuel treatment project, and the weather conditions under which they may be subjected. Under the 50^{th} percentile conditions for this area, all four treatments kept intensities to a level where ground suppression crews could safely take action and protect any values at risk. However under the 97^{th} percentile conditions, fire intensities in three of the four treatments would likely exceed all suppression capabilities. This does not indicate a success of one type of treatment over another; rather it illustrates the importance of setting clear and realistic goals when planning fuel reduction projects for the purpose of wildfire hazard mitigation.

4.0 Ecosystem Services

4.1 Introduction

In 2000 3.1% of the continental United States was classified as urban, or areas with "all territory, population, and housing units located within either urbanized areas or urban clusters" (Nowak et al., 2005). As urban sprawl increases across the nation the amount of area in the interface zones, the boundary between urban development and wildland vegetation, increases as well. This expansion alters and displaces forests, agricultural fields and other open spaces, and is likely to become one of the greatest factors affecting forests in the 21st century (Nowak et al., 2005).

The transition of land use in the interface zone from forestry or agricultural land to urban areas raises a number of environmental concerns (Alavalapati et al., 2005), including ecosystem fragmentation, increased potential for invasive species invasion, pollution concerns, and wildfire (Nowak et al., 2005). The trees and associated resources in these areas are often in close proximity to large populations, meaning they can greatly influence the health of people living in those areas (Alavalapati et al., 2005; Nowak et al., 2005). Since they are frequently close to populations, management within them is viewed by a large number of people (Nowak et al., 2005), and new neighbors can mean new or different values, lifestyles, and ethics which may lead to tension and conflicts regarding management of these areas (Alavalapati et al., 2005).

There are a number of benefits and services provided by vegetation, providing a potential important role in the wildland-urban interface (WUI) such as carbon cycling and air pollutant removal.

Carbon is sequestered from the atmosphere as trees grow and is stored in their tissues. The overall amount of carbon trees can store is directly related to their size, with larger trees estimated to store 1000 times more carbon than smaller trees (Nowak and Dwyer, 2007). Across the continental United States, the amount of carbon stored in urban forests is estimated to be equivalent to the amount of carbon emitted by the total population in 5.5 months (Nowak and Dwyer, 2007), while the current forest was estimated to store 800 million tons of carbon at the end of the last century (Rowntree and Nowak, 1991).

Air pollutants are another concern in many urban centers, and urban vegetation has been shown as a way to reduce pollution levels (Nowak et al., 2006). Urban vegetation seems to reduce ozone (O_3) in the greatest amounts, followed by particulate matter less than ten microns (PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO) (Nowak et al., 2006). Although the effect on O_3, SO_2 and NO_2 is greatest during daytime of the in-leaf season when water is being transpired, particulate matter removal occurs both day and night throughout the year (Nowak et al., 2006).

Urban vegetation also serves as fuel for wildfire, which is of great importance due to high social and economic costs and losses making the protection of homes in the interface a primary concern (Cohen, 2001). Wildfire frequency and intensity have shown a dramatic increase over the past few decades, due in part to a combination of forest fuel buildup and climate change (Westerling et al., 2006). Several disastrous fires have resulted in a number of fatalities and a large number of homes being lost, and the traditional reactive approach of wildfire suppression is proving inefficient and ineffective.

Efforts are shifting to a proactive management approach focusing on reducing the potential fire hazard through mitigation actions consisting of home building improvements, land use planning, and fuel treatments to reduce fuels and establish defensible space around homes and communities. The principle of defensible space is to disrupt the horizontal and vertical continuity of the fuels, slowing or stopping advancing wildfires and making them easier to control (Agee and Skinner, 2005). Emphasis is often placed on fuel management around homes through the manipulation of flammable biomass by reducing, removing, or rearranging the surrounding forest fuels (Omi, 2007).

There are a variety of methods to mitigate hazardous fuels including prescribed fire, mechanical treatments or a combination of the two. Rarely, however, do fuel treatments consider the impacts to ecosystem services provided by trees (Dicus et al., 2009) such as carbon storage and sequestration, reduced home energy-use and subsequent power plant emissions, improved air quality, and hydrologic filtration (Nowak and Dwyer, 2007; Dicus, 2008). To fully understand the impacts of management in the interface zone, these factors must be considered and weighed against the benefits of the fuels treatments (Dicus and Zimmerman, 2007). Therefore, the overall objective of this study was to determine how common fuel treatments impacted ecosystem services in the Klamath Mountains of Northern California.

4.2 Methods

4.2.1 Site Description

The study area is located in the western Klamath Mountains of northern California (latitude: 41.1, longitude: -123.1). The highly complex terrain there, which ranges between 30 to 2,755 m elevation and is deeply incised has contributed to complex fire regimes in the area, with a long history of lighting ignitions and anthropogenic fires (Taylor and Skinner, 2003; Skinner et al., 2006). Climate there is Mediterranean, typified by wet and cool winters followed by warm and dry summers (Skinner et al., 2006). The majority of precipitation occurs between the months of October and April, often occurring in the winter as snow, although thunderstorm occurrence is common in the summer months (Skinner et al., 2006).

Like climate, vegetation in the Klamath Mountains reflects gradients in topography and precipitation, which create a heterogeneous species distribution (Skinner et al., 2006) controlled largely by elevation and soil moisture (Taylor and Skinner, 1998; Taylor and Skinner, 2003).

Multilayered, multi-aged mixed-conifer forests are common, with Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) as the most widely distributed conifers in the local area (Agee, 1993). The prevalence of Douglas-fir and the diversity of understory hardwoods distinguish Klamath mixed-conifer forests from other forest types in the Pacific Northwest (Taylor and Skinner, 2003). Species composition in these mixed-conifer forests vary with elevation and aspect; generally lower elevation sites are comprised of a mixture of Douglas-fir, ponderosa pine and sugar pine (*Pinus lambertiana*), while higher elevation sites are characterized by a mixture of Douglas-fir, white fir (*Abies concolor*), and sugar pine (Taylor and Skinner, 1998).

Surface fuels regularly consist of continuous beds of dry forbs, grasses, hardwood leaves and conifer needles, which support frequent, low-intensity surface fires (Taylor and Skinner, 1998). Fire return intervals are generally shorter in Klamath mixed conifer forests than is found further north (Agee, 2007). Median fire return intervals are similar among species composition groups (12 – 19 years), although they were shorter on south and west slopes than north and east slopes. Fire suppression policies in the last century, however, have increased the fire return intervals from the historic range of variability (Taylor and Skinner, 1998).

4.2.2 Field Measurements

Vegetation and fuels data were obtained in three different sites located within 20 km from one another on the Klamath National Forest. Data were collected in untreated areas, as well as areas treated by one of the following fuel treatments. All data was collected within three years of the initial treatment to minimize the amount of variability.

1. Thin-only: mechanical thinning from below where cut vegetation was transported to the nearest road and subsequently chipped or burned.
2. Fire-only: broadcast prescribed fire with no pre-fire mechanical treatment.
3. Thin+Fire: mechanical thinning from below where cut vegetation was removed from the site, followed by a broadcast prescribed fire.
4. Thin + Pile & Burn: Mechanical thinning from below where cut vegetation was piled on-site and subsequently burned.

For each Site×Treatment combination, data were collected in three 0.08 ha plots. Thus, data were collected in 12 treated plots per site, or 36 treated plots over all 3 sites. Data were also collected in two adjacent, untreated 0.08 ha plots for each Site×Treatment combination. However, due to the close proximity of some treatment treated areas, untreated control plots were shared for a Site×Treatment combination at two sites. Thus, data were collected in 20 untreated control plots over all 3 sites (8+6+6).

At each 0.08 ha plot, species and diameter at breast height (1.37 m), total height, and height-to-live crown were measured on all trees > 1.37 m in height.

4.2.3 Ecosystem Services

I-tree Eco software (formerly the Urban Forest Effects model: UFORE) was used to calculate various ecosystem services based on tree measurements (table 6). It is a computer simulation used to calculate the structure, environmental effects and values of urban forests (Nowak and Crane, 1998). Field data was supplemented with calculations from existing literature to provide required variables (such as Percent Canopy Missing) that were not measured in the field.

Crown width was calculated using equations from the Forest Vegetation Simulator variant overviews. Crown Light Exposure, Percent Canopy Missing, and Crown Light Exposure were obtained or interpreted based on Forest Inventory Analysis (FIA) surveys from the Klamath National Forest (Personal Communication- David Nowak). This information allowed calculation of structural, air pollution removal, and carbon storage and sequestration by the I-tree software.

Table 6. Modeling components for the I-tree Eco software and their corresponding required variables.

Required Variable	Structural	Air Pollutant Removal	Carbon Storage / Sequestration	VOC emissions	Energy Conservation	Pollen Index
Tree Species	X	X	X	X	X	X
DBH	X		X			
Height to Live Crown	X	X		X		X
Tree Height	X	X	X	X	X	X
Crown Width	X	X		X		X
Crown Light Exposure	X		X			
Percent Canopy Missing	X	X		X		X
Crown Dieback	X		X		X	
Distance / Direction to building					X	

4.2.4 Statistical analysis

For statistical testing, the experimental unit for a given parameter was a Site×Treatment combination. Thus, n=3 replicates for each Site×Treatment combination, or total n=15 replicates (3 sites, each with 4 treatments and 1 untreated control). For treated replicates, the value for each Site×Treatment combination was the mean of 3 plots sampled for given combination. For untreated control replicates, the value for each Site×Treatment combination was the mean of 8 (or 6) control plots sampled at a given site. Means for untreated controls at a given site were utilized only after it was verified that the 8 (or 6) plots did not significantly vary ($\alpha = 0.10$). A general linear model was utilized to test if a given parameter varied among all treatments ($\alpha = 0.10$; Minitab v.15.1.30.0); if so, then Tukey's multiple comparison tests were subsequently utilized to identify specific differences between treatments/control.

Datasets were tested against the two assumptions of the general linear model for normality of the residuals and equal variance. All datasets met these requirements.

4.3 Results

All fuel treatments significantly (α = 0.10) reduced the number of trees per hectare as compared to the untreated control, with no differences appearing between the individual treatments (figure 8).

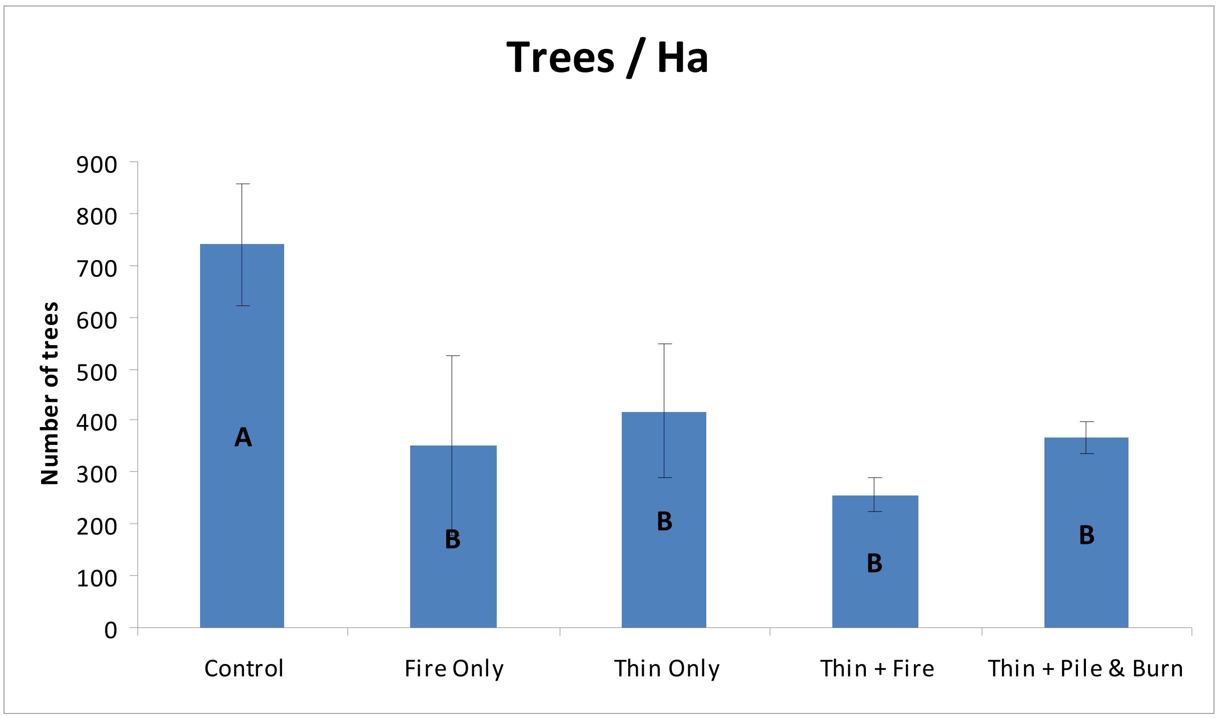

Figure 8. Mean resulting trees per hectare (with standard deviations)(n = 3 per treatment) for control and treatment plots at the Klamath Mountains study site calculated with the I-tree Eco software. Differing letters indicate statistically significant differences (α = 0.1)

Carbon storage ranged from 210,875 kg/ha to 316,984 kg/ha and did not significantly vary between treatments and the control (table 7). Carbon sequestration ranged from 4,823 kg/ha/year to 8195 kg/ha/year and was lower in all of the treated stands compared to the control.

Significant differences (α = 0.10) were found in the Thin+Fire treatment compared to the Control, but not between the other treatments (figure 9).

Table 7. Mean Fuel loads (Mg/ha) for treated and control plots calculated with I-tree Eco software in the Klamath Mountains (n = 3 per treatment). Numbers in parentheses are standard deviation of the mean.

	Control	Fire Only	Thin Only	Thin + Fire	Thin + Pile & Burn	P-value
Storage (kg/ha)	316984 (80243)	217027 (35577)	229590 (35387)	210875 (86093)	230596 (79130)	*0.44*
Sequestration (kg/ha/year)	8195 (1510)	5339 (1443)	5830 (1077)	4823 (879)	5567 (746)	*0.07*

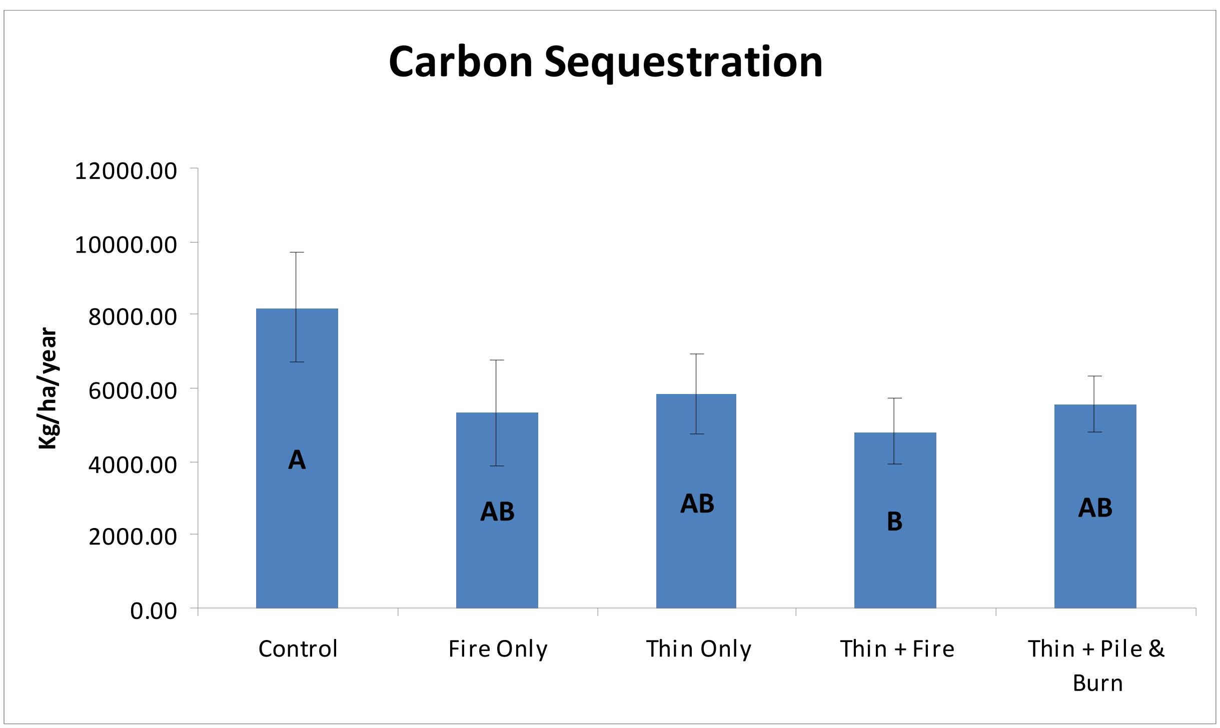

Figure 9. Mean carbon sequestration rates (with standard deviations) (n = 3 per treatment) for control and treated plots at the Klamath Mountains study site calculated using I-tree Eco software. Differing letters indicate statistically significant differences (α = 0.10)

Air pollution removal, which is directly attributable to canopy leaf area, was decreased in the fuel treatments but did not vary significantly ($\alpha = 0.10$) between treatments (table 8). Leaf area is used to calculate pollution removal.

Table 8. Mean leaf area calculated with I-tree Eco software for the control and treated areas in the Klamath Mountains (n = 3 per treatment). Numbers in parentheses are standard deviation of the mean.

Km^2	Control	Fire Only	Thin Only	Thin + Fire	Thin + Pile & Burn	P-value
Leaf Area	0.05028 (0.01007)	0.03500 (0.01229)	0.04000 (0.00866)	0.03000 (0.00200)	0.03233 (0.00451)	*0.14*

The software calculates the total pollutants removed for the group of stands (all treated and untreated areas together) (figure 10). Using the amount of leaf area per stand in conjunction with the amount of pollutants removed would allow for a calculation of removal per treatment type.

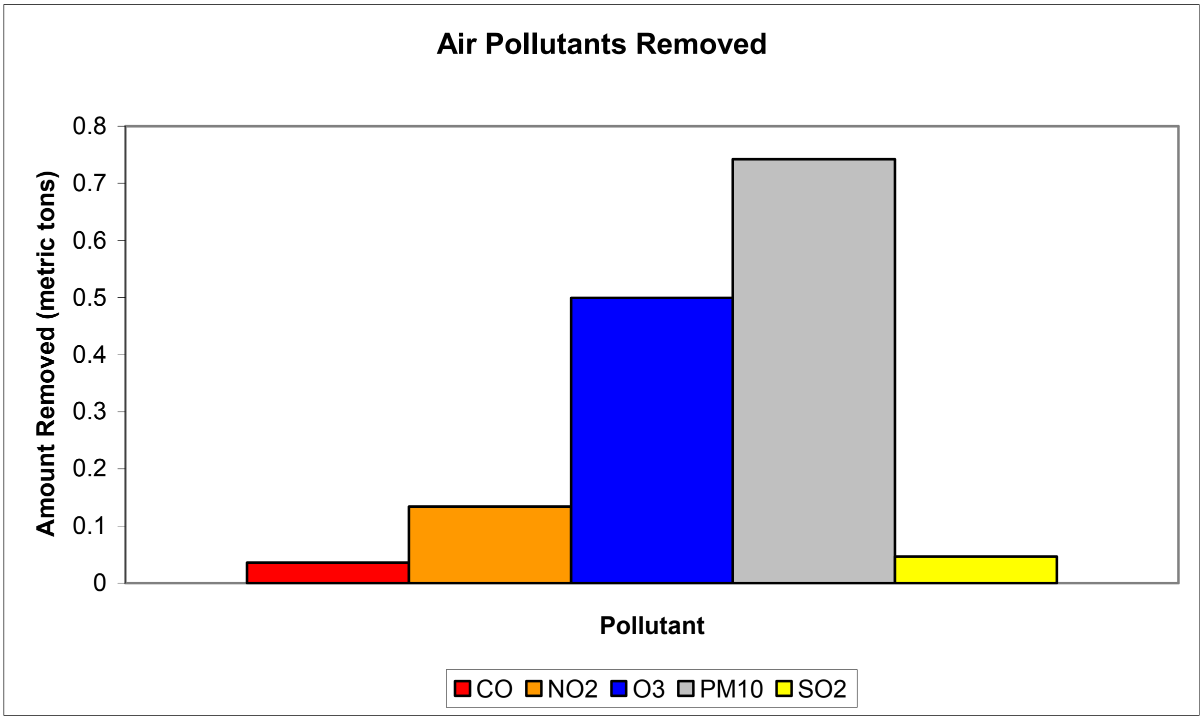

Figure 10. Total amount of pollutants removed from the forest in the Klamath Mountains study site calculated with the I-tree Eco software.

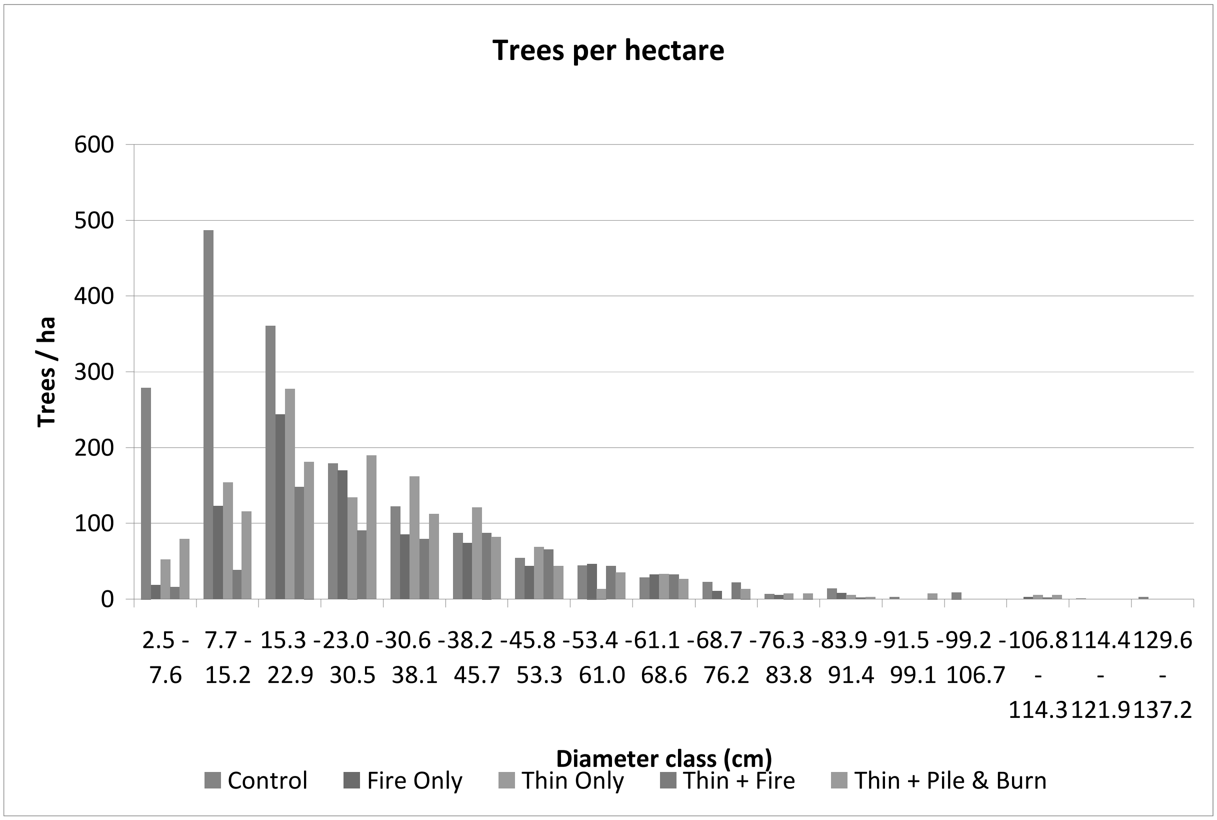

Figure 11. Mean trees per hectare by diameter class for control and treated areas in the Klamath Mountains calculated with the I-tree Eco software (n = 3 per treatment).

4.4 Discussion

Carbon storage is based upon the total biomass for each tree, which the I-tree software calculates based on equations from the literature using tree species, height and diameter. Carbon sequestration is based upon the storage potential of annual average biomass growth (Nowak and Crane, 1998). Carbon sequestration occurs through an uptake of carbon monoxide which is stored in tissues, which occurs both day and night during the in-leaf season for trees (Nowak et al., 2006). Sequestration is based on tree size with larger healthy trees estimated to sequester around 93 kilograms of carbon per year versus 1 kilogram of carbon per year for smaller trees.

This total rate of sequestration from trees in urban areas across the United States is equivalent to the total emissions from the total population over a five day period (Nowak and Dwyer, 2007).

Although carbon storage did not differ significantly between the treatments, carbon sequestration rates showed a difference between the Thin+Fire and Control treatments. This difference can be explained by considering the trees targeted in the fuel treatments. Larger diameter trees, which contribute more to the total carbon storage, were not greatly reduced under any of the treatments. Smaller diameter trees, which contribute more to the rates of carbon sequestration, were reduced (figure 11).

Trees can remove pollutants in the air either through interception and deposition on their surface areas (such as bark or branches) or by direct absorption through the stomata where they are diffused into intercellular spaces (Nowak et al., 2006; Smith, 1990 in Nowak and Dwyer, 2007). The amount of pollution removed from the surrounding air is directly influenced by the amount of healthy leaf surface area, local air pollutant concentration, and local meteorology (Nowak and Dwyer, 2007). Air pollution removal calculations are based on total leaf area and hourly pollution-concentration data (Nowak and Crane, 1998). Although no significance differences were found between treatments, examination of calculated leaf area per treatment type (table 7) shows a pattern of reduced leaf area when each treatment is compared to the control. The large degree of variability between the replications coupled with the small sample size make statistical differences difficult to detect.

4.5 Conclusions

The I-tree Eco software was able to model stand structure, carbon storage and sequestration, and air pollution removal based on forest inventory data and calculation of variables using equations from the literature. This facilitates the use of the model, as standard inventory data can be used without requiring specialized field surveys.

Statistical significance was limited in the results, which may be a result of small sample size (n = 15) and a resulting high degree of variability that made treatment effects difficult to identify.

Fuel reduction treatments will subsequently reduce ecosystem services that a stand provides dependent on the pretreatment composition and structure of the stand and on the type and intensity of the treatment. The extent of this effect will be determined by the targeted vegetation, such as smaller versus larger trees. The loss of ecosystem services by fuel treatments should therefore be weighed against the potential benefits of fire hazard reduction to justify specific management actions.

5.0 Project Conclusions

5.1 Additional Considerations

Under the circumstances presented in this study one might be led to believe certain fuel treatments excel over others. However there are a number of constraints that were not explored in this project that may influence a manager's choice of action.

The costs involved in these treatments are a large factor that was not investigated. Under most situations, a successful fire-only treatment will be significantly cheaper than comparable treatments relying on mechanical thinning methods. However the costs can significantly increase in the event of an escaped fire. One option for cost recovery has been the harvest of larger, commercially valuable timber (Keeley et al., 2004) however this propagates fears that fuel reduction treatments will be used as a cover for increased harvesting in sensitive areas (Omi and Martinson, 2004).

There are also a number of operational issues that may limit the options available, such as equipment limitations and time constraints that would factor into a managers decision. Equipment used and time frames for each fuel treatment were not explored in this study.

Social considerations also play an important role in the WUI, as actions often occur in close proximity to people with a variety of values and opinions which can create conflicts regarding potential management decisions (Winter et al., 2002; Keeley et al., 2004). Although residents generally understand the goals behind fuel treatments, their support has been shown to be associated with perceived outcome such as negative aesthetic qualities, potential for escaped fires and smoke emissions (Winter et al., 2002).

5.2 Final Remarks

The goal of fuel treatments in the wildland urban interface is often to protect values at risk, including homes and infrastructure. From this perspective, trees and wildland vegetation are considered as potential fuel to a wildfire that must be removed to mitigate the hazard. As discussed, trees and other wildland vegetation do more than combust during a fire event. Carbon storage and sequestration and air pollution removal were two ecosystem services that were measured in this study, however there are many others including hydrologic filtration, nutrient cycling, and aesthetic improvement.

The focus of this project was not only to consider the effects fuel treatments had on fire behavior and ecosystem processes, but also to compare and contrast the two categories to examine trade-offs or costs and benefits of implementing various fuel treatments. This study used computer software to quantify and compare changes in both categories. Fire behavior models have been used extensively for many years, and are continually improving and involving through the continuous improvement of hardware, software, and knowledge. Ecosystem service models such as the I-tree software suite are relatively new, but evolving quickly. No one fuel treatment stands out above the rest under all categories considered. Although some statistical differences were found, a recommended course of action would be based upon the desired management objectives.

This study has also shown the importance of meteorological factors in determining a fuel treatments impact on fire behavior. Under the average (50^{th} percentile) weather conditions, all four treatments considered would keep wildfire intensity below a controllable level. However under extreme (97^{th} percentile) weather conditions, the Thin + Fire treatment was the only one where the fire intensity was below a threshold at which suppression efforts could be effective.

This emphasizes the importance of setting clear management objectives, and recognizing limitations of the tools used.

The basic principle from either perspective is that removing vegetation, regardless of the manner in which it is removed, can have an effect. The magnitude of the effect is determined by how much vegetation is removed, and there will be trade-offs between different values. Removing all of the trees from a site would eliminate the risk of crown fires, however carbon storage and air pollution removal would be non-existent. A balance between the two goals is required, and to obtain this balance land managers must consult with local stakeholders to determine various goals, values and objectives. Computer simulations such as the programs used in this study can be useful for calculating and illustrating potential outcomes, providing tools that can be used to ensure suitable actions are taken to allow people to safely inhabit the wildland urban interface while protecting the services it provides.

6.0 References

Agee, J.K. (1993). *Fire ecology of Pacific Northwest forests.* Washington, DC : Island Press.

Agee, J.K. (1996). The influence of forest structure on fire behavior. In *Proceedings of the 17th Annual Forest Vegetation Management Conference*, January 16 – 18, 1996 (pp. 52– 68). Redding, CA.

Agee, J.K. (2003). Monitoring postfire tree mortality in mixedconifer forests of Crater Lake. Oregon. *Nat. Areas J., 23,* 114–120.

Agee, J.K. (2007). *Stewards fork: a sustainable future for the Klamath Mountains*. Berkeley and Los Angeles: University of California Press.

Agee, J.K., Bahro, B., Finney, M.A., Omi, P.N., Sapsis, D.B., Skinner, C.N. et al. (2000). The use of shaded fuel breaks in landscape fire management. *For. Ecol. Manage.*, *127,* 55 – 66.

Agee, J.K., & Skinner, C.N. (2005). Basic principles of forest fuel reduction treatments. *For. Ecol. Manage., 211,* 83-96.

Alavalapati, J.R.R., (2005). Overview of policies influencing the wildland–urban interface. In S.W Vince, M.L. Duryea, E.A. Macie, & L.A. Hermansen, (Eds.), *Forests at the Wildland–Urban Interface: Conservation and Management.* 2005 (pp. 63 – 76) Boca Raton, FL. RC Press LLC.

Alavalapati, J.R.R., Carter, D.R., & Newman, D.H. (2005). Wildland-urban interface: challenges and opportunities. *For. Pol. Econ. 7,* 705-708.

Anderson, H.E., (1982). *Aids to determining fuel models for estimating fire behaviour.* (U.S. Department of Agriculture Forest Service). Gen. Tech. Report. INT-122

Andrews, P.L., & Queen, L.P. (2001). Fire modeling and information system technology. *Int. J. Wildland Fire. 10,* 343 – 352.

Andrews, P. L., C. D. Bevins, & R. C. Seli. (2008). BehavePlus fire modeling system, version 4.0: User's Guide. (U.S. Department of Agriculture Forest Service). Gen. Tech. Report. RMRS-106

Arno, S.F., (1996) *The seminal importance of fire in ecosystem management – impetus for this publication.* In: Hardy, C.C. & Arno, S.F., (Eds.). *The use of fire in forest restoration.* (U.S. Department of Agriculture Forest Service). Gen. Tech. Report. INT-341.

Barrett, T.M., Jones, J.G., & Wakimoto, R.H. (2000). Forest service spatial information use for planning prescribed fires. *Western J. Applied Forestry, 15, 4,* 200 – 207.

Beukema, S.J., Reinhardt, E.D., Greenough, J.A., Robinson, D.C.E., & Kurz, W.A., (2003). Chapter 2 fire and fuels extension: model description. (U.S. Department of Agriculture Forest Service). Gen. Tech. Report. RMRS-116.

Bonnicksen, T.M. (2008). Greenhouse gas emissions from four California wildfires: opportunities to prevent and reverse environmental and climate impacts. FCEM Report 2. The Forest Foundation, Auburn, California. 19 p.

Busby, G., & Albers, H.J. (2010). Wildfire risk management on a landscape with public and private ownership: who pays for protection?. *Env. Manage. 45*, 296 – 310.

Certini, G. (2005). Effects of fire on soil properties: a review. *Oecologia, 143,* 1 – 10.

Cohen, J.D. (1999). Reducing the wildland fire threat to homes: Where and how much?. (U.S. Department of Agriculture Forest Service) Gen. Tech. Report. PSW-173.

Cohen, J.D. (2001). Wildland-Urban fire - a different approach, In: Proceedings of the Firefighter safety summit, International Association of Wildland Fire, Missoula, MT. November 6 – 8.

Cortner, H.J., Gardner, P.D., & Taylor, J.G. (1990). Fire hazards at the urban – wildland interface: what the public expects. *Env. Manage., 14,* 57 – 62.

Cruz, M.G., Alexander, M.E., & Wakimoto, R.H. (2005). Development and testing of models for predicting crown fire rate of spread in conifer forest stands. *Can. J. For. Res., 35,* 1626 – 1639.

Davis, J.B. (1987, October). The wildland-urban interface: what it is, where it is and its fire management problems. Paper presented at the Symposium and Workshop on Protecting People and Homes from Wildfire in the Interior West, Missoula, MT.

Davis, J.B. (1990). The wildland-urban interface: paradise or battleground?. *J. For., 88,* 26 – 31.

Debano, L.F. 1981. Water repellent soils: a state of the art. (U.S. Department of Agriculture Forest Service) Gen. Tech. Report. PSW-46.

Debano, L.F., & Krammes, J.S. (1966). Water repellent soils and their relationship to wildfire temperatures. *International Bulletin Assoc. Hydrological Scientists, 2,* 14-19.

Dicus, C.A. (2008). Changes to simulated fire behavior and societal benefits after two levels of thinning in a mixed-conifer wildland-urban interface community. Proceedings of the Royal Society of Queensland *115*, 37-44.

Dicus, C.A., Delfino, K., & Weise, D.R. (2009). Predicted fire behavior and societal benefits in three Eastern Sierra Nevada vegetation types. *Fire Ecol. 5 [special issue], 67 – 78.*

Dicus, C. A., & Scott, M.E. (2006, March). Reduction of Potential Fire Behavior in Wildland-urban Interface Communities in Southern California: A Collaborative Approach. (U.S. Department of Agriculture Forest Service) Conference Proceedings, RMRS-P-41.

Dicus, C.A., & Zimmerman, M.P. (2007). Quantifying fire behavior vs. community benefits of southern California shrublands and grasslands. Proceedings of the 23rd Tall Timbers Fire Ecology Conference: Fire in grassland and shrubland ecosystems. Tall Timbers Research Station, Tallahassee, Florida, USA.

Dixon, Gary E., (2003). Essential FVS: A User's Guide to the Forest Vegetation Simulator. (U.S. Department of Agriculture Forest Service) Internal Rep. Fort Collins, CO: Forest Management Service Center. 193p.

Fernandes, P.M., & Botelho, H.S. (2003). A review of prescribed burning effectiveness in fire hazard reduction. *Int. J. Wildland. Fire., 12,*117 – 128

Finney, M.A., & Cohen, J.D. (2003). Expectation and Evaluation of Fuel Management Objectives. (U.S. Department of Agriculture Forest Service) Conference Proceedings, RMRS-P-29.

Graham, R.T., Harvey, A.E., Jain, T.B., & Tonn, J.R. (1999). The effects of thinning and similar stand treatments on fire behaviour in western forests. (U.S. Department of Agriculture Forest Service) Gen. Tech. Report. PNW-463.

Graham, R.T., McCaffrey, S., & Jain, T.B. (2004). Science basis for changing forest structure to modify wildfire behaviour and severity. (U.S. Department of Agriculture Forest Service) Gen. Tech. Report. RMRS-120.

Haight, R.G., Cleland, D.T., Hammer, R.B., Radeloff, V.C., & Rupp, T.S. (2004). Assessing fire risk in the wildland urban interface. *J. For., Oct / Nov,* 41 – 48.

Haines, T.K., Martinez, J., & Cleaves, D.A. (1998). Influences on prescribed burning activity in the United States National Forest System. *Int. Forest Fire News, 19,* 43-46.

Hirsch, K.G., & Martell, D.L. (1996). A review of initial attack fire crew productivity and effectiveness. *Int. J. Wildland Fire, 6,* 199 – 215.

Hurteau, M., Koch, G.W., & Hungate, B.A. (2008). Carbon accounting and fire risk reduction: toward a full scale accounting of forest carbon offsets. *Frontiers. Ecol. Environ , 6,* 493–498.

Hurteau, M., & North, M. (2009). Fuel treatment effects on tree-based forest carbon storage and emissions under modeled wildfire scenarios. *Frontiers. Ecol. Environ., 7,* 409–414.

Ice, C.G., Neary, D.G., & Adams, P.W. (2004). Effects of wildfire on soils and watershed processes. *J. For., Sept.,* 16 – 20.

Keeley, J.E., Fotheringham, C.J., & Moritz, M.A. (2004). Lessons from the October 2003 wildfires in southern California. *J. For., Oct/Nov,* 26 – 31.

Lobard, J.M., & Warnatz, J. (1993). Emissions from the combustion process in vegetation. In*:* P.J.Crutzen & J.G. Goldammer (Eds.), *Fire in the environment: The ecological, atmospheric, and climatic importance of vegetation fires* (pp. 16 – 37). John Wiley & Sons ltd.

Lutes, D.C., Keane, R.E., Caratti, J.F., Key, C.H., Benson, N.C., Sutherland, S., Gangi, L.J. (2006). FIREMON: Fire effects monitoring and inventory system. (U.S. Department of Agriculture Forest Service) Gen. Tech. Report. RMRS-164.

Martinson, E.J., & Omi, P.N. (2003). Performance of fuel treatments subjected to wildfires. (U.S. Department of Agriculture Forest Service) Proceedings RMRS-P-29.

McKinney, M.L. (2002). Urbanization, Biodiversity, and conservation. *BioScience, 52,* 883 – 890.

McPherson, E.G. 1987. Effects of vegetation on building energy performance. Ph.D.Discussion, State University of New York College of Environmental Science and Forestry, Syracuse, NY.

Merriam, K.E., Keeley, J.E., & Beyers, J.L. (2007). The role of fuel breaks in the invasion of nonnative plants. (U.S. Geological Survey Scientific Investigations Report) 2006-5185, 69 p.

Moghaddas, E.E.Y., & Stephens, S.L. (2007). Thinning, burning, and thin-burn fuel treatment effects on soil properties in a Sierra Nevada mixed-conifer forest. *For. Ecol. Manage., 250,* 156 – 166.

Mohr, J.A., Whitlock , C. & Skinner, C.N. (2000). Postglacial vegetation and fire history, eastern Klamath Mountains, California, USA. *The Holocene, 10,* 587-601.

Nowak, D.J., & Crane, D.E. (1998). The Urban Forest Effects (UFORE) model: Quantifying urban forest structure and functions. In Integrated Tools Proceeding, Boise, ID. August 16 – 20. (pp. 714 – 720).

Nowak, D.J., Crane, D.E., & Stevens, J.C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban For. & Urban Greening, 4,* 115 – 123.

Nowak, D.J., & Dwyer, J.F. (2007). Understanding the Benefits and Costs of Urban Forest Ecosystems. In J. E. Kuser (Ed.) *Urban and Community Forestry in the Northeast* (pp. 25 – 46). Springer Netherlands.

Nowak, D.J., Walton, J.T., Dwyer, J.F., Kaya, L.G.a, & Myeong, S. (2005). The Increasing influence of urban environments on US forest management. *J. For,103 ,* 377-382.

Odion, D.C., Frost, E.J., Strittholt, J.R., Jiang, H., Dellasala, D.A., & Moritz, M.A. (2004). Patterns of fire severity and forest conditions in the Western Klamath mountains, California. *Conserv. Biol., 18,* 927-936.

Omi, P.N., (2007, May). Fuel treatments to prevent and manage wildfires. Paper presented at the Wildfire 2007 conference, Sevilla, España.

Omi, P.N., & Martinson, E.J. (2004). Effectiveness of thinning and prescribed fire in reducing wildfire severity. (U.S. Department of Agriculture Forest Service) Gen. Tech. Report. PSW-193.

Omi, P.N., Martinson, E.J., & Chong, G.W. (2006). Effectiveness of pre-fire fuel treatments. Final report, Joint Fire Science Project, 03-2-1-07.

Peterson, D.L., Johnson, M.C., Agee, J.K., Jain, T.B., McKenzie, D., & Reinhardt, E.D. (2005). Forest structure and fire hazard in dry forests of the western United States. (U.S. Department of Agriculture Forest Service) Gen. Tech. Report. PNW-628.

Radeloff, V.C., Hammer, R.B., Steward, S.I., Fried, J.S., Holcomb, S.S., & McKeefry, J.F. (2005). The wildland-urban interface in the United States. *Ecol. App., 15,* 799 – 805.

Reinhardt, E.D., & Crookston, N.L. (2003). The Fire and Fuels Extension to the Forest Vegetation Simulator. (U.S. Department of Agriculture Forest Service) Gen. Tech. Report. RMRS-116.

Reinhardt, E., Lutes, D., & Scott, J. (2006). FuelCalc: A Method for Estimating Fuel Characteristics. In Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management-How to Measure Success: Conference Proceedings. (U.S. Department of Agriculture Forest Service) Proceedings RMRS-P-41.

Reinhardt, E.D., Kean, R.E., Calkin, D.E., & Cohen, J.D., (2008). Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *For. Ecol. Manage., 256,* 1997 – 2006.

Rowntree, R.A., & Nowak, D.J. (1991). Quantifying the role of urban forests in removing atmospheric carbon dioxide. *J. Arboriculture, 17,* 269 – 275.

Schmidt, D.A., Taylor, A.H., & Skinner, C.N. (2008). The influence of fuels treatment and landscape arrangement on simulated fire behavior, Southern cascades range, California. *For. Ecol. Manage., 255,* 3170 – 3184.

Scott, J.H. (2003). Canopy fuel treatment standards for the wildland-urban interface. (U.S. Department of Agriculture Forest Service) RMRS-P-29.

Scott, J. H., & Reinhardt, E.D. (2001). Assessing crown fire potential by linking models of surface and crown fire behavior. (U.S. Department of Agriculture Forest Service) Proceedings RMRS-RP-29.

Skinner, C.N. (2003). A tree-ring based fire history of riparian reserves in the Klamath. In P. M. Faber (Ed.), *California riparian systems: processes and floodplains management, ecology, and restoration, 2003* (pp. 116 – 119) Riparian habitat and floodplains conference, Sacramento, CA.

Skinner, C.N., Taylor, A.H., & Agee, J.K. (2006). Klamath Mountains Bioregion, In N. G. Sugihara et al., (Eds.), *Fire in California's ecosystems* (pp. 170 – 194). Berkeley and Los Angeles, CA.: Univ. of California Press,

Stephens, S.L. (1997). Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in Sierra Nevada mixed-conifer forests. *For. Ecol. Manage., 105,* 21 – 35.

Stephens, S.L., & Moghaddas, J.J. (2005). Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. *For. Ecol. Manage., 215,* 21 – 36.

Stephens, S.L., Moghaddas, J.J., Hartsough, B.R., Moghaddas, E.E.Y., & Clinton, N.E. (2009). Fuel treatment effects on stand-level carbon pools, treatment – related emissions, and fire risk in a Sierra Nevada mixed – conifer forest. *Can. J. For. Res., 39,* 1538 – 1547.

Stewart, S.I., Radeloff, V.C., & Hammer, R.B. (2003). Characteristics and location of the wildland-urban interface in the United States. In *Proceedings of the Second International Wildland Fire Ecology and Fire Management Workshop*, 2003. November 16–20. Orlando, FL.

Strom, B.A., & Fulé, P.Z. (2007). Pre-wildfire fuel treatments affect long-term ponderosa pine forest dynamics. *Int. J. Wildland Fire, 16,* 128 – 138.

Taylor, A.H., & Skinner, C.N. (1998). Fire history and landscape dynamics in a late-successional reserve, Klamath Mountains, California, USA. *For. Ecol. Manage. 111,* 285-301.

Taylor, A.H., & Skinner, C.N. (2003). Spatial patterns and controls on historical fire regimes and forest structure in the Klamath mountains. *Ecol. Applic. 13,* 704-719.

Theobald, D.M., Miller, J.R., & Hobbs, N.T. (1997). Estimating the cumulative effects of development on wildlife habitat. *Landscape Urban Planning, 39,* 25 – 36.

Van Wagtendonk, J.W. (1996). Use of a deterministic fire growth model to test fuel treatments. Sierra Nevada Ecosystem Project: Final report to Congress, vol. II, Assessments and scientific basis for management options. Davis: University of California, Centers for Water and Wildland Resources.

Van Wagtendonk, J.W., & Sydoriak, C.A. (1987). Fuel accumulation rates after prescribed fires in Yosemite National Park. In *Ninth conference on fire and forest meteorology*, 1987 (pp. 101 – 105). Meteor. Soc., San Diego, CA.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., & Melillo, J.M. (1997). Human domination of earth's ecosystems. *Sci., 277,* 494 – 499.

Weatherspoon, C.P. (1996). Fire-silviculture relationships in Sierra forests. Sierra Nevada Ecosystem Project: Final report to Congress, vol. II, Assessments and scientific basis for management options. Davis: University of California, Centers for Water and Wildland Resources, 1996.

Weaver, H. (1943). Fire as an ecological and silvicultural factor in the Ponderosa Pine region of the Pacific slope. *J. For.,* 7 – 17.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., & Swetnam, T.W. (2006). Warming and earlier spring increase western U.S. forest wildfire activity. *Sci., 313,* 940 – 943.

Winter, G.J., Vogt, C., & Fried, J.S., (2002). Fuel treatments at the wildland-urban interface: common concerns in diverse regions. *J. For., Jan / Feb,* 15 – 21.

Woodbury, P.B., Smith, J.E., & Heath, L.S. (2007). Carbon sequestration in the US forest sector from 1910 to 2010. *For. Manage. Ecol., 241,* 14 – 27.

7.0 Appendices

Appendix A. Sample tree data recording sheet.

Appendix B. Sample surface vegetation data recording form.

Appendix C. Sample of data recording form for Browns transects.

Appendix D. Sample tree data recording sheet.

Site / Plot: ______________________ Date: ____________________

Tree #	Height to Live	Height	DBH	Species

Appendix E. Sample surface vegetation data recording form.

Site / Plot: ____________ Date: ____________

Subplot: (1 meter = 39 inch)

30 feet

Transect #	**1**	**2**	**3**
Live Herb			
Dead Herb			
Avg. Ht.			
Live Woody			
Dead Woody			
Avg. Ht.			
Litter			
Duff			
Fuelbed			

60 feet

Transect #	**1**	**2**	**3**
Live Herb			
Dead Herb			
Avg. Ht.			
Live Woody			
Dead Woody			
Avg. Ht.			
Litter			
Duff			
Fuelbed Ht.			

Densiometer:	# Dots	x 1.04		100 - x
North		0		100
East		0		100
South		0		100
West		0		100

Regeneration Plot
(3.7 feet = 44.4 in)

Species	Tally

Slope: ____________
Aspect: ____________
Elevation: ____________
Coordinates:
lat: ____________
long: ____________

Appendix F. Sample of data recording form for Browns transects.

Site / Plot: ____________________ Date: ____________________

Transect #	1		2		3	
1 - HR						
10 - HR						
100 - HR						

1000 - HR	Diameter	Decay	Diameter	Decay	Diameter	Decay

Decay Class	
1	*sound / new*
2	|
3	|
4	|
5	*fully rotten*