THE VALUE OF INFORMATION IN USING FIRE BEHAVIOR MODELS TO PREDICT CROWN FIRE IN THE AMERICAN SOUTHWEST

By Matthew S. Smith

Professional paper

Submitted in partial fulfillment of the requirements for the degree of

Master of Forestry

Northern Arizona University

July 2011

Approved:

____
Yeon-Su Kim, Ph.D., Chair

____
Molly E. Hunter, Ph.D.

____
Gary Snider, Ph.D.

Abstract

With the growing application of fire behavior models in ecosystem restoration and fire management, the accuracy of these various models has come under close scrutiny especially when considering the conditions under which crown fire may initiate. The application of fuel reduction treatments is a widely accepted means of mitigating the threat of large, historically uncharacteristic crown fires, and the analysis of their efficacy is often dependent on these models. In this paper, I bring to light the many values placed at risk by the challenges in modeling crown fire initiation, and I give some perspective as to the monetary value that may be preserved by improving the accuracy of fire behavior models. To examine how improved information can be valuable to professionals employing fire behavior models for management decisions, I created a relatively simple economic model calculating the expected total cost (ETC) of crown fire under certain management scenarios based on literature and management records from the southwestern United States. I found significant differences in both the probability and the ETC of crown fire within the various management scenarios. Land managers need to know the reduction in crown fire probability and ETC of crown fire to plan the extent and scope of treatments. Accurate information in the modeling of crown fire behavior could ultimately reduce the cost of fuels reduction treatments by specifically narrowing the parameters of the treatments that are needed to prevent such a fire. The study results can also help reduce the cost of wildfires by guiding the most efficient and safe use of suppression resources.

Introduction

Vast expanses of ecosystems adapted to frequent, low severity fires in the American West have undergone critical changes in recent decades, sparking many of the dilemmas in land management today. Studies of both pine-dominated and dry-mixed conifer forest types throughout the West have revealed that practices, such as fire suppression, overgrazing, and the selective harvesting of large trees, have caused significant structural and functional changes to these ecosystems (Covington and Moore 1994a, Arno et al. 1995, Skinner and Chang 1996). As a result of the extraordinary tree densities and fuel loadings in these forests (Covington and Moore 1994b), the wildfires that now occur are more likely to be larger, less frequent, stand replacing crown fires (Everett 2000). The need to restore landscapes in such ecologically degraded conditions is quite evident (Covington 2000). Large-scale restoration efforts are now in the works all across the West. Collaborative groups such as the Tapash Sustainable Forest Collaborative in Washington, the Montana Forest Restoration Committee, and the Four Forest Restoration Initiative (4FRI) in Arizona are assembling to design plans to treat thousands of acres of forestlands and reestablish healthier, more resilient landscapes.

To help guide restoration efforts such as these, there has been an emergence of studies analyzing the effectiveness of fuel reduction treatments as of late (Agee and Skinner 2005, Peterson et al. 2005, Roccaforte et al. 2008). In order to test whether or not the fuel treatments may be achieving the goal of reducing fire intensity, some studies have come to rely on fire behavior models to simulate the occurrence of a fire event within a stand of equivalent characteristics (Stephens 1998; Fulé et al. 2001; Raymond and Peterson 2005; Mason et al. 2007; Schmidt, Taylor and Skinner 2008). Some of the most widely used fire modeling systems are Nexus (Scott and Reinhardt 2001), Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003), FARSITE (Finney 2004), Fuel Management Analyst (FMAPlus®) (Carlton 2005), FlamMap (Finney 2006), and BehavePlus (Andrews et al. 2008). A few of these models are now being used regularly by incident management teams to model the anticipated spread and behavior of wildfires. These models have become important in helping managers assess resource needs of suppression operations and where those resources should be deployed on the incident.

The outputs generated by these models consist of fire behavior characteristics, such as the rate of spread for both surface and crown fires, fire line intensity, flame length, and crown fraction burned. Some of the models, like NEXUS, also output both the Torching index (TI) and the Crowning index (CI). These two crown fire hazard indices were developed by Scott and Reinhardt in 2001, and are especially useful to managers and researchers that wish to predict what threshold wind speeds are required for the onset of crowning and active crown fire propagation in the coniferous forest stands they are studying or administering.

Upon the analysis of outputs, like the preceding, in simulation studies looking at the potential for high intensity crown fire, numerous instances have emerged that seem contradictory to the conditions for which crown fires would occur in common wildfire events (Hall and Burke 2006, Agee and Lolley 2006, Fulé et al. 2001). This quandary was investigated in depth by Cruz and Alexander (2010) to demonstrate that modeling systems, comparable to the above mentioned, show a marked underprediction bias when used to assess potential crown fire behavior. The authors cited the sources of bias to be (1) incompatible model linkages, (2) use of surface and crown fire rate of spread models that have and inherent underprediction bias, and (3) reduction in crown fire rate of spread based on use of unsubstantiated crown fraction burned functions (Cruz and Alexander 2010). The occurrence of these errors could have serious consequences leading to the loss of valuable resources and ecosystem health. More importantly, human life could be endangered if a wildfire experienced crown fire behavior where it was not anticipated.

Accurately modeling the fire behavior in any given stand is highly relevant to forest managers and researchers for a number of reasons. Modeling systems can be employed to recommend what sorts of silvicultural treatments are necessary to prevent high severity crown fires in common fire weather conditions that are less than extreme (Keyes and O'Hara, 2002). The results of implementing a treatment on the landscape that is supposed to prevent crown fire, but fails to do so, would mean grave consequences. Economic costs due to crown fire can be incurred through multiple means, including for example, a failure to reach economic returns on investments in stands managed for sawtimber, loss of fees collected through recreational activities due to forest closures, and diversion of government funds to the rehabilitation and regeneration of affected stands. Treatments improperly applied in the wildland-urban interface can cause losses to public property and life. Ecological deficits from uncharacteristically severe wildfires may also be evident on post-burn sites outside their natural range of variability, which may not then return to historical structures in the foreseeable future (Savage and Mast, 2005). This would mean the loss of valuable wildlife habitat characteristics of the ecosystem.

When employed on wildfire incidents, fire behavior models that inaccurately predict the occurrence of crown fire may also put firefighters in serious jeopardy.

Incident commanders and fire behavior analysts now have a variety of models to help predict future developments of the fires they are managing and are doing so in growing numbers with varying degrees of understanding for those models. More skilled users can adjust model outputs or inputs based on their experience, however this can make the model more subjective to the ability of the user. Those model outputs are then used to help write daily operational plans for suppression activities. If a fire model were to underpredict a crown fire event and fire managers placed firefighter resources in a compromised area, there may be serious ramifications including firefighter injury or loss of life. Loss of life may be deemed unacceptable under any circumstances, especially those due to improper fire modeling.

It would now seem appropriate to pose the question: What sort of value might more accurate fire modeling have in the implementation of fuels reduction treatments and wildfire behavior prediction? In wildfire economics increasing expenditures on fire suppression (C) are intended to reduce net fire related damages (NVC), and the optimal level of suppression and damage is that which minimizes total cost (Simard 1976). The sum of all wildfire related costs is known as "Cost plus Net Value Change or C+NVC, C denotes all costs associated with fire suppression and NVC denotes net fire related damages. In the most recent reformulation of the C+NVC model by Donovan and Rideout (2003) the value of more accurate fire modeling could be more precisely modeled and contribute greatly to efficient fire budgeting with the National Fire Management Analysis System used by the U.S. Forest Service. This reformulation would allow presuppression to be modeled independently of suppression and help optimize fire budgeting.

The concept to be discussed here, the application of more sound information to fuels treatments and wildfire suppression, has not been specifically addressed anywhere in the published literature that we encountered. There has, however, been a considerable amount of attention paid to incorporating better information for decision making within natural resource economics, (Adams et al. 1984, Peck and Richels 1987; Gillmeister et al. 1990; Costello et al. 1998; Fox et al. 1999; Bontems and Alban 2000) primarily in the areas of pest management and agricultural decision-making. In the majority of these studies, the value of information is estimated as the cost avoided by making better-informed decisions. Only one study estimates the value of information for a forest landowner who makes decisions under uncertainty about future fire risk. Amacher et al. (2005) estimates the value of several types of improved information about fire arrival probability and fuel reduction effectiveness to a nonindustrial landowner and varies from the focus of this study by incorporating landowner decisions, specifically, the timing of fuel reduction during a rotation, planting density, and rotation age.

A goal of this analysis is to bring to light one of the major challenges in fire management today, the importance of the accurate modeling of crown fire initiation. Understanding and anticipating under what conditions a surface fire may propagate into the crowns of trees is very important for effective forest and fire management. We also wish to give some perspective as to the monetary value that may be preserved in mitigating the underprediction of crown fire. In this paper, we estimate the value that an agency or organization might expect to place on knowing the efficacy of fuel treatments through the use of a fire behavior model. The utilization of this information is geared towards state and federal agencies because they not only are beginning to widely incorporate the use of fire models in fuels and fire planning, but they are also responsible for the management of millions of fire prone acres of public forestlands. This type of improved information would allow these land management agencies to realize the value of developing and incorporating more accurate fire behavior models that they could use to decide what types of fuels treatments to employ on the landscape. Land managers with improved information would realize the value of fuels reduction efforts that minimize fire losses, and they would be more likely to use fuels reduction efficiently (Society of American Foresters 2000, 2002).

The scope of this study entails the discussion of a model created to estimate the value of information in fire behavior modeling, simulation results based on the model that calculate the costs that could be avoided in various scenarios, and an analysis of the model outcomes including some recommendations for the future development of fire behavior models.

Methods

Data and Model Assumptions. To analyze how improved information can be valuable to officials employing fire behavior models for management decisions, I created a relatively simple economic model to calculate the expected total cost of crown fire under certain management scenarios based on literature and management records from the southwestern United States (i.e. Arizona and New Mexico). The model was constructed as follows:

$$E(TC) = CPM + Prob(CPM) \times CF$$

where -E(TC) = Expected total cost of crown fire;
-CPM = Cost of applying preventative measures (fuel reduction treatments);
-Prob (CPM) = Probability of crown fire initiation. Assuming the probability is mitigated by fuel treatments. Also assuming the crown fire will cause losses in some capacity. We base the probability calculation on a model developed by Cruz et al. (2003);
-CF (r) = fires suppression costs and present value of losses associated with crown fire at discounting rate (r);

Given that the inaccurate prediction of crown fire behavior is the overarching problem with fire behavior models, it is imperative that I incorporate a variable into the equation that directly reflects the fuel complex characteristics and fire environment conditions that influence crowning potential. For this, I choose to integrate a method developed by Cruz et al. (2003) that produces a probability of crown fire initiation under a range of fuel and weather conditions in natural conifer forest stands. Due to the dichotomous nature of crown fire initiation (i.e. occurring or not occurring), the authors chose to develop and test multiple logistic regression models for goodness of fit. This allowed for the estimation of the probability of an event occurring due to a combination of fire environment factors. These factors were taken from experimental fire data based on studies carried out in Canada encompassing several different forest stand types and a wide range of fuel complex structures.

Cruz et al. compiled a database of 63 observations involving both surface fires and crown fires set for the purpose of studying fire behavior in relation to the prevailing fuel and weather conditions. The authors stated that since the data have been obtained from outdoor experimental fires, it is implied that there is a high degree of reliability in the documentation of the fire behavior characteristics and attendant burning conditions. It was not merely a modeling simulation. Table 1 displays a list of the descriptive statistics of independent variables used in the models; however, the authors point out that foliar moisture content, canopy base height, and wind speed are the three fire environment variables that theoretically are major factors in controlling the initiation of crowning (Cruz et al. 2003).

Table 1. Basic descriptive statistics of independent variables contained in the data set used in the logistic model development (n=63) (Cruz et al. 2003)

Independent variables	Min	Max	Mean	St. Dev
Foliar moisture content (%)	80	135	108.1	8.3
Canopy Base Hight (m)	0.4	12	3.9	3
10-m open wind speed in km/h	3	29	12.6	5.5
Fine Fuel Moisture Code (FFMC)	84.5	94.1	90.5	2
Duff Moisture Code (DMC)	9	89	41.4	17.5
Drought Code (DC)	60	423	193.4	86.9
Initial Spread Index (ISI)	3.2	21.5	9.2	4
Buildup Index (BUI)	13	109	51.2	19.4
Fire Weather Index (FWI)	6	43	20.7	8.3
Rate of fire spread (m/min)	0.4	49.4	8.7	10.3
Fire Intensity (kW/m)	62	45200	6322	9342

The multiple logistic regression model used was based on that of Hosmer and Lemeshow (2000), which is designed as follows:

$P(y_i=1)=e^{g(x)}/1+e^{g(x)}$ (1)
Being the logit given by the equation:
$g(\mathrm{x})= ß_0+ß_1\mathrm{x}_1+ß_2\mathrm{x}_2+\ldots+ß_i\mathrm{x}_i$ (2)
where, $P(y_i=1)$ is the probability of crown fire occurrence, x_i are the independent variables, and $ß_i$ are the coefficients estimated through the maximum likelihood method, which produce coefficients that maximize the probability density as a function of the original set of data. A decision criterion of 0.5 as the threshold of crown fire initiation was assumed. This cutoff value has been commonly used to discriminate the continuous model response in the interval between 0.0 and 1.0 (e.g. Wilson and Ferguson 1986, Ryan and Reinhardt 1988, Wilson 1988, Borchert et al. 2002). (Cruz et al. 2003, pg. 978)

Model fit was assessed through the Nalelkerke (1991) R^2 value and the C index (Hanley and McNeil 1982, Regelbrugge and Conrad 1993). The most accurate model predicted 90% of the fires in the dataset correctly. This is the model used in my equation to give a probability of crown fire initiation for a given scenario. It is important to note that this model only incorporated the independent variables of Canopy Base Height, 10-m open wind speed, Fine Fuel Moisture Code, and Drought Code.

I computed the costs of suppression as the average per acre expenditure for large fires (of 300 acres or more) in the ponderosa pine and dry mixed conifer on public lands for which the Forest Service provided suppression support during the period 2000-2010. During this period the Forest Service in Region 3 (Arizona and New Mexico) spent an average of $205/acre (Steinke: personal contact 2011). This figure contrasts earlier estimates of suppression costs of similar characteristics used in other literature. For example, Snider and others (2006) incorporated a figure of $377/acre for the suppression of large fires in Region 3 between 1993 and 2002. The significant difference may be attributed to the Forest Service's decision to begin categorizing large fires as those above 300 acres instead of the past 100 acre or more definition. The observable trend seems to be that with increase in size the per acre cost of a fire declines. This may be why the $205/acre cost is much less than that used in other studies.

For rehabilitation costs, the data integrated into the Snider et al. (2006) publication was used. The cost of rehabilitation on these fires was figured to average $22/acre per year, but only covered emergency measures to control erosion/sedimentation and only occurred on a limited number of acres (Snider et al. 2006). This rehabilitation did not cover reforestation activities either. When converting these costs to 2011 dollars according to the Consumer Price Index, I found a value of $27/acre.

As for other losses that may be incurred due to fires with crowning activity, I looked at marketable timber as a public resource with significant value to be considered in my analysis even if the land manager does not plan to harvest. I gathered timber values from two national forests in the Southwest; the Coconino and the Kaibab. The minimum stumpage prices per hundred cubic feet (CCF) earned by the Forest Service for ponderosa pine in region 3 (Arizona and New Mexico) has been valued at $1/CCF for pulpwood (5-9 inches DBH), $3/CCF for Sawtimber 1 (9-12 inches DBH), and $5/CCF for Sawtimber 2 (12+ DBH) (Lawrence 2010). Timber of these three size classes has been sold by the Kaibab NF for $5, $9 and $10, respectively (Lawrence 2010). The Coconino NF has also estimated that they have on average 8 CCF per acre in each of these size classes (Newbauer: personal contact 2011). For our analysis, we use the minimum of the above figures and assign the timber that would be lost in a crown fire, a value of $72 per acre.

It is also worth mentioning the value of timber that could be salvaged after a crown fire. As an example bear in mind the salvage operation conducted after the 2006 Warm Fire in the Kaibab National Forest in Arizona. It was reported that between 1 and 3 CCF per acre was salvaged at a price of $1 to $3 per CCF (Zona: personal contact 2011). Returns on salvage timber my help get back some of the timber revenues lost in a fire, however these operations do not occur on every fire and neither do they often encompass the whole burned area. Therefore, I did not consider salvage returns in my calculations.

When considering losses of structures due to wildfires with crowning, the total values are highly variable. Wildfires that occur in the wildland-urban interface may cause a greater amount of structural loss per acre than a fire occurring in a rural setting. The value of these structures can also vary greatly depending on size and location. To get a better idea of this variability, I can compare the structural losses per acre of the two most costly wildfires in the history of the Southwest. The Rodeo-Chediski fire burned 468,638 acres in Arizona in 2002 and caused $120 million in structural losses (Insurance Services Office Inc. 2002). This equates to about $256 per acre. In comparison, the Cerro Grande fire of 2000 burned only 48,000 acres in New Mexico, but caused $140 million in structural losses (Insurance Services Office Inc. 2008). The $2,917/acre in losses from this fire is far greater than the $305/acre from the Rodeo-Chediski fire primarily due to the density and value of the structures involved. For the sake of our analysis I used the more conservative value from the Rodeo-Chediski fire and convert the value to 2011 dollars, giving us a cost of $321/acre.

Placing a value on the number of forest ecosystems services offered in the Southwest is also extremely difficult. The various valuation techniques employed in recent literature are most often incompatible with an application such as this and fail to assign a comprehensive market valuation to these ecosystem benefits. These services do, however, have intrinsic values in the ecosystems and communities of fire prone areas.

First of all, forest ecosystems are important in maintaining global carbon balances, because the trees sequester atmospheric carbon during photosynthesis and store it in both above and below ground structures. Untreated Ponderosa Pine forests can store 30.18 Mg of carbon per acre in above-ground live and dead trees, below-ground live and dead trees and surface fuels, while stands having undergone fuel treatments can store 20.46 Mg carbon per acre (Sorensen et al. 2011). The storage of large amounts of carbon in forests of the Southwest helps to minimize atmospheric carbon that contributes to global warming. Much of this carbon would be lost to the atmosphere were a crown fire to occur. The harm to the Earth's atmosphere would be multiplied in this case as well, due to the pollution released in the form of fine particulate matter that may compromise public health.

Wildlife habitat is another invaluable asset of a forest ecosystem. Governments and activists have assigned a high priority to the protection of many endangered species. Viable habitats are often critical to the survival of these species and large fires of high intensity may do long lasting damage to these habitats. In addition, many game species that also rely on sensitive habitats are highly important to the sportsmen that contribute substantial revenues to both state and local economies with their purchase of licenses, goods, and services (International Association of Fish and Wildlife Agencies 2002).

The structure of a healthy forest can contribute to the quality of water in riparian areas, as well as down stream flows. The filtration, that the system provides, helps make waterways the healthy ecosystems they are, while also making the water usable as a resource for humans. When severely burned in a crown fire, the forest can loose its ability to filter runoff. Large amounts of sediment can end up in waterways, compromising the ecosystem services they may support. Clean drinking water for municipalities and fish habitat could both be placed at risk. Erosion can be a large problem after a crown fire since the vegetation that held the soil in place is often consumed. It may be difficult to place a value on all of these ecosystem services, but there are a number of techniques discussed by Greenwald and McGrath (2009) to accomplish this including hedonic pricing, contingent valuation, benefits transfer and replacement and avoided costs. A well-developed forest management plan can assist landowners and municipalities in projecting watershed maintenance costs that can serve as the basis for the valuing of these ecosystem services (Greenwald and McGrath 2009). Each unique watershed may hold factors that demand certain techniques most applicable to the valuation and subsequent management of that specific area.

The aesthetic value many people place on forest ecosystems could be quite considerable yet is so variable that a monetary value may be unattainable. The forest can be a place of solace, worship or therapy for some people and when it is destroyed by crown fire, this ecosystem service may be lost for years to come. Visitation to areas recovering from crown fires by recreationist has been found to decrease and slow the economic stimulus resulting from these types of behaviors (Hesseln *et al.* 2003). The recreational value of a forest varies for individuals depending on their preferred activities. The benefits derived from recreation like hiking, biking, hunting, bird-watching or fishing, would be extremely difficult to place a per acre monetary value on. Other studies have assigned value to this type of activity (Hesseln *et al*. 2003) but only on a per trip basis, which is not compatible for use within this study.

The final model input that does need to be defined is the cost of applying preventive measures in defense against crown fire occurrence. In this case, I consider fuel reduction treatments. The cost of the treatments we considered for our analysis have been gathered from an economic study by Yeon-Su Kim (2010), where values were provided by the four national forests of Arizona involved in the 4FRI (Kaibab, Coconino, Apache-Sitgreaves, and Tonto). The average operational and administrative costs of mechanical thinning ranged from $408-$542 per acre. Additionally, the average operational and administrative costs of prescribed burning ranged from $80-$250 per acre. When totaled, the cost of fuel reduction in the Southwest can range from $488 to $791 per acre, so I considered both values in my model.

Analytical Scenarios. I developed multiple analytical scenarios by varying two critical model inputs. The probability of crown fire initiation was analyzed multiple ways by using the minimum, the maximum, and the mean of the independent variables specific to weather, climate or topography. These variables were then coupled with a specific crown base height and incorporated into the most accurate logistic model from Cruz et al. (2003). Using a range of the independent variables in my model gives an idea of how variable the fire environment can be and how it affects the probability of crown fire initiation. I also chose to look at how spending the minimum on common fuel reduction treatments in the Southwest ($488/acre) might contrast with spending the maximum ($791/acre).

When incorporating these values with the cost of fire suppression and the value of the losses associated with crown fire, which were held constant in each of the scenarios, I was able to calculate a range of Expected Total Cost (ETC) of crown fire according to the probability of crown fire initiation for each scenario.

Table 2. Fire suppression costs, present value of losses associated with crown fire, and treatment cost per acre

	Costs/acre
Fire suppression	$205
Timber losses	$72
Structure losses	$321
Rehabilitation cost	$27
Low estimate (minimum treatment)	$488
High estimate (maximum treatment)	$791

Each of the four subsets of results were grouped together based on the independent variable, canopy base height (CBH), that would characterize the type of fuel treatment used. Within each subset is a range of Expected Total Costs (ETC) that would result from the occurrence of a crown fire event in each of three categories. These three categories contain either the minimum, the mean, or the maximum values for the independent variables of 10-m open wind speed, Fine Fuel Moisture Code, and Drought Code (i.e. variables influenced by either weather, climate, or topography, not a fuel treatment) from the data set of experimental fires used by Cruz et al. (2003) to develop the logistical model for crown fire initiation. With this information, a probability of crown fire initiation was generated corresponding to each category of fire environment characteristics, thus giving an ETC for each scenario.

Results

In scenarios 1-3 (Table 3), there was no fuel treatment implemented, so the CBH was assumed to be 2m which is the average for a stand in the Southwest that has not undergone such a treatment (Morfin: personal contact 2011). For scenario 1, the probability of crown fire was well below 0.01, so the ETC was $0/acre. However, in scenario 2 where conditions were considered average (mean) in the experimental fires, the probability of crown fire was still 0.94 and capable of inflicting an ETC of $588/acre. The 0.99 probability of crown fire in scenario 3 would be expected to cost $625/acre.

Table 3. Scenarios 1,2,3 No Treatment (CBH = 2m)

Independent variables	Parameter Values	Min (1)	Mean (2)	Max (3)
Constant	-66.62	1	1	1
Crown Base Height (CBH)	-0.993	2	2	2
10-m open wind speed in km/h (U10)	0.568	3	12.6	29
Fine Fuel Moisture Code (FFMC)	0.671	84.5	90.5	94.1
Drought Code (DC)	0.018	60	193.4	423
g(x)		-9.1225	2.7575	18.6211
Probability (p)		0.0001091	0.94033552	0.99999999
Expected Total Cost/acre		$0	$588	$625

Table 4 displays scenarios 4,5, and 6 where the CBH is 3m. These scenarios were calculated to give some perspective on what costs might be inflicted if a fuels treatment were carried out initially, but subsequent management actions failed to maintain the desired CBH of 4 to 5 meters over time. In the event of a crown fire within the stand under the mean conditions of scenario 5, there is an 85% chance that a crown fire could inflict an ETC from $1,022 to $1,325 per acre.

Table 4. Scenarios 4,5,6 Expired Treatment (CBH = 3m)

Independent variables	Parameter Values	Min (4)	Mean (5)	Max (6)
Constant	-66.62	1	1	1
Crown Base Height (CBH) in meters	0.993	3	3	3
10-m open wind speed in km/h (U10)	0.568	3	12.6	29
Fine Fuel Moisture Code (FFMC)	0.671	84.5	90.5	94.1
Drought Code (DC)	0.018	60	193.4	423
g(x)		-10.1155	1.7645	17.6281
Probability (p)		4.04E-05	0.85377235	0.99999997
Expected Total Cost/acre (low estimate)		$488	$1,022	$1,113
Expected Total Cost/acre (high estimate)		$791	$1,325	$1,416

The CBH was set at 4m for scenarios 7,8, and 9 (Table 5), assuming that a normal fuels treatment accomplished its minimum goal. In scenario 8, where the independent variables, excluding CBH, were considered average, the ETC ranged from $915/acre to $1,218/acre and the probability of crown fire was 0.68.

Table 5. Scenarios 7,8,9 Minimum Standard Treatment (CBH = 4m)

Independent variables	Parameter Values	Min (7)	Mean (8)	Max (9)
Constant	-66.62	1	1	1
Crown Base Height (CBH)	-0.993	4	4	4
10-m open wind speed in km/h (U10)	0.568	3	12.6	29
Fine Fuel Moisture Code (FFMC)	0.671	84.5	90.5	94.1
Drought Code (DC)	0.018	60	193.4	423
g(x)		-11.1085	0.7715	16.6351
Probability (p)		1.498E-05	0.68384528	0.99999994
Expected Total Cost/acre (low estimate)		$488	$915	$1,113
Expected Total Cost/acre (high estimate)		$791	$1,218	$1,416

In the last subset of results displayed in table 6, the CBH was set at 5m given that a standard fuel treatment in the Southwest accomplished its goal of raising the CBH to what would be, on average, a maximum of 5m throughout the stand. The probability of crown fire initiation in scenario 11 would be lowered to 0.44 and the ETC would range from $759 to $1,069 per acre in the event that such a fire was to occur under these mean conditions.

Table 6. Scenarios 10,11,12 Maximum Standard Treatment (CBH = 5m)

Independent variables	Parameter Values	Min (10)	Mean (11)	Max (12)
Constant	-66.62	1	1	1
Crown Base Height (CBH) in meters	0.993	5	5	5
10-m open wind speed in km/h (U10)	0.568	3	12.6	29
Fine Fuel Moisture Code (FFMC)	0.671	84.5	90.5	94.1
Drought Code (DC)	0.018	60	193.4	423
g(x)		-12.1015	-0.2215	15.6421
Probability (p)		5.551E-6	0.44485029	0.99999983
Expected Total Cost/acre (low estimate)		$488	$759	$1,106
Expected Total Cost/acre (high estimate)		$791	$1,069	$1,1416

Some common outputs emerged for a number of scenarios that could then be placed into two particular groupings. In scenarios 4,7, and 10 the variables, other than CBH, were at a minimum making the probability of crown fire extremely low at less than .01. Therefore, the ETC would only be about the cost of the fuels treatment, which would range between $488 and $791 per acre. A similar trend occurred in calculating the ETC for crown fires that might initiate in the most extreme conditions of scenarios 6,9, and 12. All of these scenarios would expect a crown fire greater than 99% of the time, thus incurring a maximum ETC ranging from $1,113 to $1,416/acre. These two groups are of a lesser significance to this study because they represent far less common fire weather conditions.

Discussion

In calculating the ETC that may be incurred in the Southwest as a result of a crown fire event, it is evident what costs may be avoided by implementing a fuels treatment that would prevent a crown fire. In order to determine the targets of the fuels treatment, such as the desired CBH, the use of a fire behavior model to determine under what stand conditions a crown fire is likely to initiate has become common practice. I have expressed concerns over the accuracy of these fire behavior models. Errors in these models may result in the recommendation of a fuels treatment on a landscape that would not prevent a crown fire from happening under most conditions of the fire environment common throughout the fire season. Therefore, in our analysis we can consider the value of improving the accuracy of fire models as an avoided cost expressed as the ETC of crown fire in our scenarios. Land managers and fire officials in particular may find our investigation interesting and useful because they are the ones dealing with budgets and fire operations that may be strongly impacted by large crown fires. If improving the accuracy of fire models can save money time, resources, and human life, then this study may serve to give a new perspective as to the extent of these possible losses.

It is possible to make a number of observations based on my results in order to clarify what all the numbers mean. For my first point, it must be assumed that a fire behavior model would be employed to define the necessary fuel treatment guidelines, such as desired CBH, needed to prevent a high severity crown fire event from occurring, and this fire model would not underpredict the likelihood of such an event. Then we can see the value of accurate information expressed as the ETC of a crown fire in each of the fuel treatment scenarios. In addition, it is important to note the probability of such a fire in each scenario in tandem with its ETC. For instance, while the ETC of a crown fire occurring during the average weather and climate conditions of this study for a stand that has not been treated (CBH of 2m) may be lower than any other scenario ($588/acre) with similar conditions, the probability of such an event occurring is very high (i.e. 0.94). Figures 1 and 2 give a visual perspective as to the trends in probability and ETC of crown fire respectively in scenarios of mean independent variables save CBH. Knowing that carrying out a fuels treatment may cost more initially, but could ultimately save money in fire prone areas over time is quite valuable. Ignitions across the Southwest are inevitable, and managing forests to encourage low intensity surface fires rather than high intensity crown fires can save a sizeable amount of money.

Consider a stand treated to its maximum prescribed CBH at 5m. The probability of a crown fire initiating here under mean conditions is lowered from 0.94, as in an untreated stand, to 0.44. This is significant because if you consider the increased number of ignitions in an untreated stand that are likely to progress into crown fires, the costs can add up over time. It is most likely that the slightly greater costs that would be incurred due to a crown fire event in a treated stand would happen less often, thus costing less over time. This observation spurs the consideration of an important limitation that exists within this analysis. According to Agee (1996) a minimum canopy bulk density of 0.1 kg/m^3 is needed in order to ensure active crown fire spread in a horizontal dimension. In my calculations a probability of crown fire initiation is generated, but that does not ensure horizontal crown fire spread, especially in stands that have witnessed a fuels treatment. Therefore, the assumption must be made that such a crown fire would have to spread horizontally as well in order to inflict the costs that are calculated. Otherwise, the ETC generated for scenarios concerning treated stands may be an overprediction.

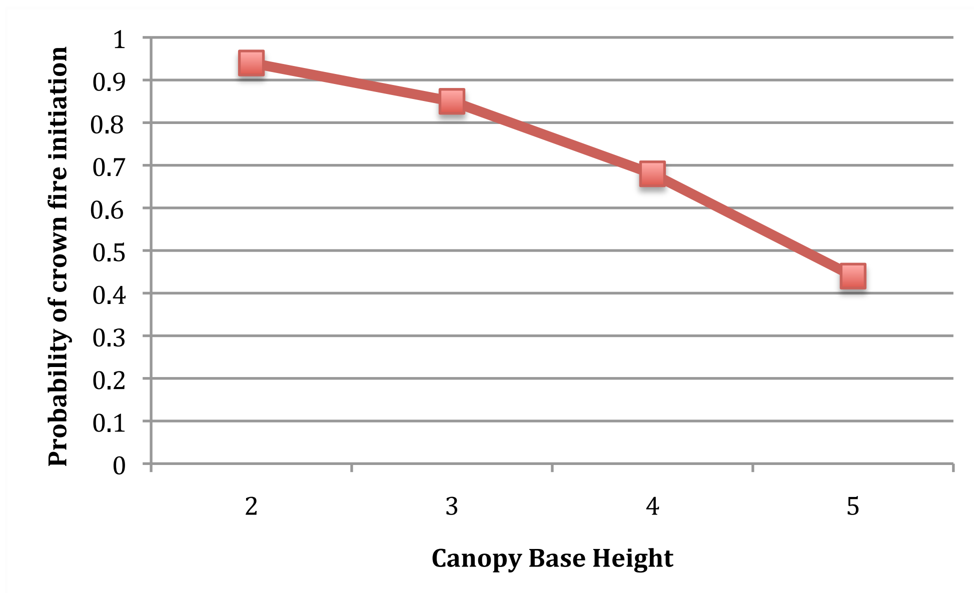

Figure 1. The probability of crown fire initiation according to canopy base height where all other independent variables of the model were of mean values.

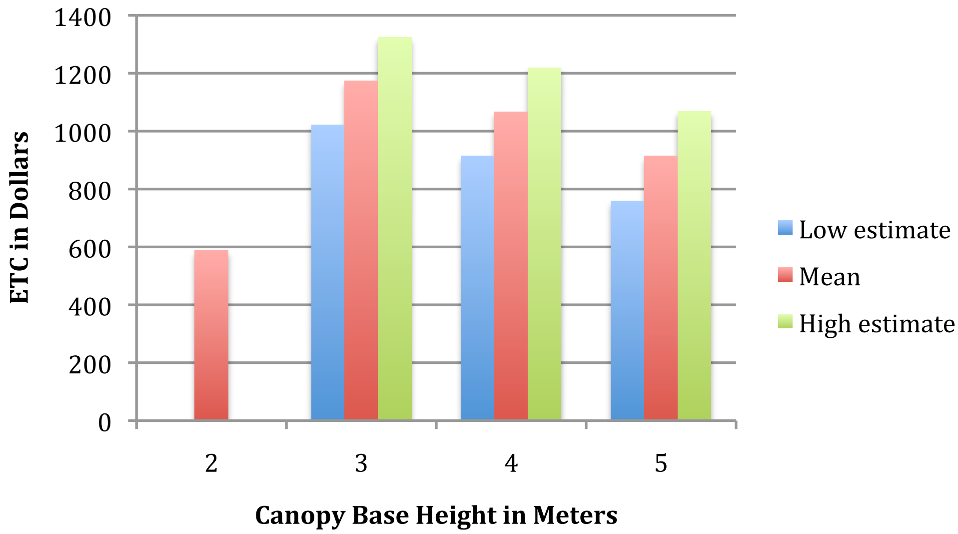

Figure 2. Expected Total Costs of crown fire in dollars according to Canopy Base Height where all other independent variables of the model were of mean values.

In my analysis the scenario with both the highest probability of occurring and the highest ETC would be scenario 5, where a fuels treatment is carried out but subsequent management actions have failed to maintain the desired CBH of 4 to 5 meters over time. If a fuels management plan is not successful at maintaining a critical variable such as CBH, then the probability of crown fire remains high (0.85) as in this case. Investing resources into fuels reduction treatments adds a significant amount to the value that may be lost in the event of a crown fire. The figure in scenario 5 can give managers an idea of the costs that may be avoided if they fail to perform necessary management actions such as prescribed burns following mechanical treatments.

While the ETC's of scenarios defined by maximum independent variables describing weather, climate, or topography characteristics may be the highest of any of the scenarios, the likelihood of a crown fire occurring during such extreme conditions is much lower than during a scenario with the mean independent variables. In addition, a fuels treatment is not designed to prevent a crown fire during the most extreme fire weather conditions. Treatments must be designed with many other environmental, economic, and social concerns in mind than simply fire protection, or valuable forest stands would be left vulnerable to catastrophic fire events.

A noteworthy comparison can also be made between scenario 8 and scenario 11 in consideration of how differently minimum standard fuel treatments and maximum standard fuel treatments effect the probability and ETC of crown fire. The U.S. Forest Service in the Southwest prescribes that CBH be raised to a level somewhere between 4m and 5m in their standard fuels treatments. I have generated some values that may be advantageous for land managers to bear in mind when implementing a fuels treatment to these standards and the associated costs that may result from favoring either the minimum 4m CBH or the 5m CBH. While the cost of a treatment that favors one CBH or the other would still be in the same range of $488/acre to $791/acre according to our data, the costs that could be avoided are substantially less when the maximum treatment is conducted. When we consider the scenarios characterized by the mean independent variables other than CBH, the ETC of crown fire would be $153/acre less in a stand that had been treated to the 5m CBH than in a stand that had only been raised to 4m. In addition, the probability of crown fire in a stand with a CBH of the former would be 24% less than in a stand of the latter, greatly reducing the chances of having to incur such costs. Values such as these may be important to think about when planning fuels work, because either implementing the minimum treatment to save on initial costs or implementing the minimum treatment based on a fire model that underpredicted the crown fire hazard could have costly consequences. Understanding the difference in total losses that may be incurred as the result of a crown fire may help managers weigh their fuels treatment decisions more precisely.

I have calculated, through the model, an expected total cost of crown fire in the Southwest, but I stress that this may be a particularly conservative estimate in some scenarios for a number of reasons. For one, I used only minimal values that could be gained on returns of marketable sawtimber. It is highly possible, especially in more productive stands, that timber harvests could fetch higher numbers. Also be mindful that timber values could be higher in areas more fit to handle larger volumes of harvest, where transportation and processing costs would be lower. Secondly, the figure I used to represent the possible structure losses that could be incurred due to a crown fire was relatively low. As I pointed out earlier, the value of facilities burned up in a crown fire could be much greater in areas of higher concentration or higher value and this would significantly increase the ETC of a fire event.

More importantly, like many other researchers attempting such a task, I was unable to put a monetary value on the many ecosystem services that may be lost in a conflagration. The wildlife habitat, clean water, carbon sequestration, recreational worth, and aesthetic qualities that a forest ecosystem provides may very well bear a higher value than that of a subdivision of homes or deck of logs. However, I must operate this analysis in terms that can be easily identified and assigned.

The value of knowing under what conditions a crown fire may take place, and employing the necessary measures to mitigate this threat is also an issue of personal safety. I did not include a value for the human life that could be lost in a crown fire. Other studies have done so in accordance with numbers generated by the Environmental Protection Agency (Mason et al. 2006). However, I chose not to include this variable in my calculation of losses due to its controversial nature. Nevertheless, it is important to understand that the accurate prediction of crown fire behavior is not simply a matter of avoiding the economic costs. The lives of firefighters and civilians living, working and playing in rural or wildland-urban interface settings could be at stake.

Lastly, I would like to stress that this model was created and I conducted this simulation on the basis that it is merely theoretical and it will hopefully spur the creation of better models in the future. Not only could the costs associated with fuels reduction treatments, fire suppression or other potential losses be updated, pinpointed or applied to other locations besides the Southwest but the model created to define fire probability could be improved. The inclusion of variables such as percent slope, canopy bulk density, and surface fire intensity could significantly improve the accuracy of the crown fire initiation model.

Accurate information in the modeling of crown fire behavior could ultimately reduce the cost of fuels reduction treatments by specifically narrowing the parameters of the treatments that are needed to prevent such a fire. It could also reduce the cost of wildfires by guiding the most efficient and safe use of suppression resources. It is for these reasons that the development of highly reliable fire behavior models needs to be more pro-active.

Recommendations

As I have made a case that there may be substantial monetary and priceless values preserved by improving the accuracy fire behavior models, it would then seem fit that more resources be devoted to this cause. Forest and fire managers alike are increasingly relying upon these models in decision-making processes. So how can they be made better? Cruz and Alexander (2010) offer a few suggestions to mitigate the sources of bias they have found in the models. First off, they suggest that modeling systems that utilize model linkages for gauging potential crown fire behavior be evaluated against independent datasets or empirical observations. Secondly, they say that modifying the method used to calculate the surface fireline intensity for the purpose of assessing crown fire initiation potential could rectify this underprediction bias inherent in these fire modeling systems (Cruz and Alexander, 2010). Lastly, they suggest reassessing the use of a crown fraction burned function to resolve the underprediction bias associated with predicting active crown fire rate of spread inherent in the Rothermel (1991) model (Cruz and Alexander, 2010). I propose that finding solutions to these problems should be at the forefront of our federal agencies agenda on research into fire behavior. Not only would a better knowledge increase our efficiency of managing wildfires in many ways, but it would increase public and firefighter safety as well as avoid the loss of valuable resources and amenities.

Finally, I recommend that more studies be conducted on the value of improved information in the fields of fuels treatment and wildland fire suppression. This type of analysis could be applied to many different ecosystems with their own unique variables that influence costs. At this point, the value within the preservation of such resources is incalculable.

Literature Cited

Agee, J.K. 1996. *The influence of forest structure on fire behaviour*. In Proceedings of the 17th annual forest vegetation management conference. Redding, California, January 16-18, 1996. pp 52-67.

Agee, J.K., and C.N. Skinner. 2005. Basic principles of forest fuel reduction treatments. *For. Eco. Manage.* 211(1/2):83-96.

Agee, J.K., M.R. Lolley. 2006. Thinning and prescribed fire effects of fuels and potential fire behavior in an Eastern Cascades forest, Washington, USA. *Fire Eco.* 2:3-19.

Amacher, G.S., A.S. Malik, and R.G. Haight. 2005. Forest landowner decisions and the value of information under fire risk. *Can. J. For. Res.* 35(11):2603-2615.

Andrews, P.L., C.D. Bevins, R.C. Seli. 2008. *BehavePlus fire modeling system, version 4.0: users guide*. US For. Serv. Gen Tech. Rep. RMRS-GTR-106WWW Revised.

Arno, S.F., J.H. Scott., M.G. Hartwell. 1995. *Age-class structure of old-growth ponderosa pine douglas-fir stands and its relationship to fire history*. USDA For. Serv. Intermt. Res. Stn. Res. Pap., Int. Exp. Sta., 481:1-25.

Bontems, P., and T. Alban. 2000. Information value and risk premium in agricultural production: the case of split nitrogen application for corn. *Am. J. Agric. Econ.* 82(1):59-70.

Borchert, M., D. Shreiner, T. Knowd and T. Plumb. 2002. Predicting postfire survival in coulter pine (*Pinus coulteri*) and Gray pine (*Pinus sabiniana*) after wildfire in central California. *West. J. Appl. For.* 17(3):134-138.

Carlton, D. 2005. *Fuels Management Analyst Plus software*, *version 3*. Fire Program Solutions LLC: Estacada, OR. Available online at http://www.fireps.com/fmanalyst3/index.htm. ; last accessed March 29, 2011.

Costello, C., R. Adams, and S. Polasky. 1998. The value of El Nino forecasts in the management of salmon: a stochastic dynamic assessment. *Am. J. Agric. Econ.* 80(4):765-777.

Covington, W.W., and M.M. Moore. 1994a. Southwestern ponderosa forest structure and resource conditions: Changes since Euro-American settlement. *Forestry* 92 (1): 39-47.

Covington, W.W. and M.M. Moore. 1994b. Postsettlement changes in natural fire regimes and forest structure: ecological restoration of old-growth ponderosa pine forests. *J. Sust. For.* 2(1/2):153-181.

Covington, W.W. 2000. Helping western forest heal: the prognosis is poor for US forest ecosystems. *Nature.* 408(6809):135-136.

Cruz, M.G., M.E. Alexander, R.H. Wakimoto. 2003. Assessing the probability of crown fire initiation based on fire danger indices. *For. Chron.* 79(5):976-983.

Cruz, M.G., and M.E. Alexander. 2010. Assessing crown fire potential in coniferous forests of western North America: a critique of current approaches and recent simulation studies. *Int. J. Wildland Fire*. 19(4):377-398.

Donovan, G. H., and D. B. Rideout. 2003. A reformulation of the cost plus net value change (C+NVC) model of wildfire economics. *For. Sci.* 49(2):318-323.

Everett, R.L., R. Schellhaas, D. Keenum, D. Spurbeck, P. Ohlson. 2000. Fire history in the ponderosa pine/douglas-fir forests on the east slope of the Washington Cascades. *For. Eco. Manage*. 129. (1-3):207-225.

Finney, M.A. 2004. *FARSITE: Fire area simulator-model development and evaluation*. US For. Serv. Res. Pap. RMRS-RP-4 Revised.

Finney, M.A. 2006. An overview of FlamMap fire modeling capabilities. P. 213-220 in *'Fuels Management-How to Measure Success: Conf. Proc.'* RMRS-P 41, US For. Serv., Ft. Collins, CO.

Fox, G., J. Turner, and T. Gillespie. 1999. The value of precipitation forecast information in winter wheat production. *Agric. For. Meteorol.* 95(2):99-110.

Fulé, P.Z., C. McHugh, T.A. Heinlein, W.W. Covington. 2001*a*. Potential fire behavior is reduced following forest restoration treatments. P. 28-35 in *Ponderosa Pine Ecosystems Restoration and Conservation Steps Toward Stewardship*. RMRS-P 22, US For. Serv., Ogden, UT.

Fulé, P.Z., A.E.M. Waltz, W.W. Covington, T.A. Heinlein. 2001*b*. Measuring forest restoration effectiveness in reducing hazardous fuels. *J. For*. 99(11):24-29.

Gillmeister, W., J. Moffit, and P. Bhowmilk. 1990. Information value in weed management. Northeast. *J. Agric. Econ.* 19:24-28.

Greenwalt, T., and D. McGrath, 2009. Protecting the city's water: Designing a payment for ecosystem services program. *Nat. Res. Environ.* 24(1).

Hall, S. A., and I.C. Burke. 2006. Considerations for characterizing fuels as inputs for fire behavior models. *For. Eco. Manage.* 227(1/2):102-114.

Hanley, H.A., and B.J. McNeil. 1982. The meaning and use of the area under the receiver operating characteristic (ROC) curve. *Radiology*. 143(1):29-36.

Hesseln, H., J.B. Loomis, A. Gonzalez-Caban, and S. Alexander. 2003. Wildfire effects on hiking and biking demand in New Mexico: a travel cost study. *J. Environ. Manag.* 69:359-368.

Hosmer, D.W., and S. Lemeshow. 2000. *Applied logistic regression*. 2nd edition. John Wiley & Sons, New York. 375 p.

Insurance Services Office, Inc.'s (ISO) Property Claim Services (PCS) Unit. 2002. *Insurers to pay $120 million for insured-property damage from Arizona wildfire, estimates ISO's property claim services unit.* Available at http://www.iso.com/Press-Releases/2002.html. Accessed March 2011

Insurance Services Office, Inc.'s (ISO) Property Claim Services (PCS) Unit. 2008. *According to PCS, the Cerro Grande Fire in May 2000 caused $140 million in estimated insured losses.* http://www.isopropertyresources.com/Landing-Pages/On-Location.html. Accessed March 2011.

International Association of Fish and Wildlife Agencies. 2002. Economic Importance of Hunting in America

Keyes, C.R., and K.L. O'Hara. 2002. Quantifying stand targets for silvicultural prevention of crown fires. *West. J. Appl. For.* 17(2):101-109.

Kim, Y.S. 2010. *Ecological Restoration as Economic Stimulus: A Regional Analysis.* Ecological Restoration Institute, Northern Arizona University, Flagstaff, AZ. 17p.

Lawrence, L.M. 2010. *The centennial forest as a financial, educational, and research asset of Northern Arizona University: The first Decade*. Unpublished Edition.

Mason, G.L., T.T. Baker, D.S. Cram, J.C. Boren, A.G. Fernald, D.M. VanLeeuwen. 2006. Mechanical fuel treatment effects on fuel loads and indices of crown fire potential in a south central New Mexico dry mixed conifer forest. *For. Eco. Manage*. 251(3):195-204.

Morfin, V. Personal Communication. 2011. Fuels Management Officer. Coconino National Forest. Flagstaff, AZ.

Nagelkerke, N.J.D. 1991. A note on a general definition of the coefficient of determination. *Biometrika*. 78(3):691-692.

Newbauer, K. Personal Communication. 2011. Timber Sales Contracting Officer. Coconino National Forest. Flagstaff, AZ.

Peck, S., and R. Richels. 1987. The value of information to the acidic deposition debates. *J. Bus. Econ. Stat.* 5(2):205-217

Peterson, D.L., M.C. Johnson, J.K. Agee, T.B. Jain, D. McKenzie, and E.D. Reinhart. 2005. *Forest structure and fire hazard in dry forest of the Western United States*. US For. Serv. Gen. Tech. Rep. PNW-GTR-628. 30p.

Raymond, C.L. and D.L. Peterson. 2005. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. *Can. J. For. Res*. 35(12):2981-2995.

Regelbrugge, J.C., and S.G. Conard. 1993. Modeling tree mortality following wildfire in *Pinus ponderosa* forests in the central Sierra Nevada of California. *Int. J. Wildland Fire.* 3(3):139-148.

Rienhardt, E.D., and N.L. Crookston (Tech Eds). 2003. *The Fire and Fuels Extension to the Forest Vegetation Simulator*. US For. Serv. Gen Tech. Rep. RMRS-GTR-116.

Roccaforte, J.P., P. Z. Fulé, W.W. Covington. 2008. Landscape-scale changes in canopy fuels and potential fire behavior following ponderosa pine restoration treatments. *Int. J. Wildland Fire* 17(2):293-303.

Ryan, K.C., and E.D. Reinhardt. 1988. Predicting postfire mortality of seven western conifers. *Can. J. For. Res.* 18(10):1291-1297.

Savage, M., and J. Mast. 2005. How resilient are southwestern ponderosa pine forest after crown fires? *Can. J. For. Res.* 35:967-977

Schmidt, D.A., A.H. Taylor, and C.N. Skinner. 2008. The influence of fuel treatments and landscape arrangement on simulated fire behavior, Southern Cascade Range, California. *For. Eco. Manage*. 255(8/9):3170-3184.

Scott, J.H., and E.D. Reinhardt. 2001. *Assessing crown fire potential by linking models of surface and crown fire behavior*. US For. Serv. Res. Pap. RMRS-RP-29

Simard, A.J. 1976. *Wildland fire management: The economics of policy alternatives.* Can. For. Serv. Tech. Rep. 15. Ottawa, Ontario. 52 p.

Skinner, C.N., and C. Chang. 1996. *Fire regimes, past and present*. Pages 1041-1069. Sierra Nevada Ecosystem Project: Final Report to Congress. Volume II: Assessments and scientific basis for management options, Center for Water and Wildlife Resources, University of California, Davis, California, USA.

Society of American Foresters. 2000. *Managing the impact of fires on communities and the environment: report to the President in response to the Wildfires of 2000*. Available at http://www.safnet.org/policyandpress/firereport.pdf. Accessed April 2011.

Society of American Foresters. 2002. *Wildfire season heats up debate in Washington*. Forestry Source. October 2002.

Sorensen, C. D., A.J. Finkral, T.E. Kolb, C.H. Huang. 2011. Short-and long-term effects of thinning and prescribed fire on carbon stocks in ponderosa pine stands in northern Arizona. *For. Eco. Manage*. 261(3):460-472.

Snider, G., P.J. Daugherty, and D. Wood. 2006. The irrationality of continued fire suppression: an avoided cost analysis of fire hazard reduction treatments versus no treatment. *J. For.* 104(8):431-437.

Steinke, A. Personal Contact. 2011. Data Analyst. University of Montana, College of Forestry. Cooperator for RMRS. Missoula MT. Data provided in Excel spreadsheet on file with author.

Stephens, S.L. 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in Sierra Nevada mixed conifer forests. *For. Eco. Manage.* 105(1/3):21-35.

Wilson, A.A.G. 1988. Width of firebreak that is necessary to stop grass fires: some field experiments. *Can. J. For. Res.* 18(6):682-687.

Wilson, A.A.G., and I.S. Ferguson. 1986. Predicting the probability of house survival during bushfires. *J. Environ. Manage*. 23(3):259-270.

Zona, D. Personal Contact. 2011. SO Silviculture. Tongass National Forest. Ketchikan AK Supervisors Office.