AN ABSTRACT OF THE THESIS OF

Rachel M. Houtman for the degree of Master of Science in Forest Resources presented on May 19, 2011.

Title: Letting Wildfires Burn: Modeling the Change in Future Suppression Costs as the Result of a Suppress Versus a Let-burn Management Choice

Abstract approved:

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Claire A. Montgomery

Wildfire management policy over the past century, which attempts to exclude fire from fire-adapted ecosystems, has led to a build-up of fuels across the western United States. As a result, current wildfires contain larger areas of high severity, high intensity burns than seen prior to the policy implementation. There are three leading methods for dealing with this build-up of fuels. The first two, mechanical thinning and prescribed fire, are techniques used to enter an ecosystem and reduce the fuel loads in a specific area. Either can cost anywhere from a few hundred to several thousand dollars per hectare. The third method, wildland fire use, is comparatively cheap, while maintaining the benefit of reduced current and future suppression costs. However, it is commonly over-looked, in part because the fire management officer who allows a wildfire to spread when it could have been suppressed can be held liable for damage to property and loss of life, should such events occur.

In this thesis, I describe a method for estimating the future suppression cost savings that result from allowing a fire that occurs in the current year to burn. It was hypothesized that under some known, current conditions, given a random selection of future ignitions and weather, the present value of a landscape would be higher given that a fire in the current year was allowed to burn, rather than suppressed.

A computer program was used to simulate 100-year sample pathways, which included fire and growth events, on a study area in the southeastern Deschutes National Forest. Based on avoided suppression costs, and a crude estimate of timber losses, some of these potential futures demonstrated a higher present value of the landscape resulting from the let-burn management choice. Size of the current fire was the most important characteristics of a given sample pathway in determining the magnitude of the change in future suppression costs. As the size of the current fire increased, the benefit from the sample pathway also increased.

In the future, this analysis can be used as a framework for exploring questions pertaining to the use of weather, fuel, and ignition characteristics of current fires to determine when an ignition should be suppressed, and when it might be advantageous to let a fire burn.

Letting Wildfires Burn: Modeling the Change in Future Suppression Costs as the
Result of a Suppress Versus a Let-burn Management Choice

by

Rachel M. Houtman

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APPROVED:

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

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Rachel M. Houtman, Author

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Thank you to Dave Calkin at the Forest Service Rocky Mountain Research Station for providing the funding for my research and to Matt Thompson for answering all of my numerous questions about suppression costs. Also, thanks to

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Letting Wildfires Burn: Modeling the Change in Future Suppression Costs as the Result of a Suppress Versus a Let-burn Management Choice

Introduction

Across the western United States, costs associated with wildfires have increased over the past 40 years, both as a result of suppression expenditures and fire-related damages (Calkin et al. 2005). This is due in part to the buildup of fuels that is the result of wildfire exclusion and suppression policies of the past 100 years. Fuels management, in the form of mechanical and chemical treatments and prescribed burning, has been suggested as a way to reduce fuel loads and hence reduce the intensity of large conflagrations, even during severe fire weather conditions. Unfortunately, the cost of fuel treatments is often high, ranging from hundreds to thousands of dollars per hectare, and the federal budget funding for such treatments is limited.

The placement of fuel treatments on a landscape with the goal of optimizing the benefit is being explored, but with limited success. Optimal fuel treatment placement is computationally challenging because it depends on combinations of potential future conditions, such as timing and location of ignitions, and vegetation characteristics that are practically infinite. Although attempts have been made to attack the problem using heuristic methods (Sullivan 2010), they have fallen short of assessing optimal solutions in terms of long-term future impacts.

Wildland fire use (allowing some fires that start naturally to continue to burn) is one way that land managers can treat fuels at a lower cost. Allowing fires to burn reduces fuels on the landscape, which has the effect of diminishing future suppression costs for some period of time. The trade-off comes from the additional loss that results from allowing a wildfire to burn. Timber, housing, and non-market goods, like recreational value, are all potential current losses from wildfire. These, along with risk to human life, are the reasons that wildfire suppression became the baseline policy in the first place.

In order to examine the potential gain from allowing wildfires to burn, I created a platform that integrates a wildfire spread model with a forest vegetation growth model. I used the program to simulate a range of different futures, in order to estimate the expected present value of the suppression cost savings that would result from allowing a wildfire that occurs today to burn, instead of suppressing it, for a study area located in the southeast corner of the Deschutes National Forest. If the net loss resulting from the current wildfire were estimated to be less than this amount, it might be optimal to allow that wildfire to burn.

To start analyzing this problem, I developed the platform discussed above to track changes on a landscape, due to both wildfire and growth, over 100-year sample pathways. I used stand conditions, weather conditions, and topography to place burn events on a landscape, and then to update the vegetation. Multiple grow and burn

events were compiled into individual sample pathways. A sample pathway consists of ignition events drawn from a probability distribution on the landscape (Rorig and Ferguson 1999), weather and wind data for each day a wildfire burned, and fire start and end dates for each event. For each sample pathway, I tracked the suppression costs and burn activity on the landscape. The cost data were then used to compare the present value of future suppression costs resulting from full suppression versus a let-burn scenario for an ignition in the starting year.

In the Literature Review, I discuss the role that past forest land management played in shaping the current landscape, the current state of dry western forest lands, current management trends, and the techniques that have been employed to value forests and suppression expenditures. The Analytical Methods section describes the theory used to evaluate the impact of the choice to suppress ignitions or let them burn. The Data and Methods section contains information on the study area, weather, and ignition inputs, and describes the procedures set up to calculate the expected present value of future suppression costs. The Results section contains a description of the model outcomes. The Discussion expounds on and explores the potential meaning of the results and suggests improvements to the model. Finally, I conclude with my findings and recommendations for future work.

Literature Review

Wildfire exclusion over the past century has created a backlog of unburned fuels in many western forests. As a result, historically uncommon large, high intensity, high severity wildfires are increasing in frequency (Donovan and Brown 2007). This is especially true in many dry ponderosa pine (*Pinus ponderosa*) forests where frequent, low-intensity, low-severity wildfires were common in the pre-suppression-era (Everett et al. 2000). In addition to favoring fire-adapted species, such as ponderosa pine, these frequent wildfires removed surface fuels, and diminished fuels that would carry fire into the canopy (Weaver 1943; Everett et al. 2000; Pollet and Omi 2002).

According to one United States Department of Agriculture (USDA) general technical report (GTR), the Department of the Interior estimates that approximately 10% of lands under its management, or 9.51 million hectares, is in condition class 3 (which indicates that it is well outside of its historical range of variability) as a result of wildfire exclusion and suppression (Schmidt et al. 2002). The Forest Service has three times the area (or 20% of lands under their purview) in this category, classifying a total of approximately 30.15 million hectares of these lands as well outside of historical ranges (Schmidt et al. 2002).

In addition to altering the ecology of these systems, the resulting high fuel loads make it very difficult to suppress wildfires that occur in hot, dry, windy conditions (Salazar and González-Cabán 1987). This increase in high fire-risk area, coupled with the expansion of the wildland-urban-interface (WUI), and a suppress-all-wildfires policy, has resulted in a marked increase in wildfire suppression costs over the last 40 years (Calkin et al. 2005). At the same time, the area burning each year increased. Finally, based on a range of climate change projections, the weather in which the largest, most expensive fires occur is likely to become more prevalent, lending urgency to fuel reduction and removal (Brown, Hall, and Westerling 2004).

Fuel treatments (mechanical or prescribed burn fuels reductions) have become dominant, both in proposal and practice, in the debate of how to go about restoring western forests to a more fire resilient state (Agee and Skinner 2005; Kauffman 2004). However, expense is a major barrier to implementing such treatments on a widespread scale. Since the areas that would benefit from fuels reductions are vast, and the cost of such treatments can be hundreds or even thousands of dollars per hectare, most areas will remain untreated in the near future (Donovan and Brown 2007).

As public land managers work to restore forest ecosystems to wildfire-resistant/resilient states, the option to use natural wildland fire as a low-cost fuels reduction management tool, while at the same time decreasing current suppression

costs, has become more attractive. Ideally, it can give managers the opportunity to treat large areas for a reduced cost (Miller 2003).

In spite of these potential benefits and the fact that wildland fire use has been allowed on Forest Service lands since 1977 (Nelson 1979), a policy most recently clarified in 2009 (Fire Executive Council 2009), many managers remain hesitant to apply such a strategy. There are several reasons for this. First, the public expects that wildfires will be suppressed in order to protect lives and property. When wildfires are not suppressed, or prescribed fires escape containment, perceived or actual mismanagement of the fire can result in political and/or legal fallout for fire management officers (FMOs) (Cortner et al. 1990; Williamson 2007). As a result, FMOs tend to be risk-averse, placing a greater value on current losses from a wildfire than on future costs and benefits which follow alternative actions that might be optimal (Snyder, Daugherty, and Wood 2006). Finally, because of the uncertainty of when and where wildfire ignitions occur, it is difficult for land managers to include and justify wildland fire use part of a structured, long-term strategy.

In one attempt to address the issue of risk-averse land managers, Donovan and Brown (2005) examine the potential impact of altering the incentives to which land managers are reacting through the Cost plus Net Value Change model. The precursor to this model, the least Cost plus Loss model, was originally proposed by Sparhawk (1925) to measure the amount that would be justifiably spent to suppress

wildfires in national forests. Donovan and Rideout (2003) modify the basic concept to include potential benefits resulting from a reduction in current suppression efforts. The modifications to the model suggest that it might be optimal to allow wildfires to burn if the combination of expected suppression cost reductions and benefits resulting from the wildfire are greater than the losses incurred.

In this thesis, I estimate the present value of the change in future suppression costs for a study area in the Deschutes National Forest, which is one portion of the total potential benefit that may result from allowing a current wildfire to burn. I also provide a crude estimation for the timber losses resulting from current and future fires. However, extending the analysis to include the non-market, as well as benefits that result from reduced suppression, will be important future steps for this research.

Analytical Methods

Define the net present value of a landscape as the benefits less costs over the time-horizon, plus the value of the ending state of the landscape (Equation 1).

Equation 1

$$v(\boldsymbol{s}, \boldsymbol{w}, x_0) = r(s_0, w_0, x_0) - c(s_0, w_0, x_0) + \sum_{t=1}^{T-1} \{\beta^t (R(s_t, w_t) - C(s_t, w_t))\}$$
$$+ \beta^T V_T(s_T)$$

Where:

$T - 1$ represents the total number of periods that occur in a time-horizon in which the landscape can have a burn event.

T is the ending period during which the final landscape is evaluated.

s is a vector $(s_0, s_1, \ldots, s_{T-1})$ of variables defining the state of the landscape in periods 0 through $T - 1$. This includes aspect, elevation, slope, and vegetation characteristics.

w is a vector $(w_0, w_1, \ldots, w_{T-1})$ of variables defining the weather and ignition information for periods 0 through $T - 1$. The weather information consists of wind, temperature, relative humidity, and precipitation for each date during the wildfire event. Ignition information includes location and number of ignitions that occur.

x_0 is a dichotomous variable for which a 0 value indicates let-burn and a 1 value indicates suppress. In this study, all future wildfires are suppressed.

$R(s_t, w_t)$ is the benefit generated by the landscape in period t. Landscape benefits can include value of market goods, such as timber values, or non-market goods, such as recreational use.

$C(s_t, w_t)$ is the cost of suppression of a fire in period t.

$r(s_0, w_0, x_0)$ is the benefit generated by the landscape in period 0.

$c(s_0, w_0, x_0)$ is the cost of suppression in period 0. In the let-burn pathway, this value is equal to 0.

V_T is the value of the landscape at the end of the time-horizon.

The value change function (Equation 2) represents the change in present value of the landscape when the current wildfire is allowed to burn as opposed to suppressed. This indicates the potential savings gained or lost from allowing a current wildfire to burn. It is optimal to let a current wildfire burn when the value of the landscape without suppression exceeds that with suppression. In equation 2, for $\Delta v > 0$, the optimal choice is to allow the wildfire to burn, while the optimal choice for $\Delta v < 0$ is to suppress.

Equation 2

$$\Delta v = v(\mathbf{s}, \mathbf{w} | x_0 = 0) - v(\mathbf{s}, \mathbf{w} | x_0 = 1)$$

Equation 3

$$\Delta v = -c(s_0, w_0 | x_0 = 1) + \left(r(s_0, w_0 | x_0 = 0) - r(s_0, w_0 | x_0 = 1) \right)$$

$$+ \{\beta^T V_T(s_T | x_0 = 0) - \beta^T V_T(s_T | x_0 = 1)\} + \sum_{t=1}^{T-1} \beta^t \{R(s_t, w_t | x_0 = 0)$$

$$- R(s_t, w_t | x_0 = 1)\} - \sum_{t=1}^{T-1} \beta^t \{C(s_t, w_t | x_0 = 0) - C(s_t, w_t | x_0 = 1)\}$$

In Equation 3, Δv is split into its component parts. It is composed of five distinct sections. The first term is the cost of suppressing the current wildfire. Note that there is no suppression cost from a let-burn policy for the current fire (when $x_0 = 0$), so it is not necessary to include it in the equation. The second term is the expected loss due to the current wildfire. The third term is the value change of the ending landscape, V_T. The fourth term is the expected change in present value of the benefits resulting from a let-burn policy for a current wildfire. The final term is the expected change in present value of suppression costs resulting from a let-burn policy for a current wildfire.

The final expression in the value change function is what I estimate in this thesis. This is an estimate of fuel treatment benefits provided by a current wildfire resulting in a reduction in fuels and assuming all future wildfires will be suppressed (Equation 4).

Equation 4

$$B = \sum_{t=1}^{T-1} (\beta^t C_t(s_t, w_t | x_0 = 0) - \beta^t C_t(s_t, w_t | x_0 = 1))$$

Where:

B is the present value of the change in future suppression costs.

At time 0, future conditions are unknown. Since B is dependent on future conditions, its actual value is also unknown. In order to estimate this value, I used $r = 1 \ldots N$ Monte Carlo simulations to determine the expected value of B (Equation 5).

Equation 5

$$E[B] = \frac{\sum_{r=0}^{N} B^r}{N} = 1/N \sum_{r=1}^{N} \sum_{t=1}^{T-1} \{(\beta^t C_t(s_t, w_t^r | x_0 = 0) - \beta^t C_t(s_{t,} w_t^r | x_0 = 1)\}$$

Where:

w_t^r represents the stochastic variables for time t, iteration r.

B^r is the future suppression cost savings for iteration r.

A Monte Carlo simulation represents one possible future drawn from probability distributions for all the stochastic events that are being considered. In this case, the stochastic events include weather and ignitions. The number of repetitions in a simulation (N) is determined by a criteria, such as convergence to mean, or meeting a standard deviation threshold.

Data and Methods

The study site is an area of approximately 72,164 hectares on the south side of Newberry Crater in the southeast section of the Deschutes National Forest (Figure

1). The topographical, vegetation, and fuels data were provided to us by Alan Ager of

the Forest Service's Western Wildland Environmental Threat Assessment Center

(WWETAC) in Prineville, Oregon.
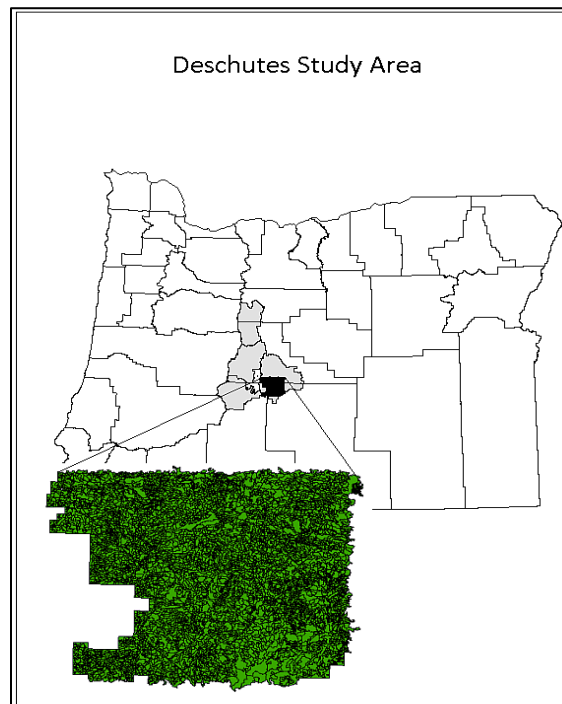
Figure 1: The study area, located on the southeast side of the Deschutes National Forest. This area has been targeted for restoration by the Forest Service.

This area was selected for the project for two reasons. First, Forest Service

land managers may have some amount of leeway in implementing a let-burn policy

for select wildfires because it has been targeted for restoration work (Alan Ager,

personal communication, May 6 2010). In addition, the area has few structural

components of value that would have the potential to overshadow any benefits that

result from allowing a wildfire to burn. Although La Pine is located to the northwest

of the study area, there are no structures within the perimeter and distance to nearest town is included in the suppression cost estimation.

The site is predominantly populated with ponderosa pine (*Pinus ponderosa*) and lodgepole pine (*Pinus contorta*), but also contains some mixed conifer and mountain hemlock (*Tsuga mertensiana*) cover types. There is variability in topography, including some ridges and buttes across the site, although the overarching theme is a gentle decline in elevation from north to south. Elevation ranges from approximately 1,300 to 2,300 meters.

The Oregon Centennial Wildfire Simulator

Currently, there is no prepackaged model that will simulate wildfire spread and update vegetation characteristics on the landscape level. To address this issue, I integrated a vegetation growth model with a fire spread model, to create the Oregon Centennial Wildfire Simulator (OCWS).

OCWS simulates vegetation changes that are the result of growth and wildfires over a 100-year time-horizon. Each 100-year timeline was broken into 1-year time steps. In each time step, OCWS uses ignition inputs (described below) to determine if a wildfire occurs, spreads the wildfire if there is one, then updates the vegetation based on if and how it burns in each pixel. A pixel is representative of a 30m² plot, which is the standard for LANDFIRE data (LANDFIRE 2011), but does result

in some loss of heterogeneity on the landscape. LANDFIRE is a government-funded project that provides spatial fuel and topographical data for the entire United States.

Fire spread is simulated using a dynamic-link library (dll) version of the Forest Service program FARSITE (Finney 1998). I used a vegetation growth model (described below) to build a look-up table that tracks and updates vegetation characteristics at the end of each year, based on whether each pixel grew or burned. OCWS reports the area burned in each time step, as well as the expected cost of suppression if suppression occurred. It then updates the landscape and loads it, along with weather conditions, into FARSITE. FARSITE simulates potential wildfires, generates the total burned area for the suppression cost estimates, and creates a burn-type map that is then used to update the landscape file via the look-up table. The new landscape file is used in the next FARSITE simulation, along with the next weather and ignition information indicated by the sample pathway. Figure 2 demonstrations how the different parts of the OCWS function together. Each component is described in greater detail in the following subsections.
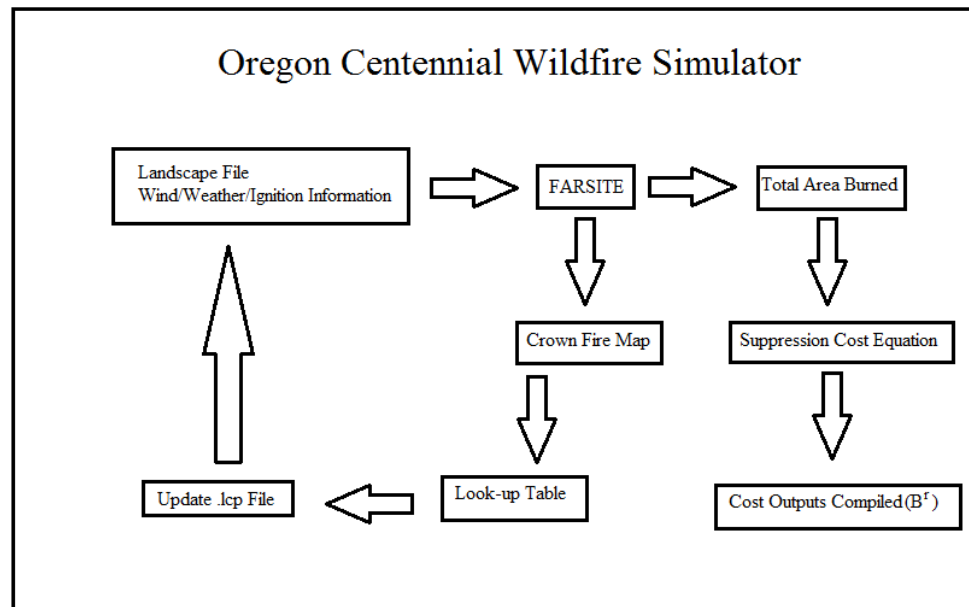
Figure 2: The Oregon Centennial Wildfire Simulator. The platform requires a landscape file (.lcp), and wind, weather, and ignition information to run. These inputs are used by FARSITE to spread fires on the landscape. FARSITE creates output files which describe the total area burned, and the fire type for each pixel (the crown fire map). The total area is used in the OCWS to calculate suppression costs. The crown fire map is used in the OCWS in conjunction with a vegetation transition look-up table to update each pixel in the landscape file.

FARSITE

FARSITE is a model that was created to simulate wildfire behavior on a landscape using landscape characteristics, weather, and ignition points (Finney 2008). It is spatial and temporal, allowing weather and wind to vary during a wildfire simulation, unlike other related programs. I used FARSITE to simulate fire spread on the landscape, create crown fire activity maps, and report total area burned per year (Figure 2). There are six pieces of information required to run FARSITE: 1) a landscape file, 2) a weather file, 3) a wind file, 4) an ignition file, 5) a fuel model moisture file, and 6) fire duration.

1) A landscape file contains information about the topography, and surface and crown fuel characteristics for each pixel, or point, on the landscape (Finney 2006). Rothermel's (1972) original fuel models were used to describe surface fuels. These data are used by FARSITE to determine the fuel and topographical conditions for each cell and how wildfire behaves as a result of that information. I generated the original landscape file using topographical and vegetation data provided by Alan Ager, and the Forest Vegetation Simulator (FVS), in conjunction with the ArcFuels program, maintained by WWETAC. Landscape files representing the study area after the first year were created using a look-up table to evolve vegetation at the end of each time-step, which in this case was one year.

The microclimate data in FARSITE is broken into daily weather observations and hourly wind observations. 2) Weather files contain maximum and minimum daily temperature, relative humidity, and precipitation. 3) Wind files consist of wind speed, direction, and cloud cover. FARSITE uses weather information to condition fuels and wind information to determine fire spread behavior. Historical hourly wind and weather data were obtained for the closest remote automated weather station (RAWS), Cabin Lake, from the Western Regional Climate Center. There are only 24 years of data available for the Cabin Lake station, which limits the variability in the weather. However, because ignition start dates also vary, the specific weather that is selected for each ignition is quite variable.

4) Ignition information is entered in the form of a geographic projection called a shapefile. The shapefile indicates where on the landscape an ignition occurs using a coordinate system. Actual historical ignitions, for which suppression was attempted, were obtained from Lauren Miller at the Deschutes National Forest Supervisor's office in Bend, Oregon and were used to determine where to place ignitions on the landscape.

5) The fuel moisture file provides FARSITE with a starting value for the moisture content for fuels of different sizes. This indicates how much energy release would occur when the fuels burned, and is dependent on the weather conditions before the wildfire. The fuel moisture information that I used was generalized for the area throughout the wildfire season. In order to include the impact of the pre-fire weather, I edited the weather files within OCWS so that FARSITE would condition fuel moistures based on weather in the four days prior to the fire. By conditioning the fuels, FARSITE calculates how fuel moistures shift due to the weather stream.

6) I generated start dates from the historical ignition record. FARSITE does not simulate the end of a wildfire based on weather, nor does it estimate suppression success. Instead, it requires the user to provide the start and end dates for each event. End dates were generated in two ways, depending on suppression effort. First, for the let-burn fires, in which no suppression actions were taken, end dates were determined as a function of fire weather characteristics. Second, for wildfires in

which suppression was attempted, weather, fuels, and time since ignition were used

in a regression equation created by the Forest Service to determine probability of

suppression success each day after the ignition (Finney, Grenfell, and McHugh 2009).

Generating Future Events

The expected benefit of allowing current fires to burn (equation 5) is the

average of estimated values over all possible futures. Since there are essentially an

infinite number of possible future trajectories when simulating landscape-level

vegetation change due to wildfire and growth, I created a set of sample pathways as

a representative sample of the trajectories. Each sample pathway includes a Monte

Carlo realization for weather, ignitions, and burn dates over a 100-year time-horizon.

The initial landscape (s_0) was identical across the sample pathways. Each

estimate of equation 5 required two simulations, which differed only in the current

wildfire event. The current wildfire in the first simulation was suppressed. The

current wildfire in the second simulation was allowed to burn until a wildfire-ending

weather event or the end of the fire season. As a result, the state of the landscape

after the first fire varied within each paired suppressed/unsuppressed simulation.

Variation between pairs of simulations resulted from using different realizations for

ignitions, suppression success for spreading wildfire, and weather and wind.

There were three issues to consider with respect to ignitions. The first issue was the dates on which ignitions occurred; the second issue was whether or not an ignition resulted in a spreading wildfire; and the third issue was determining the location for any ignition that spread.

First, the number of days in each year on which at least one ignition occurred was determined. The historical average was 9 ignition days per year for this landscape, with a range from 4 to 19. This distribution is shown in Figure 3. Once the number of days upon which at least one ignition occurred was drawn, dates were assigned based on the distribution of ignition days across all years, displayed in Figure 4.

Number of Days with at Least 1 Ignition
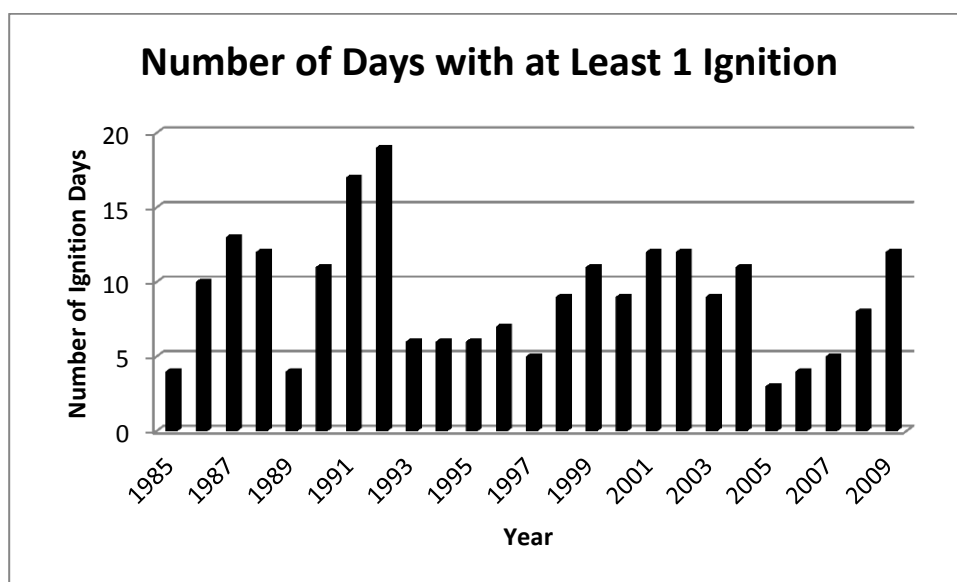
Figure 3: The distribution of days with 1 or more suppressed ignitions across years 1985 through 2009. The historical dataset on which this distribution is based accounts only for those ignitions which the Forest Service attempted to suppress.

Frequency distribution of lightning ignitions responded to by the Forest Service by day (1985-2009)
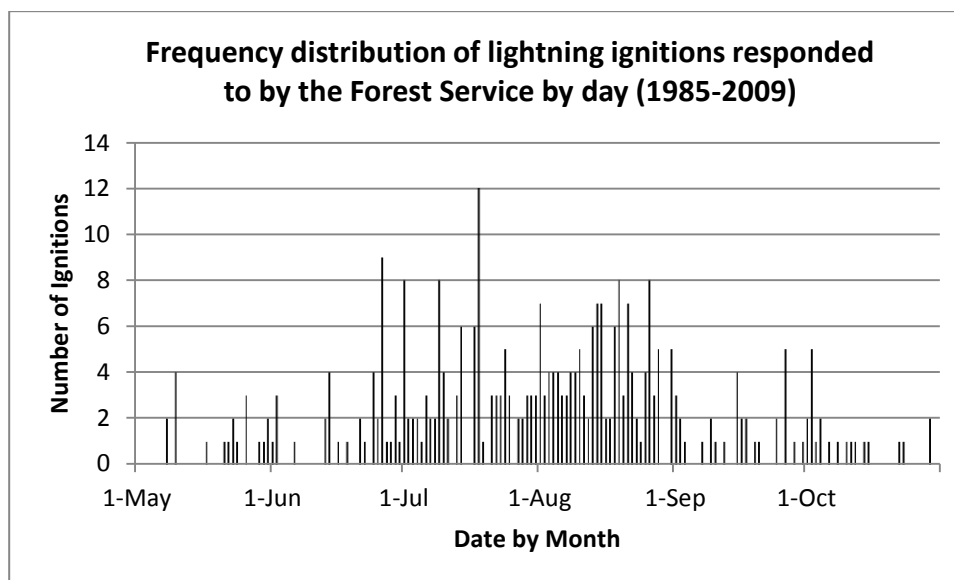
Figure 4: The frequency of lighting ignitions by day during the fire season. This is based on a historical dataset available from the Forest Service. The Forest Service records the ignitions to which fire crews respond on Forest Service land.

Only about 2% of all ignitions in which suppression is attempted escape containment by initial attack (Mark Finney, personal communication, February 4, 2011). The historical data for this site show that only 1.5% of wildfires have spread to greater than 20 hectares in the past 25 years. The fact that this is lower than 2% may be due to the fact that the study area has an extensive road system so accessibility is less likely to impede initial attack.

The number of ignitions that occurred on a given day was also drawn from historical distributions. The average number of ignitions was 1, but as many as 8 ignitions occurred on a single date, as demonstrated in Figure 5. The number of ignitions was generated based on the cumulative distribution of number of ignitions per day, shown in Figure 6. If at least one ignition occurred on a day, all the ignitions

that occurred on that date were treated as a single event. If an ignition was

successfully suppressed, all ignitions on that date were suppressed. Any ignitions that

occur on the date of the selected let-burn ignition will be simulated simultaneously.

Current ignitions for which a choice was made between suppress and let-burn is

referred to as the "current fire" throughout the paper.
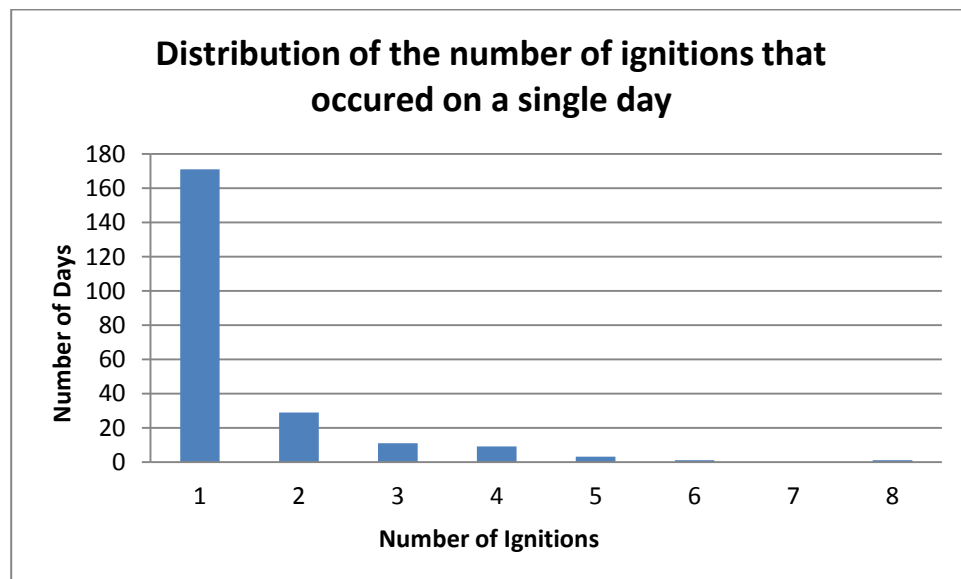
Figure 5: The distribution of the number of historical ignitions for which suppression was attempted, per day, over the period from 1985 through 2009.

Cumulative probability of number of ignitions per day
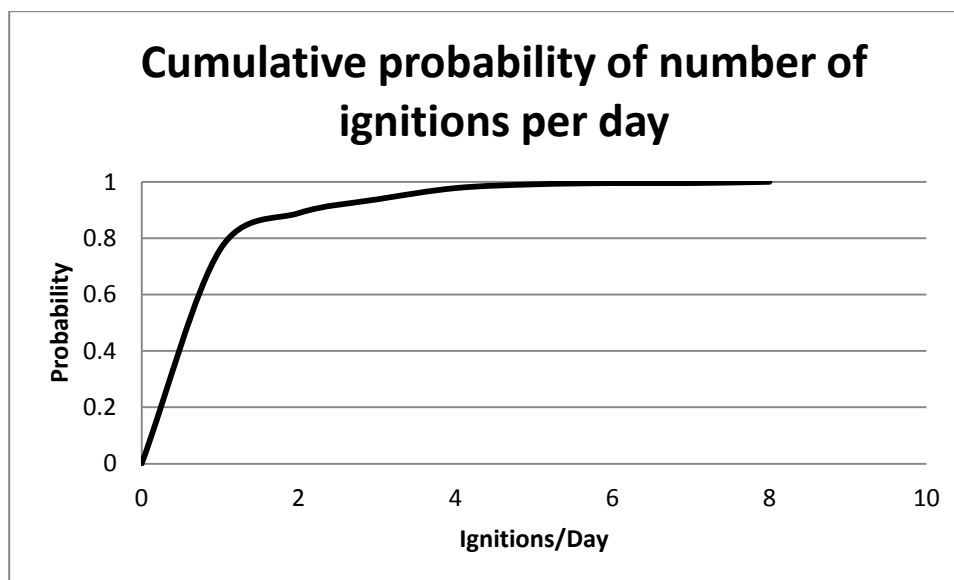
Figure 6: The cumulative probability distribution of ignitions per day from 1985-2009.

Ignition locations are only required for modeling wildfires in FARSITE, so ignition locations for which initial attack is successful do not need to be drawn. Therefore, the next step was to determine dates upon which ignitions escape initial attack. Most ignitions escape initial attack during weather events in which fire spread rates are high and fuel moisture is low. I set the expected number of escapes equal to 2% of all suppressed ignitions, conditional on the ignition occurring during a day where both the spread component and the ERC were in the 90th percentile or above. Spread component is a measure of how fast a wildfire will spread through a given fuel model, given the wind and weather, and is equivalent to rate of spread for a wildfire (Bradshaw et al. 1984). Energy release component, or ERC, is a measure of expected energy released in BTU/ft² by a wildfire for a given fuel model (Bradshaw et al. 1984). Fire weather percentiles are a measure of severity for a given area. For

example, only ten percent of days have a higher spread component or ERC than a

90th percentile day. Based on historical fire weather and ignitions, I calculated that

36% of ignitions that meet the weather percentile criteria would escape initial attack

in order for 2% of all ignitions to escape initial attack. In creating the pathways, each

day on which an ignition event occurred, that also met the weather percentile

criteria, was assigned a 36% chance of escaping initial attack.

Once the spreading ignitions were identified, it was necessary to determine

the duration for each wildfire. For ignitions that escaped initial attack (which included

all future fires), end-of-spread dates were determined using the regression equation

estimated by Finney, Grenfell and McHugh (2009). The regression was used to

determine daily probability of containment based on the days in which the wildfire

was considered spreading, the number of changes between spreading and non-

spreading periods, and fuel types. Under the suppression policy, end dates were

generated based on the probability of successful suppression each day the wildfire

burned. I established spreading versus non-spreading days, using the BEHAVEPlus fire

model to examine the impact of altering the wind speed, which has a major influence

on spread component, and 1-hour fuel moistures, a component of ERC. The

BEHAVEPlus fire model is a PC-based freeware program which is used to examine fire

spread characteristics on a uniform landscape, and is available through the Forest

Service (Andrews, Bevins, and Seli 2005). As demonstrated in Figure 7, wildfire

spread is negligible when fuel moisture is above 12%. Given fuel moistures below

12%, spread increased almost linearly with wind speed in the most common fuel

conditions for the study area. I established the threshold for distinguishing spreading

and non-spreading days at wind speeds of 15 mph, given a fuel moisture content of

less than 12%.
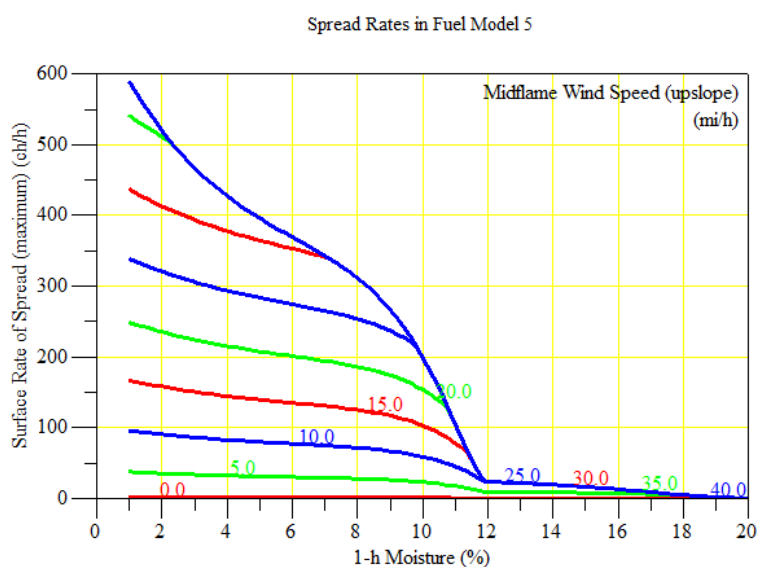
Figure 7: Outputs from the BEHAVEPlus fire spread model. The spread rates shown here are based on fuel moisture content and wind speed. There is a clear break-point for spread rates for 1-hour fuel moistures of 12% or more. As winds increase to 15 mph, spread rates pass 100 chains/hour, which is considered "spreading" in this study.

A kernel density map was created for the landscape using ArcGIS, to generate

ignition locations. ArcGIS is a program that is used to edit, analyze, and manipulate

geographical data sets (ESRI 2011). A kernel density map is a representation of the

landscape in which each 30m x 30m pixel has a probability of ignition, which is

determined based on historical ignitions that occurred in that pixel, and in neighboring pixels.

The map I created was based on 20 years of historical ignition suppression information, and is shown in Figure 8. The lighter areas had a higher density of historical ignitions, and were assigned a higher probability of ignition than areas with fewer ignitions. Each ignition impacted an area called a footprint that included 2000 ha surrounding the ignition point. This accounted for interaction between discrete ignition points.
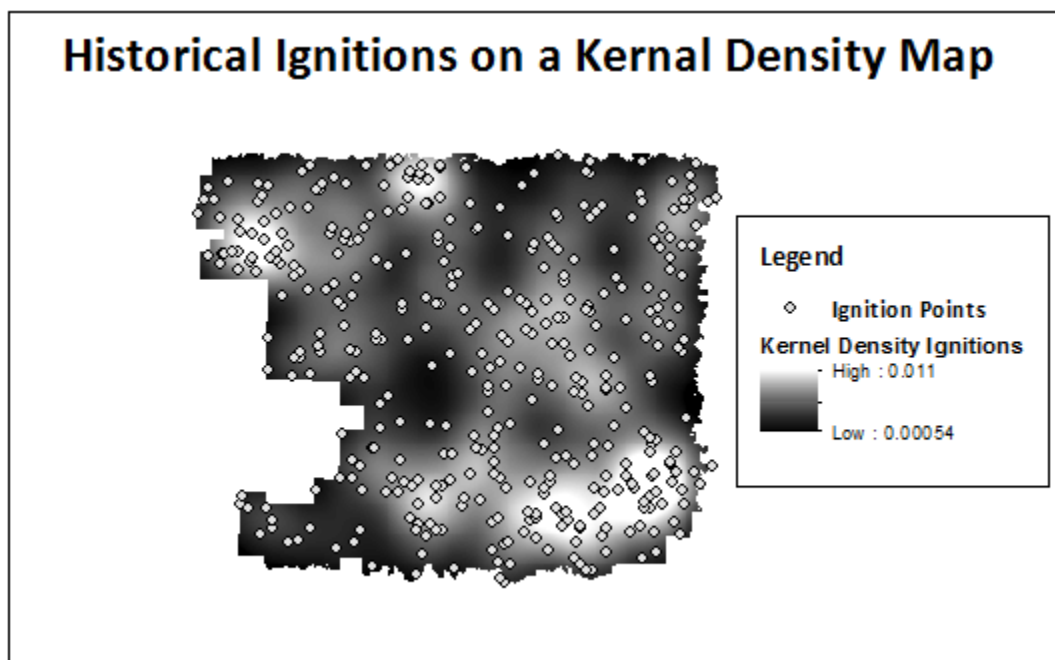
Figure 8: Kernel density map of historical ignitions.

Fire-ending weather events were used to determine the duration in the let-burn scenarios for the current wildfire. A fire-ending weather event was defined as

weather in which both ERC and spread component fell below the 30th percentile or the end of the fire season was reached. I defined the fire season as between May 1st to October 31st, based on historical records for suppressed ignitions and percentile fire weather events throughout the year.

Specific weather and wind information were the final input required for each spreading fire. I randomly selected a year from the 24 years of historical weather data to assign weather streams to each fire event. Weather streams for a particular fire began four days before the date of ignition to allow for conditioning of the fuels, and continued through the end date.

The actual values used in the simulations were analyzed to ensure that they approximated historical values. The comparison is presented in Figure 9. For the most part, simulated and historical values were comparable. The percent of ignitions that resulted in large fires was smaller in the simulations because ignitions were created during pre-processing. All reported historical ignitions occurred in burnable fuel models, because the Forest Service deployed suppression efforts. By pre-processing ignitions, it was not possible to ensure that every escaped ignition would occur in a burnable fuel model. In addition, there were no very large fires (>5000 ha) located in the study area in the historical data set. Large fires did occur outside the study area, and there it is reasonable to assume that over a longer time scale, large fires could occur in the study area. An average of one very large fire occurred in each

100-year pathway, which caused the average area burned per year in the simulations

to be higher than the average for the historical values.

Historical and Simulated Values		
	Simulated Values	Historical Values
Average ERC (all ignitions)	65.44	66.23
Standard Deviation (ERC)	24.02	21.88
Average SC (all ignitions)	62.64	61.85
Standard Deviation (SC)	25.99	22.58
Average Ignitions/Year	15.86	13.08
Standard Deviation	6.32	7.71
Ignitions escape initial attack (%)	1.81	1.52
Average area burned per year (ha)	222.34	65.12

Figure 9: A comparison of the simulated and historical values for selected variables. The simulated values for weather and ignition variables aligned closely with historical values. The historical record for area burned was only reliable for 30 years. During that period, no very large fires (>5000 ha) occurred within the study area. However, these fires did occur outside of the study area, and so were not excluded from the simulations. The average was just under one very large fire per 100-year pathway.

Updating the Vegetation

Since OCWS simulates a progression of events, the vegetation characteristics

must be updated to reflect the events of each time-step. I built a look-up table which

contains links between initial states and ending states, based on the transition type

and vegetation cover type. Transition types are defined by the FARSITE crown fire

activity output and include a surface fire, a crown fire, or grow (no fire). I used FFE-

FVS (described below) to simulate grow and burn events in order to track the impact

of these events on vegetation for each state. These outcomes were stored in the

look-up table, that was then accessed by the OCWS.

Each state includes the characteristics for the vegetation on the landscape at time t and topographical characteristics. A list of these characteristics can be found in Table 1. The fuels characteristics can be broken down into canopy fuels and surface fuels. The fuel model provides a measure of all surface fuels. A fuel model is a representation of surface fuels that allows for broad classification of a wide number of ecosystems for the purpose of describing wildfire behavior. The 13 fuel model set used here was created by Anderson (1982). Canopy fuels are measured by canopy cover, canopy height, canopy bulk density, and canopy base height.

Vegetation Characteristics	Topographical Characteristics
Canopy Cover (%)	Elevation (ft)
Canopy Height (ft)	Slope (degrees)
Canopy Bulk Density (kg/m³)	Aspect (degrees)
Canopy Base Height (ft)	
Fuel Model (Anderson 1982)	
Cover Type (by dominant species)	

Table 1: The list of state attributes required by FARSITE. These attributes include the most important landscape and vegetation characteristics for estimating fire spread and behavior.

In another attempt to limit the size of the state space, I used mainly those variables required by FARSITE to track transitions, namely surface and crown fuels. However, in order to update the vegetation after a burn even, I determined that tracking vegetation type was also necessary. Different vegetation types have diverse responses to wildfire that are not tracked within FARSITE. For example, ponderosa pine is resilient to surface fires, and, except in situations where an individual tree is already compromised by disease or damage, will typically survive surface fires

without difficulty. Lodgepole pine, however, is a resilient species, and though individuals do not survive fire easily, their cones are serotinous, and they can regenerate vigorously after fire. In order to capture that variation in the post-fire environment, I included a category for cover type. The main cover types present on the study site were ponderosa pine dry, lodgepole pine dry, mixed conifer dry, and mountain hemlock. There was a small number of stands listed as ponderosa pine wet and lodgepole pine wet, but due to the limited area populated by these stands, they were combined with the dry types.

Since the topography remains the same over the time-horizon, it was not included in the final look-up table. I did note that including slope and aspect could have an impact on transitions, but by removing those variables I was able to decrease the array of potential states to a computationally manageable number.

The Forest Vegetation Simulator (FVS) was used to generate the grow transitions. FVS is a stand-based, individual tree growth model maintained by the Forest Service (Dixon 2002). It is used to simulate the development of vegetation based on growth and disturbances in forested ecosystems across the United States. Variants are available for different climate and vegetation zones because the program is calibrated using growth algorithms that take into account some geographic and climatic variation. The program applicable to our area is the Southern Oregon and Northeast California (SO) variant (Keyser 2002).

FVS also has an associated program called the Fuel and Fires Extension to the Forest Vegetation Simulator (FFE-FVS) that allows a user to input weather information to simulate a wildfire in a single stand. I used FFE-FVS to evaluate the burn transitions between states. In order to achieve both surface and crown fires, I altered fuel moistures, wind speed, and temperature until the desired wildfire behavior was produced. In most cases, the conditions required to create crown or surfaces fires were the same within cover types, even between different ages. The weather requirement varied more between cover types.

The landscape was simplified by assigning a single representative tree list to each of the four cover types in order to generate transitions. A tree list is a data set which contains characteristics of individual trees on the landscape, such as height, species, and diameter at breast height (DBH). The tree list is one of the inputs required to run FVS, but not required to run FARSITE. By simplifying down to a single tree list for each cover type, I was able to account for transitions from every possible state that could occur over a 100-year pathway. The representative tree lists were selected based on average number of trees per hectare and basal area per hectare for the given cover type. I then divided each state characteristic into representative ranges and assigned a unique value to represent each range, as shown in Table 2.

I simulated each stand under a grow-only scenario in FVS for 100 years in 4-year increments to obtain a baseline set of states. Any state that burned was set to

remain unburnable for a given amount of time by assigning it a non-burnable fuel

model, based on vegetation type. For this exercise, I assumed that ponderosa pine

could burn again 20 years post wildfire; lodgepole pine after 50 years; mountain

hemlock after 40 years; and mixed conifer after 30 years (John Bailey, Personal

Communication, October 15, 2010). Since the stands were assigned a non-burnable

fuel model, I had to track the state changes on the landscape for the fuel

characteristics in order to determine the state of the pixel when it emerged from the

non-burnable state.

Canopy Cover Values (%)	
Range	Assigned Value
0	0
1-40	25
40-75	55
75-100	90
Crown Base Height (m)	
Range	Assigned Value
0	0
1-5	2
1-10	7
10-20	15
>20	30
Canopy Height (m)	
Range	Assigned Value
0	0
1-15	8
15-30	24
>30	40
Crown Bulk Density (kg/m³)	
Range	Assigned Value
>.01	0
0.01-0.05	0.03
.06-.1	0.08
.1-.2	0.15
.2-.35	0.28

Table 2: State characteristic ranges with corresponding assigned values. These ranges were determined by examining the full range of values for each characteristic over the time-horizon and splitting the ranges into a set that was manageable for creating the look-up table manually.

Each characteristic was represented by wide ranges, so in many cases a single year would not move any characteristics from one range into another. By tracking time-in-state, I was able to track long-term residency in a state, and the eventual transition that occurred. Time-in-state is the amount of time it takes for at least one characteristic in a state to move from one range to another. These vary from 4 years to as many as 60 years. Some states never transition, appearing to have reached a climax state for the vegetation type based on the defined ranges. Once the time-in-state elapses in the program, the pixel is updated for growth. Time-in-state is only applicable to stands that are growing; any burn always causes an immediate transition to a new state.

Once I generated all the states and their associated transitions, each pixel on the current and any possible future landscape over 100 years then had a state definition. The characteristics for each transition were placed into a look-up table that could be accessed by the program at the end of each time-step.

Once the look-up table was in place, the OCWS accessed the crown fire map output from FARSITE to ascertain the transition applied to each pixel. The transition could be a grow, a type of burn, or a decrease of time-in-state, as shown in Figure 10. In this example, State 1 reaches the maximum time in state at the end of the period. The grow transition is triggered at the end of the time-step, and the pixel is moved from State 1 to State 2, as a result of a change in the canopy cover. As in this

example, it only takes a change in one state characteristic (canopy cover) to change states.

The initial time-in-state among the stands on the landscape at time 0 was unknown. I assigned these by taking the maximum time-in-state for the initial state, multiplying that by a random number between 0 and 1, and rounding to the nearest integer. This ensured that large, contiguous portions of the landscape would be less likely to update simultaneously during a grow transition.
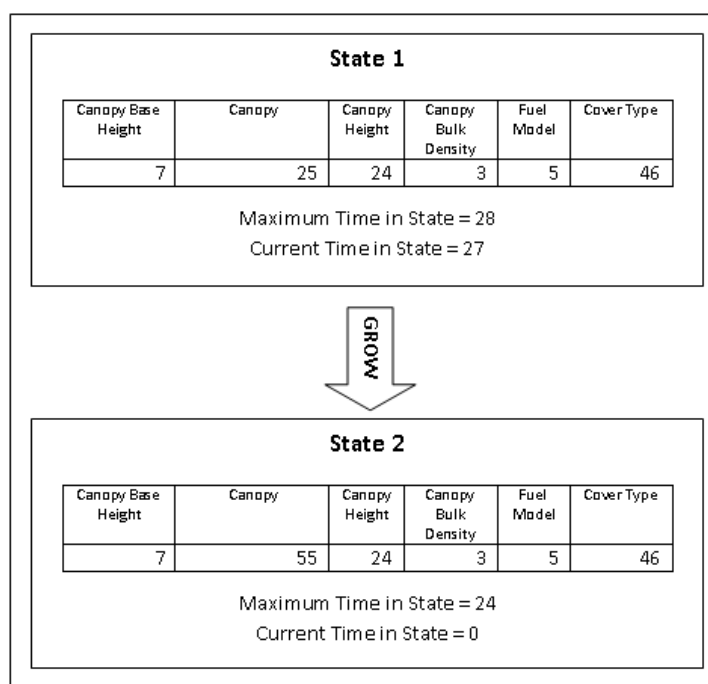

Figure 10: The growth transition of a pixel from state 1 to state 2. At the beginning of the time-step the pixel is in its final year in that state. At the end of the time-step, the current time in state is incremented by one, and the conditions for transition are met.

The Suppression Cost Model

Depending on wildfire size, there were three ways I calculated suppression costs. The three wildfire size categories were: fires less than 0.4 hectares (1 acre), fires between 0.4 and 121.4 hectares (300 acres), and fires greater than 121.4 hectares. There is no current model for calculating costs of suppressing small wildfires, so I used the data set provided by the Deschutes National Forest office that gave each suppressed ignition over the past 20 years, with associated fire size and suppression cost. The average cost of suppression for all fires that burned 0.4 hectares or less was $5,822. I determined the per-hectare cost for small fires that escaped initial attack as the average cost of suppression for all wildfires between 0.4 and 121.4 hectares ($11,384/hectare or $4,734/acre) during that time period. All costs accounted for inflation in 2004 dollars.

To calculate the cost of suppression for large wildfires (>121.4 hectares), I used the logarithmic regression of suppression costs estimated by Gebert et al. (2007), which informed the equation now used by the Forest Service to estimate suppression costs for large fires. The most recent version of this equation was provided by the USFS Rocky Mountain Research Station (Matt Thompson, personal communication, August 23, 2010).

The cost equation uses the logarithm of area burned, as reported in output from FARSITE. It is not possible to distinguish area burned in FARSITE between

wildfires that spread simultaneously, so these wildfires are treated as a single fire. As a result, the fire area estimates resulted in an under-estimation of suppression costs. However, because I compared two values, both of which were underestimates, the magnitude of the difference should be a more reasonable estimate. In addition, only 24% of wildfires involved more than one ignition.

The cost regression equation includes the following: ERC (based on fire weather percentiles); region in which wildfire occurs (the study area is in region 6); in what vegetation type the wildfire started (brush, timber, slash); a wilderness dummy (0 for the study area); total number of acres burned; distance to nearest town; value of housing within 20 miles of ignition (La Pine is the only town within 20 miles); slope; elevation; and aspect. The full regression equation is presented in Equation 6. I used landscape averages for all the variables except ERC and total acres burned because the number of simulations should result in a convergence to the mean. ERC was computed for each day using a program that processes weather events with regards to wildfires, Fire Family Plus (FFP). FFP is free software made available from the Missoula Fire Science Laboratory (Missoula Fire Lab 2011).

Equation 6

$$ln\left(\frac{cost}{acre}\right)$$

$$= 1.982345 + 0.019546(ERC) + 1.202795(Region\ 6\ dummy)$$

$$- 0.00228(brush\ dummy) + 0.512832(brush4\ reference)$$

$$+ 0.855297(timber\ dummy) + 0.56725(slash\ dummy)$$

$$- 0.32068\ ln(total\ acres\ burned) - 0.26234\ ln(distance\ to\ town)$$

$$+ 0.142163\ ln(housing\ value\ 20) + 0.113394\ ln(slope) + 0.360279\ ln(elev)$$

$$- 0.14305cos(aspect) - 0.05089sin(aspect)$$

All future suppression costs were discounted using a 4% discount rate, which is standard policy for the Forest Service (Row, Kaiser, and Sessions 1981), and were assumed to be constant over the time-horizon. The cost equation is in terms of 2004 dollars per acre. These data were converted into dollars per hectare for consistency.

Estimating Timber Losses

In order to determine whether the suppression cost savings are enough to allow an ignition to spread, the issue of value lost to the wildfire must also be considered. Loss of timber due to wildfire is one counterweight to the suppression cost savings. This is the value loss component of Δv from Equation 3, and is presented in Equation 7 for iteration r, as the difference between revenue under the let-burn scenario, and revenue under the suppress scenario.

Equation 7

$$L^r = \{r_0(s_t, w_t^r | x_0 = 0) - r_0(s_t, w_t^r | x_0 = 1)\} + \sum_{t=1}^{T-1} \beta^t \{R(s_t, w_t^r | x_0 = 0)$$

$$- R(s_t, w_t^r | x_0 = 1)\}$$

To fully account for the loss due to wildfire, the value lost in each wildfire over the time-horizon would have to be calculated. Value, in this instance, can include both market (timber) and non-market (scenic, habitat, ecosystem services, etc.) values. In addition, the impact of harvesting on the fuels must to be taken into account in the look-up table, greatly increasing the number of vegetation transitions required. Estimating loss is beyond the scope of my thesis, but because it is useful to the understanding of when it would be optimal to let-burn, I created a rough estimate of the average net present value of timber lost to current and future fires. Lodgepole and ponderosa pine stands, which comprised most of the study area, were included in the loss estimate.

In order to get a rough estimate for the value lost, I calculated the land and timber value (LTV), in dollars per hectare, for lodgepole pine and ponderosa pine. I computed the LTV for both ponderosa pine and lodgepole pine, based on whether there was no fire, a surface fire, or a crown fire. These calculations assume a perpetual management regime, that the forest is currently regulated, and that there was no salvage logging post-fire. In the following section, $LTV_{Sp,\ fire\ type}$ refers to

the land and timber value for species, lodgepole pine (*LP*) and ponderosa pine (*PP*), and fire type includes no fire (*NF*), surface fire (*SF*), and crown fire (*CF*). Finally, I assumed that the current dominant cover type would not change throughout each simulation.

Lodgepole pine stands were managed on an 80-year rotation and assumed a yield of 38.5 MBF/ha for site index 60 (50-year base) (Emmingham et al. 2005). The assumption that the forest is regulated on an 80-year rotation means that the stands are evenly distributed across age from 1 to 80 years. If there is no fire, the $LTV_{LP,NF}$, in $/ha (Equation 8), is the land and timber value for a regulated, lodgepole pine stand, with a rotation age of 80 years.

Equation 8

$$LTV_{LP,\ NF} = \sum_{a=1}^{80} b_a \frac{H + \dfrac{H}{(1.04)^{80} - 1}}{(1.04)^a}$$

Where:

$LTV_{LP,\ NF}$ is the average land-and-timber value at time 0 in $/ha.

H is the harvest revenue in $/ha, calculated as the stumpage price in $/MBF times the clearcut volume in MBF/ha.

a is the years remaining until a clearcut harvest.

b_a is the proportion of lodgepole pine area with a years until harvest.

I assumed a 50% volume loss from a surface fire for existing lodgepole pine stands (Equation 9), and no change in the timing of harvest.

Equation 9

$$LTV_{LP,SF} = \sum_{a=1}^{80} b_a \frac{(.5)(H) + \dfrac{H}{(1.04)^{80} - 1}}{(1.04)^a}$$

I assumed a total volume loss from crown fire for existing lodgepole pine stands, so in the case of crown fires, the land and timber value is equal to the soil expectation value, $LTV_{LP,CF} = SEV_{LP,CF}$ (Equation 10).

Equation 10

$$LTV_{LP,CF} = \frac{H}{(1.04)^{80} - 1}$$

Ponderosa pine stands were managed under a selective harvest regime, assuming a site index of 80 (50-year base), and a base growing stock of 43.5 MBF/ha (Bennett 2002) which occurs at age 60. These stands were then grown and thinned on a 20-year cycle, with an estimated thinning volume of 27.5 MBF/ha to maintain the growing stock (Bennett 2002), so the first thinning would occur at age 80. The actual stand volume estimates were used, along with the yield tables, to determine how many hectares would be harvested in each 10-year period.

Ponderosa pine is highly resilient to surface fires but is susceptible to crown fires. As a result, I assumed no volume loss from a surface fire and a total volume loss from a crown fire. The land and timber value for a ponderosa pine stand with no fire, or a surface fire is presented in Equation 11.

Equation 11

$$LTV_{PP,NF} = LTV_{PP,SF} = \sum_{a=1}^{80} b_a \left(\frac{H + \frac{H}{(1.04)^{20}-1}}{(1.04)^a} \right)$$

Where:

H is the harvest revenue in $/ha, calculated as the stumpage price in $/MBF, times the thinning volume in MBF/ha.

a is the years remaining until a thinning.

b_a is the proportion of lodgepole pine area with a years until the first thinning.

The land and timber value for a ponderosa pine stand in which a crown fire occurs is the same as the bare land value, because crown fire is assumed to result in a total loss of timber value. The bare land value is presented in Equation 12.

Equation 12

$$LTV_{PP,NF} = \frac{H + \frac{H}{(1.04)^{20} - 1}}{(1.04)^{80}}$$

The change in the timber value loss between the suppress scenario and the let-burn scenario for time t in sample pathway r is in Equation 13.

Equation 13

$$L^r = \sum_{t=0}^{T-1} \beta^t \sum_{y \in [NF,SF,CF]} (LTV_{PP,Y,x_0=0}) * (F_{t,PP,Y,x_0=0})$$

$$- \sum_{y \in [NF,SF,CF]} (LTV_{PP,Y,x_0=1}) * (F_{t,PP,Y,x_0=1})$$

$$+ \sum_{y \in [NF,SF,CF]} (LTV_{LP,Y,x_0=0}) * (F_{t,LP,Y,x_0=0})$$

$$- \sum_{y \in [NF,SF,CF]} (LTV_{LP,Y,x_0=1}) * (F_{t,LP,Y,x_0=1})$$

Where:

F_{t,Sp,Y,x_0} is the number of hectares of species $sp = PP, LP$ burned in fire type Y, in the let-burn scenario for $x_0 = 0$, and the suppress scenario for $x_0 = 1$, in time period t.

Stumpage value for lodgepole pine was $200/MBF. This assumed $325/MBF in revenue, based on Camp Run grade logs from Oregon Region 5 (ODF [1] 2011), and average harvest and haul costs of $125/MBF (ODF [2] 2011). Stumpage value for ponderosa pine was $295/MBF, based on timber with a DBH of 14"-22", from Oregon

Region 5. The pond value for this type of log was $470/MBF (ODF [1] 2011). The

average harvest and haul costs were assumed to be $175/MBF (ODF [2] 2011).

The average land and timber values for lodgepole and ponderosa pine are

summarized in Table 3.

Land and Timber Values (in 2004 $/ha)		
Fire Type	Lodgepole Pine	Ponderosa Pine
No Fire	$2,675.78/ha	$6505.73/ha
Surface Fire	$1,395.93/ha	$6505.73/ha
Crown Fire	$349.20/ha	$352.11/ha

Table 3: The estimated average land and timber values for lodgepole pine and ponderosa pine stands.

Results

Benefits

The estimated benefit, $E[B]$, described in Equation 5, is the present value of

the change in future suppression costs that result from a choice between suppressing

the current fire and allowing that fire to burn. I determined that 500 observations for

B^r was a large enough sample because, for a sample size of approximately 300, $E[B]$

appeared to stabilize, as did the standard deviation. Due to the skewedness in the

sample, I simulated 200 more in order to capture outliers. The cumulative average

over increasing sample size is presented in Figure 11, and the stabilizing trend is

clear. $E[B]$ for this data set was $2,287,214, or $31.70/ha. The sample values ranged

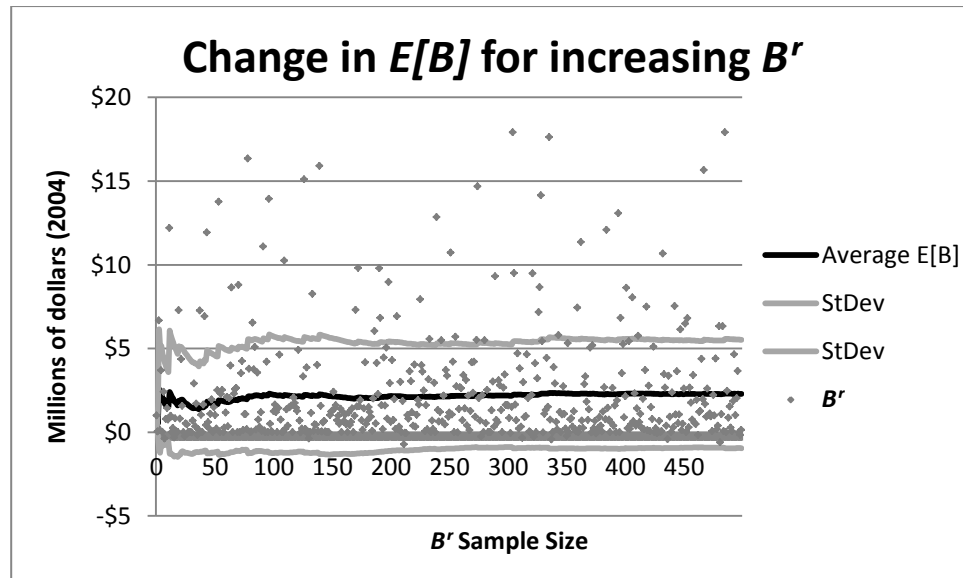from negative \$721,051 to positive \$17,918,341, with a standard deviation of

\$3,237,428.

Figure 11: The present value of the change in estimated future suppression costs resulting from allowing the current fire to burn. As B^r increases, the mean and standard deviations stabilize.

In order to explore the data more thoroughly, the sample set can be split into

two obvious categories: $B^r > 0$ and $B^r < 0$. In addition, due to the fact that the

distribution of the sample points is skewed towards the lower end of the range of

positive values, as seen in Figure 12, I further separated the positive pathways into:

$0 < B^r < E[B] + 1 \; standard \; deviation$ and $B^r > E[B] + 1 \; standard \; deviation.$

Pathways which were positive and fell within one standard deviation from the mean

were the "positive" sample, and accounted for 84.2% of the total sample. Those

sample points which were greater than one standard deviation above the mean were

designated as the "high positive" sample. These accounted for approximately 11.2%

of the total sample. The negative values accounted for 4.6% of the total sample. The

large number of sample points with a value between $0 and $100,000 is the result of

those pathways in which future wildfires never spread into the area treated by the

current fire. Under those circumstances, no future fuel treatment savings were

realized.

Histogram of Expected Benefits ($E[B]$) in $100,000 Increments

Median
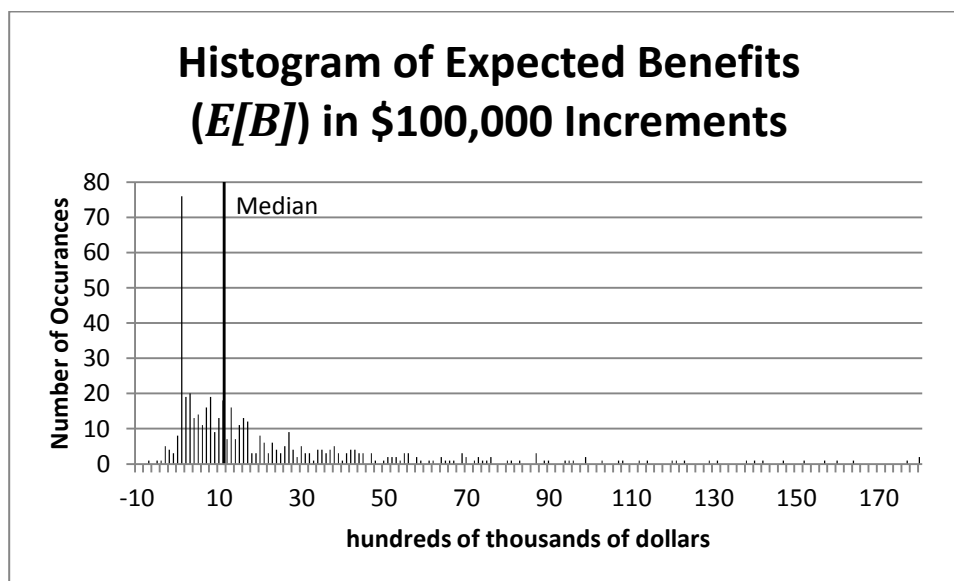
Figure 12: Distribution of sample points resulting from 500 sample pathways.

Although the average difference in suppression cost savings was positive

across simulations, and in all, positive data points composed 95.4% of the total

sample, some pathways did exhibit a higher NPV for suppression costs in the let-burn

scenario than in the full suppression scenario, which resulted in a negative expected

benefit. There were two explanations for this outcome.

First, it happened when an ignition occurred in an area that had been previously burned only in the let-burn scenario. When the same ignition resulted in a wildfire in the full suppression scenario, that wildfire created fuel treatment in the full suppression scenario that was not realized in the let-burn scenario. Second, once an area that burned in the original wildfire transitioned from non-burnable to burnable, there were cases in which the new fuel model had a higher rate of spread than the corresponding fuel model in the suppress scenario. This resulted in a larger future wildfire in the let-burn scenario. Pathways exhibiting positive, high positive, and negative benefits are described in more detail next.

Positive B^r Case

This pathway is an example from the positive sample set. In this case, $B^r = \$493,457$.

An ignition occurred in year 0, represented in Figure 13 (a) by a red point surrounded by a circle. The ignition occurred to the east of the middle of the study area. The fire burned 44,700 ha in the let-burn scenario, and was fully suppressed upon initial attack in the full suppression scenario.

In year 7, Figure 13 (b) shows that the area that was burned in the current fire is still non-burnable, and as a result, can act as a fuel break. In year 8, represented in Figure 13 (c), an ignition occurred in the southeast. Due to the fuel treatment, that

ignition did not spread in the let-burn scenario. In the full suppression scenario, the ignition escaped initial attack and spread, but it was quickly suppressed, resulting in a fire of 286 ha and a cost of $398,265, or $1393/ha.

As time passes and fuels continue to accumulate, much of the area burned in the current fire transitions into a burnable fuel model. Despite the re-growth, by year 83 (Figure 13 (d)) there are still some fuel breaks on the landscape, and when an ignition occurs in year 84 (Figure 13 (e)), those fuel breaks in the let-burn scenario result in a smaller fire than in the suppress scenario. To clarify the difference, the area burned by this ignition in the full suppression scenario is 11,489 ha. The undiscounted value of suppression costs is $11,042,196. The area burned in the let-burn pathways is 9,005 ha. The undiscounted value of suppression costs is $9,352,488.
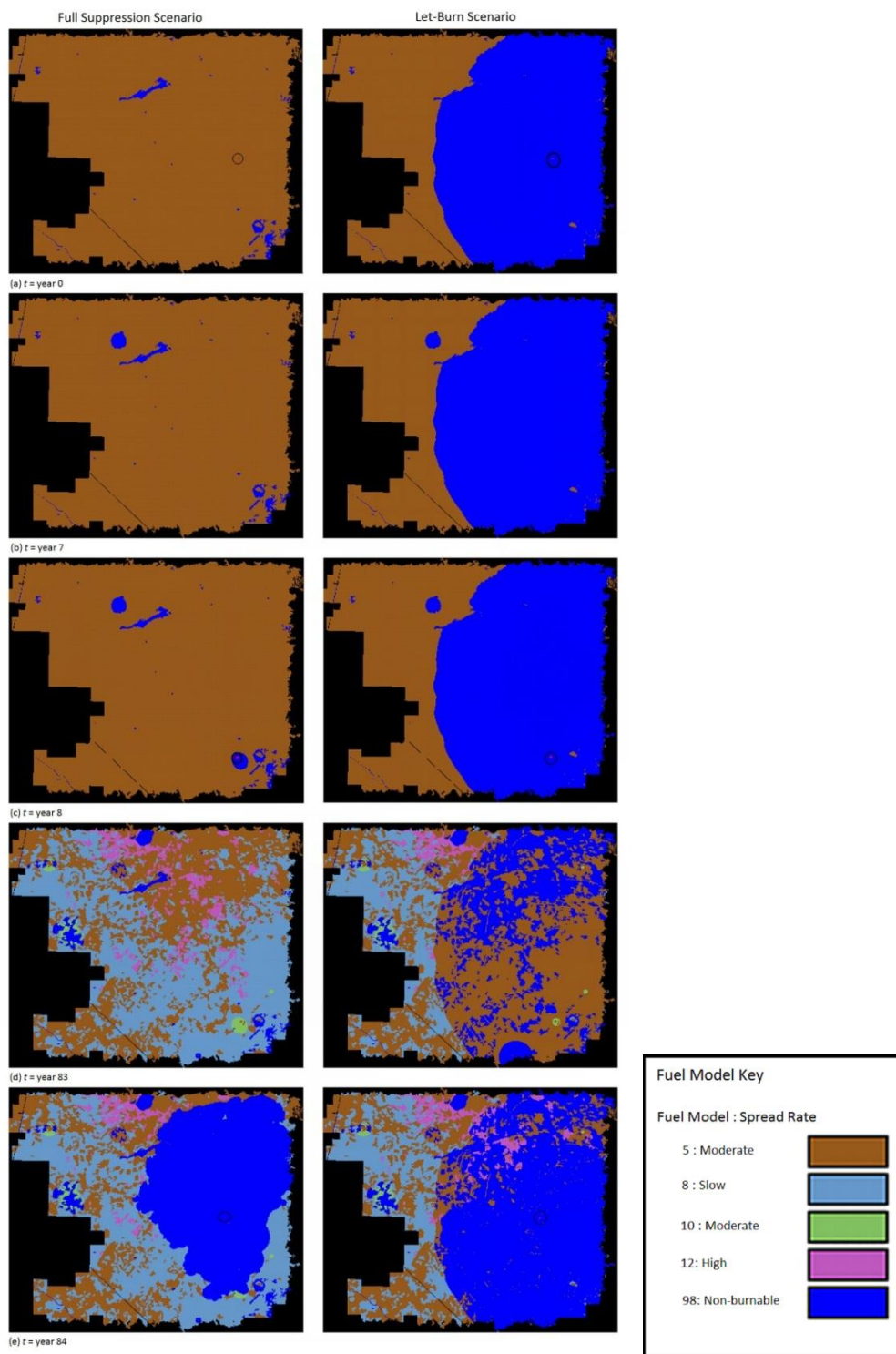
Figure 13: A progression of maps showing fuel model changes for an example positive sample pathway.

High Positive B^r Case

This pathway is an example from the high positive sample set. In this instance, B^r = \$15,124,275, the seventh highest foregone fuel treatment observed in the sample.

In year 0, an ignition occurred in the southwest corner of the study area, resulting in a 57,562 ha fire in the let-burn scenario. The ignition is denoted by a red point, surrounded by a circle in Figure 14 (a). The post-fire landscape represented in Figure 14 (a) became the pre-fire landscape for the next fire, which occurred in year 8 Figure 14 (b). The ignition for this fire was located in the northeast, in a location that was treated by the current fire in the let-burn scenario, and was still in a non-burnable fuel model. In the suppression scenario, the ignition spread into a fire, with a final size of 56,145 ha. The undiscounted cost of this fire was \$20,427,759 (present value of the cost \$14,926,363.55). At this point, both pathways had comparable treated areas, and fires that occurred past year 8 were comparable in size and cost.

The order of events in this pathway was common in the high positive sample set. Typically, high positive pathways have fires that escape initial attack early in the time-horizon. Those fires tend to be very large in the full suppression scenarios, in comparison to being small or absent in the corresponding let-burn scenarios.
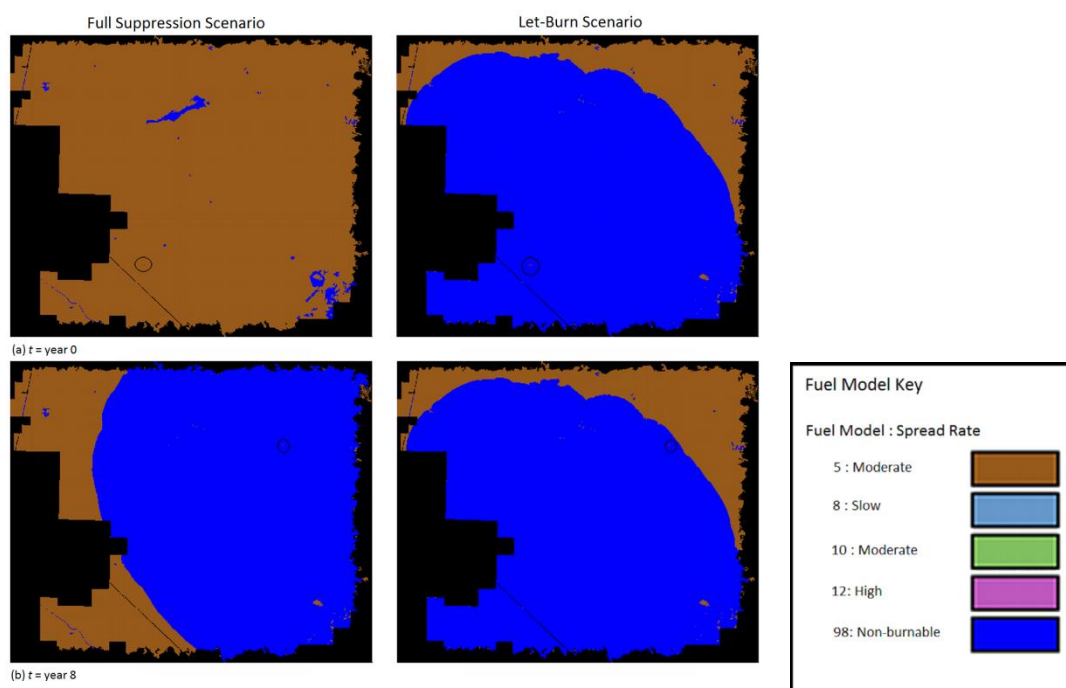
Figure 14: A progression of maps showing fuel model changes for an example high positive sample pathway.

Negative B^r Case

This pathway is an example from the negative sample. In this instance, $B^r = -\$253{,}541$.

An ignition occurred in year 0, denoted in Figure 15 (a) by a red point surrounded by a circle, in the southeast corner of the study area. The ignition resulted in a burn of 28,866 ha in the let-burn scenario. The ignition was successfully suppressed in the full-suppression scenario. By year 40, the fuel models in much of the area burned by the current fire have transitioned from non-burnable into burnable, as demonstrated in Figure 15 (b).

The biggest difference between the two scenarios was the result of the fire that occurred in year 41, presented in Figure 15 (c). It ignited in the location that had been burned by the current fire in the let-burn pathway, but had transitioned into a burnable fuel model with a higher spread rate than the corresponding fuel model in the suppression scenario, and exhibited different behavior as a result. The ignition, which occurred in the southeast, spread faster in fuel model 10, which was present in the let-burn scenario than in fuel model 8, which was present in the suppression scenario. The fire size in the let-burn scenario was 2072 ha. The undiscounted value of the suppression costs was $1,864,918 (the present value of costs was $373,502). The fire size in the suppression scenario was 181 ha. The undiscounted value of suppression costs was $355,920 (the present value of costs was $71,283).

In general, for $B^r < 0$ to occur, an ignition must occur in a location where the fuel model in the let-burn scenario has a higher spread rate than the corresponding fuel model in the suppression scenario.
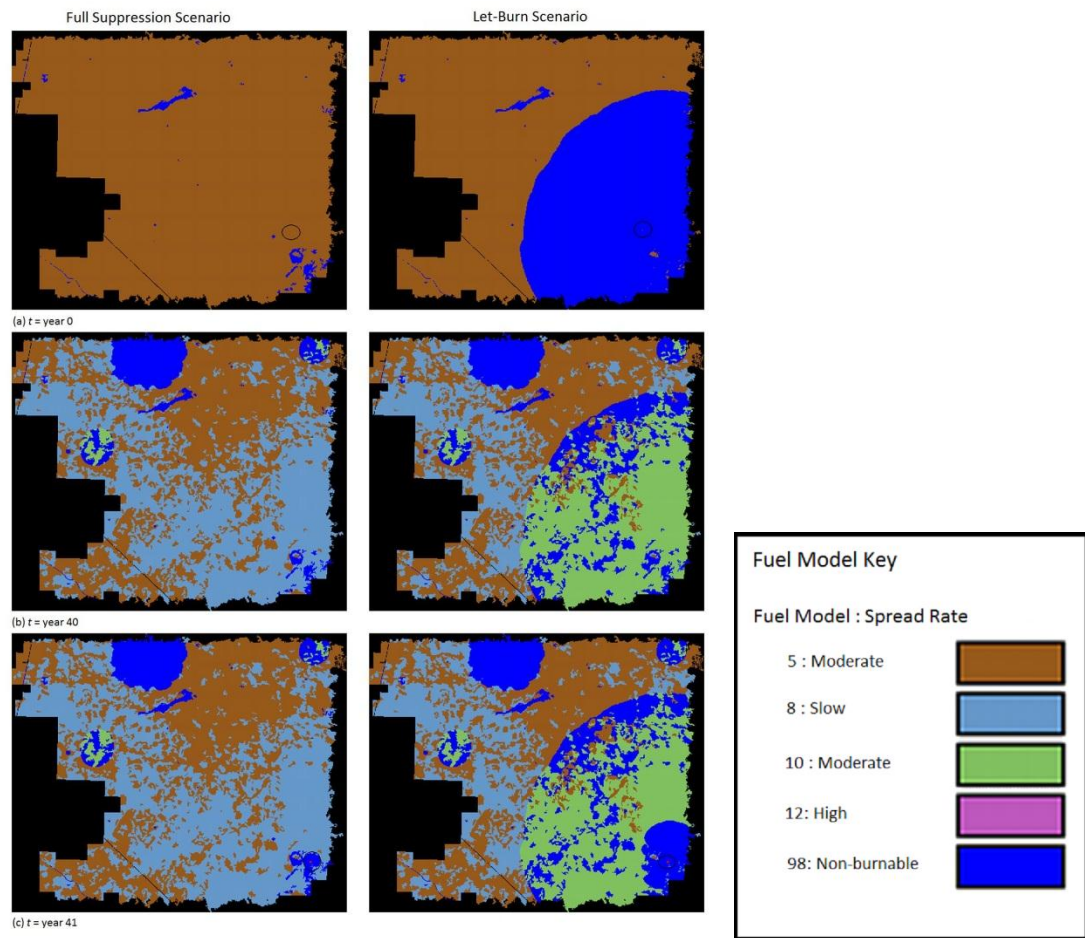
Figure 15: A progression of maps showing fuel model changes for an example negative sample pathway.

Fire Size and Expected Benefits

As the area burned by the current fire increases, the estimated suppression cost savings increases, as can be seen by the histogram in Figure 16. The high positive sample points cluster at the high end of the current fire size, while the positive and negative sample points trend lower. The average size of the current fire for the positive sample was 32,801 ha. The average size of the current fire for the high

positive sample was 53,229 ha. The average size of the current fire for the negative

sample was 18,617 ha.
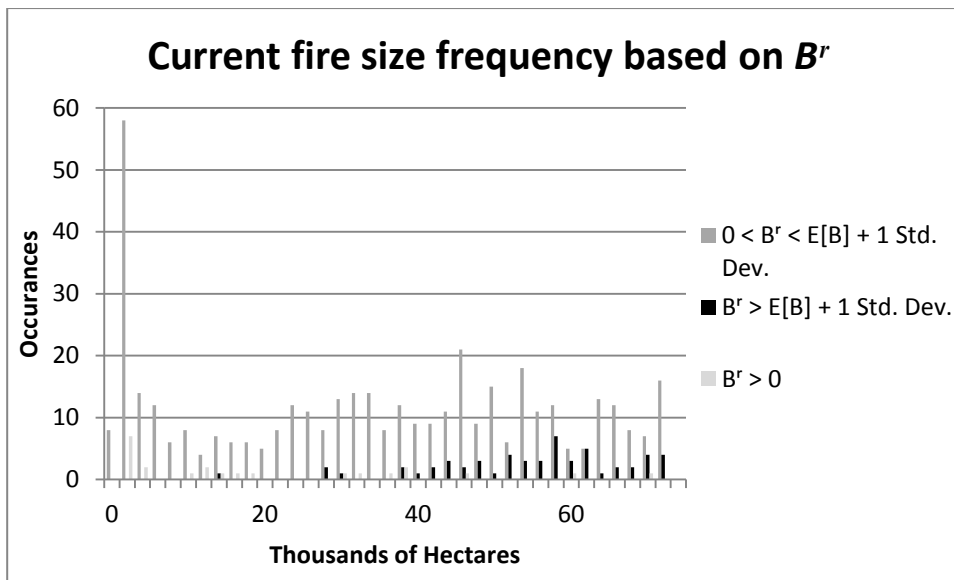
Figure 16: Fire size frequency dependent on E[B].

Area Burned

The average area burned in the future for suppress scenarios (22,235 ha/100

years) was greater than the average area burned the future in let-burn scenarios

(13,640 ha/100 years), as demonstrated in the graph in Figure 17. The average area

burned by year indicates that the largest area burned in the first 25 years of each

pathway. However, in Figure 18, which displays the difference in average area

burned between the two scenarios, the average area burned in the suppress

pathway was greater than in the let-burn pathway during this period.

The current fire in each let-burn scenario removes fuels from the current landscape that are not removed in the suppress scenarios. As a result, the suppress scenarios had higher average fuel loads during the first 25 years, which resulted in larger fires, that incurred higher suppression costs throughout that period. This is because the fuels that were treated in the let-burn scenario by the current fire were typically burned in the suppress scenario by the ignitions that escaped initial attack over the first 25 years. This explains the greater area burned in the first 25 years. The majority of the suppression cost savings also occurred in that period, as shown in Figure 19.
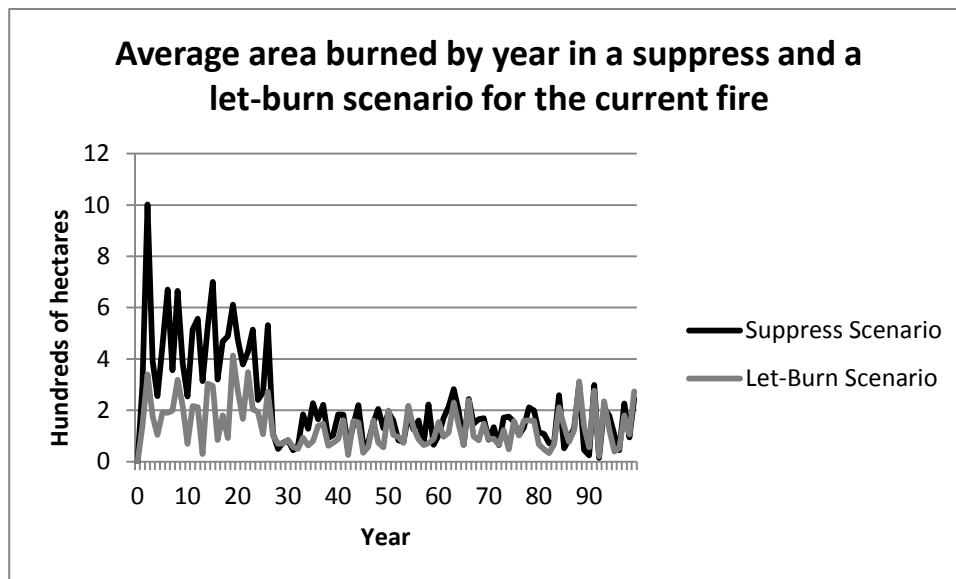
Figure 17: The average future area burned by year, given that the current fire is suppressed or let-burn.
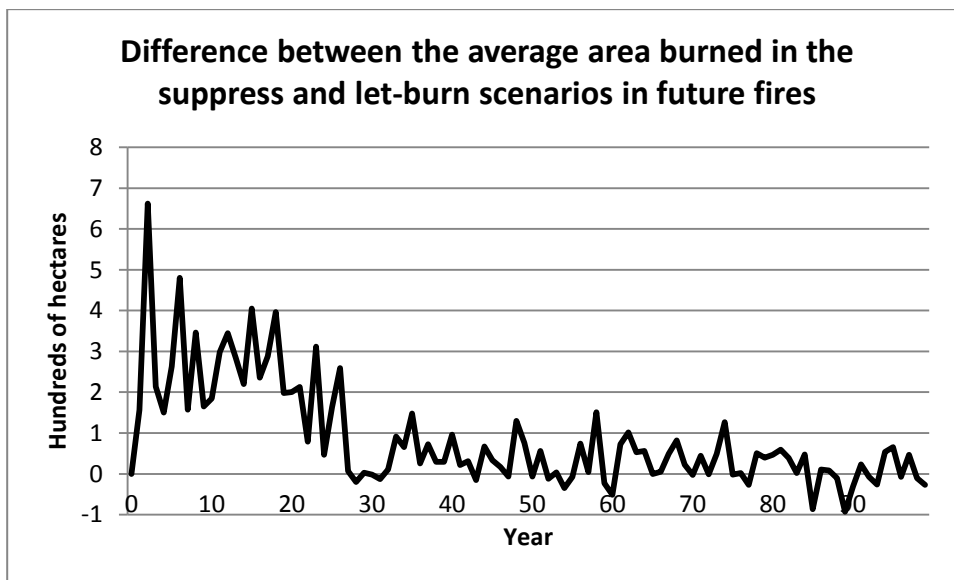
Figure 18: The difference between the average area burned in the suppress and let-burn scenarios for future fires indicates that the majority of the fuel treatment benefits occur in the first 25 years.

Figure 19: The difference in the average cost of suppression by year, between the suppress and the let-burn scenarios. These costs are in 2004 dollars and are not discounted.

Fire Type

Surface fire and crown fire have very different impact on forest ecosystems. Crown fire is often stand-replacing, resulting in a greater loss of timber value, recreational opportunities, and habitat, while surface fire 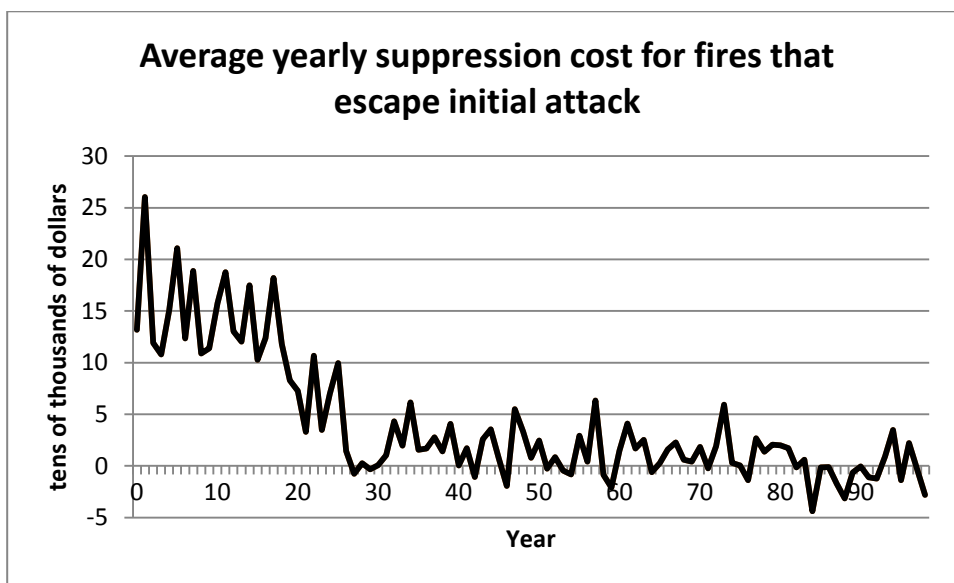typically results in reduced fuel loads and stands with lower densities of trees, and hence, can be beneficial. In Figure 17, the total area burned in future wildfires was greater in the suppress scenarios than in the let-burn scenarios. Crown and surface fire were separated out in Figure 20 and Figure 21, and again, the amount of area burned in surface fire and crown fire was greater in the suppress scenarios than in the let-burn scenarios. The average percent burned in crown fire was quite small, and approximately the same in both scenarios (7% in the suppress scenario; 8% in the let-burn scenario). As a result, there is a greater total area burned by crown fire in the suppress scenario than in the let-burn scenario. The percent by year can be seen in Figure 22.
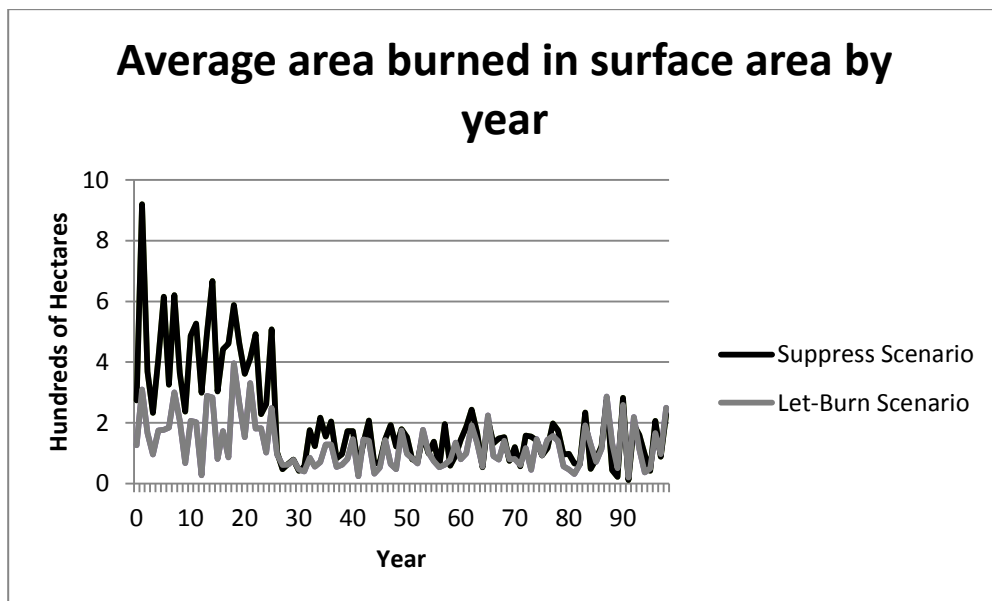
Figure 20: Average area burned in surface fire by year.
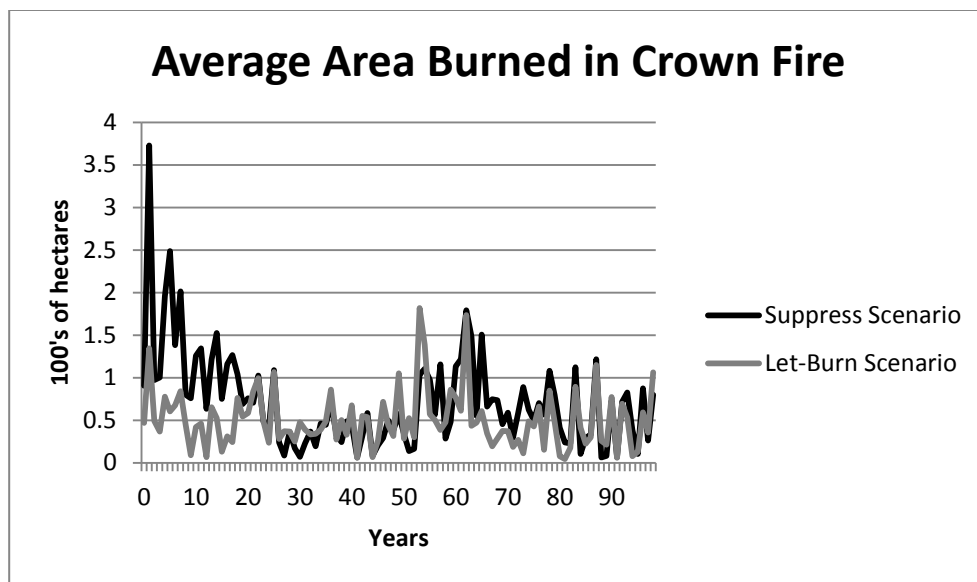
Figure 21: Average area burned in crown fire by year.
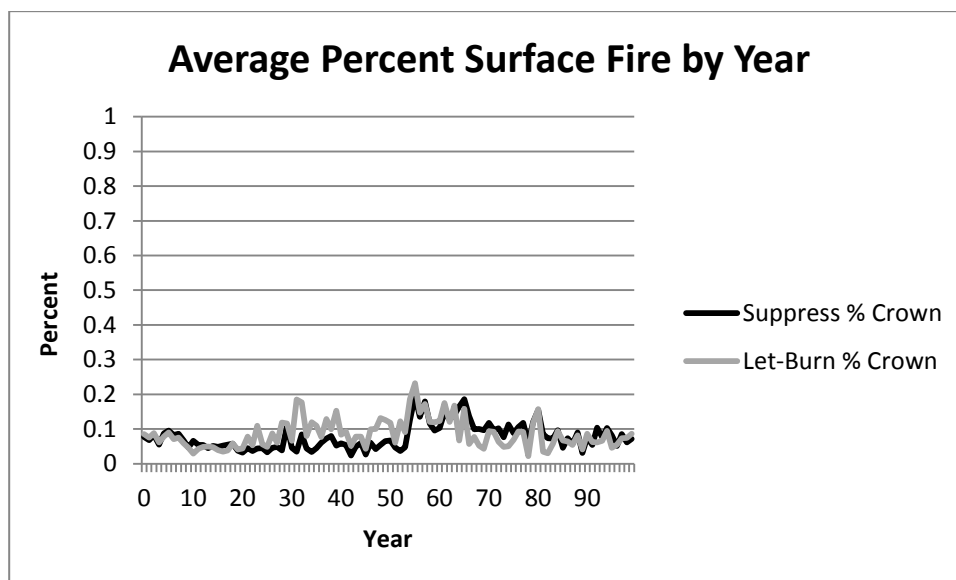
Figure 22: Average percent crown fire by year.

There is a spike in the amount of crown fire that occurs in both the full suppression and let-burn scenarios between 50 and 70 years. Lodgepole pine forests typically do not burn for 50-80 years after a crown, or stand-replacing, fire, and when they do burn, these forests tend to burn in stand-replacing fires (John Bailey, Personal Communication, October 15, 2010). The look-up table represents that behavior by setting lodgepole pine stands to a non-burnable fuel model for 50 years after a crown fire. As a result, the lodgepole pine forests that burn in the current fire, or early in the time-horizon, transition to a state where they can again burn around year 50. The spikes account for those forests moving into a burnable state, and then burning in a manner characteristic to dense, 50-70 year old lodgepole pine forests.

Losses

An estimate of losses is necessary to explore which ignitions would result in a net positive value change on the landscape. The rough estimate presented here only accounts for timber value lost, but is a first step towards addressing the issue. Timber losses due to wildfire take into account the fact that, as the expected benefit from avoided future suppression expenditures increases, the damages resulting from wildfire also increase. For the value change estimate, I included losses and avoided suppression costs for the current fire, due to the size of losses incurred by the let-burn decision.

The timber value loss for each of r iterations was calculated using Equation 13. The area burned in each time period was determined, for each iteration, from FARSITE outputs, and was divided based on species and fire type. The total expected loss is defined in Equation 14.

Equation 14

$$E[L] = \frac{\sum_{r=0}^{N} L^r}{N}$$

The average timber loss due to fire, based on a let-burn decision, was $20,940,740, with a standard deviation of ±$17,777,988. The majority of these losses were incurred during the current fire. The average timber loss due to *future* fires was -$3,173,771, with a standard deviation of $7,300,608. In other words, the was less

damage incurred by future fires in the let-burn scenarios than in the suppress scenarios.

Once losses were estimated, it was possible to calculate the value change on the landscape for each pathway. In this calculation, non-timber losses and the ending state of the landscape represented in Equation 3 are omitted.

Using the rough estimate of costs, average losses due to all fires were $E[L] = \$20$ million, over ten times the average benefits $E[B] = \$2.3$ million. The estimated value for the value change of the landscape was negative \$18,644,828, which indicates that, based only on the costs and losses that are taken into account here, the average ignition should be suppressed. The standard deviation was \$17,776,270. Values ranged from negative \$79,869,325 to positive \$31,154,532.

Pathways with a positive value change indicate the point in which the optimal action for the current fire would be to let-burn. Of the 500 pathways, a total of 73, or 14.6%, had a positive value change. The common characteristic in these pathways was that the current fire was smaller on average (15,000 ha), than the current fires for pathways exhibiting a negative value change (37,000 ha). In addition, a relatively high percent of the area was burned in surface fires in ponderosa pine stands, which incurred no losses. In the positive value change pathways, ponderosa pine surface

fire composed 50% of burned area, while in the negative and zero value change pathways, that figure was only 44%.

Discussion

The OCWS model was created by integrating a fire spread model, a vegetation growth model, and economics models to estimate value change on the landscape over a long time-horizon. The model is spatially explicit, requiring the same initial landscape inputs, but is temporally dynamic. The temporal component is the result of tracking the vegetation and fuels on a landscape, and the realization of ignition dates and locations from probability distributions. The ignitions can occur under a range of different weather conditions, depending on the date that is realized.

The results from this model indicate that the greatest benefits occur when the current fire is large, and subsequent fires occur early in the pathway, which reflects both the uncertainty of the location of future ignitions and the short-term future benefits of fuel treatments. Clearly, larger wildfires will result in more fuel being treated by fire. However, when losses are included, those pathways with the greatest net benefits are those in which the current fire is smaller, and occurs in ponderosa pine stands as a surface fire. In terms of foregone suppression costs, the greatest benefit from the current fire occurred in the first 25 years of the time-horizon.

Assumptions regarding value loss on the landscape will be key in decision-making surrounding the decision to let a fire burn. The assumptions I made favored fires which burned in surface, rather than crown fires, and in cover types which were assumed to have no loss of value, such as ponderosa pine in surface fire. By changing the assumptions, based on real management goals for the landscape, the value change on the landscape will be different. Including other future benefits from fire in the benefits analysis may offset some of the losses as well. Some of these future benefits include the creation of desired habitat structures, recreation areas, and ecosystem services.

My thesis lays the groundwork for future work examining characteristics of an ignition, current or future, which would impact the benefits in terms of foregone suppression costs. However, the OCWS requires some modifications to explore this question further.

Improving the Model

The OCWS is a model in which wildfires can be spread on the landscape and the vegetation can be updated. These are complex processes, and there are areas of the model that would benefit from further research and more accurate data. I discuss three areas of model development that would benefit from improvements: look-up table creation, ignition location, and the impact of spatial characteristics on

vegetation change. Then I examine potential improvements regarding the inputs and assumptions surrounding suppression cost estimates, wildfire duration, and weather.

The Look-up Table

The current method used to update landscape vegetation requires that the initial vegetation states be highly simplified. By oversimplifying the states, complex spatial configuration of vegetation, and the impact that configuration has on wildfire behavior, is also lost. In addition, variables that could be used to track back to tree lists for examining future losses should be added (discussed in the Improvements to Value Loss Estimates section below). In order to create a more complex, realistic landscape, and to increase the number of state variables, the creation of the look-up table must be automated.

FVS tracks the build-up of fuels over time, so it is possible that the fuel loads estimated for the current landscape are low. The simulation of current wildfires would be improved by obtaining original fuel load estimates from the landscape, rather than using the FVS to estimate fuel loads based on tree lists.

Ignitions

Historical ignition frequency was determined using a Forest Service dataset that contained ignitions for which suppression was attempted. This indicates that all these ignitions occurred in fuel conditions that were conducive to spread. The

historical ignitions should be somewhat comparable with those in the suppress scenario. However, because the computer-generated ignitions were created prior to the simulations, in some instances, these ignitions landed in non-burnable fuel models, which wouldn't be included in the historical data set. As a result, there were some ignitions that did not spread into fires, but should have.

In order to rectify this problem, generating ignitions within the program would allow the user to ensure that each ignition that occurred was located in a burnable fuel model in the suppress scenario.

Vegetation

In this analysis, I assumed that the current vegetation in a given location determined the future vegetation for that location. However, there are spatial interactions that influence vegetation change over time. In the absence of fire, for example, lodgepole pine can encroach on sites currently dominated by ponderosa pine. By reintroducing low-intensity surface fires, sites currently dominated by lodgepole pine could return to a condition favoring the success of ponderosa pine.

Future vegetation change on the landscape under different management options can be considered by including this type of spatial interaction.

Suppression Costs

The change in suppression costs measured here is a crude first estimate of the fuel treatment benefit of letting a current ignition spread. It provides an analysis of potential future benefits from allowing a current ignition to spread, which are often overlooked by fire managers who are focused on potential current losses. However, it is currently set up to work on a single landscape that is highly simplified; assumes management goals that are not actually in practice; and assumes no future management impact on fuels.

Suppression cost estimates and wildfire duration estimates were both based on research that is still in progress. Historical suppression cost information has been tracked in the National Interagency Fire Management Integrated Database, but these reports do not line up with the actual dollars spent by the Forest Service (Gebert, Calkin, and Yoder 2007). In 2004, the Forest Service implemented a requirement that the tracking code for each wildfire be included on the incident report, which reports the characteristics of the fire. When those data become available it is likely that a better estimate of suppression costs will follow (Gebert, Calkin, and Yoder 2007).

Fire Duration

Determining wildfire duration, especially when suppression is not a factor, is challenging. Here, this was based primarily on ERC and spread component percentiles. Future work to include extinction probability as a function of weather

and fuel moistures at each point on the landscape, within the FARSITE model, would

be superior.

Fire Weather

More exploration of weather variables that lead up to the ignitions, and

spatial information about ignition locations and the surrounding area may provide

insights into which ignitions warrant suppression attempts, and which should be

allowed to spread.

Finally, creating weather files by integrating historical data with information

from different climate change models would allow managers to consider a range of

potential values resulting from an uncertain future climate.

Improvements to Value Loss Estimates

The easiest market value to track is timber value. The estimated timber losses

resulting from wildfire are very rough, and are based on the assumption that the

study area is currently being managed for timber. In order to more accurately assess

losses, the existing management goals must be clearly defined, and non-market goals

must be assigned value based on those goals.

Timber loss estimates would benefit from including simulated harvest

activities on the future landscape in order to capture future expected losses due to

wildfire. This requires an expansion of the look-up table, based on an increased

number of states, and must include harvest transitions. Variables such as basal area/ha and trees/ha should be added to the state variables in order to track the expected volume present in each state. In addition, minimal harvest activities are currently being carried out in this area, so alternative non-market values should also be considered.

Non-market values, such as recreational use, wildlife habitat, and carbon storage could be considered, to the extent to which they are included in the management objectives for the area. For example, there are locations within the study area that are used for horse camping. These areas are generally small patches from which the underbrush and lodgepole pine regeneration have been removed, suggesting a preference for more open camping areas. The landscape can be scored based on recreational habitat preferences, and risk of death or injury for individuals utilizing the area. A total use value could then be calculated for each year over the pathway, and compared between different management regimes.

Conclusion

As a society, we have put ourselves in a situation where the status quo for wildfire policy is no longer a realistic possibility, both in terms of financial output and the physical ability to suppress wildfires that are occurring with increasing fuel loads and likely climatic patterns. The shift of population into the wildland-urban interface,

combined with the build-up of fuels resulting from a century of suppression of all wildfires which we had the power to suppress, have led to higher expenditures for wildfire suppression. In addition, despite increased suppression expenditures, wildfires which escape initial attack are getting larger, more intense, and increasingly severe as a result.

Land managers have the potential to decrease current and future suppression costs by allowing some ignitions to spread in order to provide fuel treatment benefits. However, due to the uncertainty of future events, it is difficult to ascertain today which ignitions will result in a positive net change versus a negative net change in suppression costs.

Federal policy now dictates the implementation of wildland fire use as a natural ecosystem process as a management objective, as long as it can be done while maintaining a high level of firefighter and public safety (NWCG 2001). Every forest must have a Fire Management Plan (FMP) that dictates how ignitions will be treated (NWCG 2001). However, there are barriers to wildland fire use, which include everything from too few natural ignitions to make it feasible to put the time into including wildland fire use in the FMP, to concerns from fire managers regarding personal liability, should the wildfire destroy property, or result in loss of life (Doane et al. 2006).

My analysis sets the stage for developing a tool and methodology for exploring how to optimally treat ignitions on a landscape, given weather, wind, fuels, ignition location, and ignition timing, and current and future costs and losses. In addition, a long-term goal is to modify the OCWS explore the optimal placement of fuel treatments on that landscape, with regards to cost, safety, and ecosystem restoration goals.

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