Fuel Treatment Timing and Suppression for Wildfire Risk Mitigation[1]

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Abstract

Wildfire risk mitigation through *ex ante* vegetation management is receiving more attention in the United States after a strong emphasis on suppression for a hundred years. This paper presents a dynamic economic model with three sets of input choice variables: the timing of pre-harvest vegetation management interventions, harvest date, and expected suppression effort in a context where pre-harvest vegetation management reduces the risk of wildfire. The model is applied to three important policy issues: 1) a general characterization of the relationship between *ex ante* risk mitigation via vegetation management and wildfire suppression that can be applied to a broad range of specific settings; 2) the consequences of high potential damage from fire as on the wildland-urban fringe for vegetation management regimes, 3) the structure of liability for both prescribed fire and excess fuel loads on vegetation management decisions. Numerical simulation results are presented and discussed as illustrations of the implications from the model.

Introduction

Many approaches exist for reducing the risk of economic losses associated with wildfires. Various forms of mechanical thinning and chemical treatments can reduce wildfire risk, as can the application of fire-proofing methods to human-made structures. Fire itself in the form of a planned controlled burn can be useful for reducing wildfire risk (Prestemon, and others 2001; Pattison 1998; Babbitt 1995).

This paper explores the economic tradeoffs between *ex ante* fuel management and *ex post* suppression. Because fuels grow and mature over time and wildfire risk changes with it, we focus on the timing of fuel management interventions, where these interventions can take the form of prescribed fire or mechanical thinning. The analysis is composed of two parts. First, a dynamic economic model of the timing of wildfire risk mitigation interventions, harvest timing, and suppression. Second, we examine three specific policy and management issues: a) a general characterization of the relationship between *ex ante* risk mitigation via vegetation management and wildfire suppression that can be applied to a broad range of specific settings; b) the consequences for vegetation management regimes of high potential damage from fire as on the wildland-urban fringe, c) the effect of liability for excess fuel loads and for suppression costs on vegetation management decisions. Numerical simulation results are presented as illustrations of the analytical model.

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A model of timing for fuel management and harvest

The net benefit from forest stand management is modeled as a modified Faustmann rotation in which the landowner maximizes the expected net present value of the rotation by choosing the expected dates of vegetation management interventions, harvest, and suppression given a wildfire. At any point in time in the maturation of the forest stand, a wildfire might occur that can impose damage on both the forest stand and other non-timber property. The time-path of wildfire risk is affected by fuel management interventions (*interventions* for short), and the extent of damage given that a wildfire occurs before harvest can be reduced by suppression effort. Other models of timber rotations under wildfire risk and vegetation management have been developed by Reed (1984, 1987), Yoder (in press), and others. This model is different in that it amounts to a nested rotation that considers both timing intervention dates and harvest dates.

Optimization in this context, amounts to jointly maximizing over *n*-1 pre-harvest interventions and one harvest date (the n^{th} intervention), and suppression effort in the event of a fire. A central component of the problem is that interventions affect the probability of wildfire. Given the optimal timing vector $\mathbf{T}_n = [T_{n,1}, T_{n,2}, \ldots, T_{n,n}]'$, the probability of wildfire occurring at any time t_0 within the rotation is

$$F(t_0, \mathbf{T}_n) = \int_0^{T_1} f(t)dt + \int_{T_1}^{T_2} f(t - T_1)dt + \ldots + \int_{T_{i-1}}^{t_0} f(t - T_{i-1})dt$$

where $f(t)$ is the probability of a fire occurring at time t. Note also that every intervention results in resetting the probability of destructive wildfire back to the initial state. In the calculations below, we shall need a discounted version of $F(t_0, \mathbf{T}_n)$, evaluated at intervention times:

$$G(T_{n,i}, \mathbf{T}_n) = \int_0^{T_1} e^{-rt} f(t)dt + \int_{T_1}^{T_2} e^{-rt} f(t - T_1)dt + \ldots + \int_{T_{i-1}}^{T_i} e^{-rt} f(t - T_{i-1})dt \, .$$

The manager maximizes the expected net present value of the benefits given the uncertainty of wildfire occurrence. The components of benefits and costs of timber production and wildfire risk mitigation can be broken down as follows:

1. If no wildfire occurs before harvest, the owner receives the stumpage value, the present value of which is $e^{-rT} V(T_{n,n})$. For simplicity we assume that timber growth is not a function of interventions, just time from planting.
2. If a wildfire occurs, the owner receives $(1 - g(s))V(T_{n,n})$ in period $T_{n,n}$, where $g(s)$ is the fraction of timber value lost to wildfire. Suppression effort s reduces the fraction lost, but at a diminishing rate, such that $g'(s)<0$ and $g''(s)>0$. No financial loss in terms of timber value is realized at the time of the wildfire because the timber is not sold then. We assume that timber is harvested at the same time regardless of whether a wildfire occurs or not.
3. If a wildfire occurs at some time X, total suppression costs $\tau \cdot s$ are expended, the present value of which is $e^{-rX} \tau s$. However, because X is

random, the owner will maximize over the discounted expected value of this random variable, which is $s \cdot \tau \cdot G(T_{n,n}, \mathbf{T}_n)$.

4. Some fraction of non-timber property of value may be damaged. To allow this, we introduce a constant *D* that represents potential damage to non-timber property. This damage accrues when and if there is a wildfire, and the extent of loss can be mitigated by suppression. Thus the expected present value of damage to non-timber assets is $g(s) \cdot D \cdot G(T_{n,n}, \mathbf{T}_n)$.
5. Given marginal intervention costs *w*, the present value of intervention costs at intervention *i* of *n* are $we^{-rT_{n,i}}$ if there is no wildfire before $T_{n,i}$. However, a wildfire might occur before any given intervention. Therefore, the expected present cost of any given intervention $T_{n,i}$ is $w \cdot e^{-rT_{ni}} \cdot \left(1 - F(T_{n,i}, \mathbf{T}_n)\right)$.

Putting each of these components together and discounting appropriately for an infinite series of harvest rotations, the present value of the expected net benefit function to be maximized is

$$E\left[PV\left(NB\right)\right]_n = \frac{1}{1-e^{-rT_{n,n}}}\begin{pmatrix} E\left[\text{PV(timber value)}\right] \\ -E\left[\text{PV}\left(\text{suppression costs +damage}\right)\right] \\ -E\left[\text{PV}\left(\text{intervention costs}\right)\right] \end{pmatrix}$$

$$= \frac{1}{1-e^{-rT_{n,n}}}\begin{pmatrix} \left[e^{-rT_{n,n}}(1-F(\mathbf{T}_n, T_{n,n})g(s))V(T_{n,n})\right] \\ -\left[G(\mathbf{T}_n, T_{n,n})\left(\tau s + g(s)D\right)\right] \\ -I_{n>1}\left[w\sum_{i=1}^{n-1} e^{-rT_{n,i}}\left(1-F(\mathbf{T}_n, T_{n,i})\right)\right] \end{pmatrix}$$

Where, to summarize the notation:

- $E\left[PV\left(NB\right)\right]_n$ is the present value of the expected net benefit given *n* interventions;
- *r* is the discount rate;
- $\boldsymbol{T_n}$ is an $(n \times 1)$ vector of (*n*-1) intervention dates and a harvest date;
- $T_{n,i}$ is the time of the i^{th} intervention; harvest is the n^{th} intervention;
- $V(T_{n,n})$ is the timber's stumpage value at harvest time;
- $F(\boldsymbol{T_n}, T_{n,i})$ is the probability of wildfire occurring before time $T_{n,i}$ given the intervention vector $\boldsymbol{T}_{\text{n}}$;
- $G(\boldsymbol{T_n}, T_{n,i})$ is the discounted (present value) probability of wildfire occurring before time $T_{n,i}$ given the intervention vector $\boldsymbol{T}_{\text{n}}$;
- *s* is the fire suppression effort in the event of a wildfire;
- *g*(*s*) is the fraction of potential value lost in case of fire.

- D is the potential damage to non-timber property value;
- τ is the cost per unit of suppression effort;
- w is the cost for each prescribed fire**.** If no pre-harvest interventions are applied, the sum of total intervention costs equals zero;
- $I_{n>1}$ is an indicator variable that equals one if there are pre-harvest interventions (i.e. if n>1), and zero otherwise.

The number of choice variables, and therefore the number of first-order conditions for the problem, depends on the number of interventions before harvest. Therefore, assuming that a solution for a maximum exists, finding the vector of arguments that maximizes this function is approached in two steps. First, the vector of optimal intervention times $\boldsymbol{T_n}$ and suppression effort s is chosen conditional on a specific number of interventions. Conditional optimization is performed over feasible intervention sets $n=1...m$, to find the m conditionally optimal vectors $\boldsymbol{T_1 \ldots T_m}$ and each of their associated values of optimal s**.** The vectors $[\boldsymbol{T_i}, s]$ that maximize $E\left[PV\left(NB\right)\right]_n$ is then chosen.

Simulation specification

The above model must be specified completely for simulation. For a base case, we specify the model in an attempt to approximate ponderosa pine forest of the inland northwest region. For the fire return interval, we use a Weibull distribution with location, scale, and shape parameters of a=0, b=30, c=2, respectively. This results in a probability density function of $f(t) = 0.002e^{-0.001t^2}t$, and a cumulative density function of $F(t) = 1 - e^{-0.001t^2}$, for which the mean fire return interval is approximately 26.6 years (see Smith and Fischer 1997). We follow Yang, Kozak and Smith (1978) and use a Weibull distribution to represent the timber volume growth function, the parameters of which were estimated from data presented in Oliver and Powers (1978), and then rounded. The estimated Weibull density function was then weighted by 500,000 to represent the growth in timber value over time: $V(t) = 500000\left(1 - e^{-0.0005t^2}\right)$. The productivity of suppression is measured in terms of damage foregone. For simplicity in this illustration, we define this function in terms of the fraction of potential damage saved, and base this savings function as an exponential density function, $g(s_n) = e^{-0.1\,s_n}$, where suppression effort s_n is defined such that one unit of suppression costs $\tau = 5{,}000$. The unit cost of one fuel management intervention is set at 1,000, and the discount rate is set at 0.05. Finally, to allow for damage from wildfire in addition to timber value losses, we set D to equal either 200,000, or zero (in the case of no external damage or no liability for damage).

Results

Table 1 contains the results for four sets of management strategies: the use of both fuel management interventions and suppression, intervention only, and suppression only with no fuels management. Each of these management strategies is examined for two different scenarios: one with non-timber damage potential of zero, and one with non-timber damage potential of 200,000. Landowners are generally not legally liable for wildfire damage that was in part due to fuel buildup on their land, although the law in relation to these risks may be changing (see Bakken 1995).[4] Thus, even if external damage may occur, landowners have weak incentive to account for it fully in their decision process. The timber rotation lengths for the scenarios are rather short. However, the results suffice to illustrate the tradeoffs being made in terms of fuels management, timber harvest, and wildfire suppression.

Table 1— *Simulation results*

Management strategies	Liability structure	Timing for Prescribed fires	Optimal # of Fuels Treatment	Optimal rotation length	Units of Suppression	Net Benefit
Case 1: Intervention and Suppression	Not liable	$x_{6,1}$=4.8, $x_{6,2}$=9.1, $x_{6,3}$=13.1, $x_{6,4}$=16.7, $x_{6,5}$=20.0, $x_{6,6}$=22.8, s_6=1.9.	5	22.8	1.9	45419.3
	Liable ($200,000)	$x_{4,1}$=4.6, $x_{4,2}$=9.6, $x_{4,3}$=15.0, $x_{4,4}$=20.8, s_4=16.5.	3	20.8	16.5	37696.5
Case 2: Intervention only	Not liable	$x_{6,1}$1=4.9, $x_{6,2}$=9.2, $x_{6,3}$=13.1, $x_{6,4}$=16.6, $x_{6,5}$=19.8, $x_{6,6}$=22.5.	5	22.5	--	45351.7
	Liable ($200,000)	$x_{7,1}$=2.7, $x_{7,2}$=5.5, $x_{7,3}$=8.3, $x_{7,4}$=11.2, $x_{7,5}$=14.2, $x_{7,6}$=17.2, $x_{7,7}$=20.3.	6	20.3	--	33018.8
Case 4: Suppression only	Not liable	--	--	13.4	--	42003.2
	Liable ($200,000)	--	--	7.1	14.3	9221.6

Consider case 1, where both fuel interventions and suppression are applied, and there is no external damage to worry about (*D*=0 from the timber owner's perspective). Given the parameters of the model, the expected net present value of the objective function is maximized with the application of 5 fuel management interventions, a harvest date of 22.8 years, and suppression effort of 1.9 units. The intervention rotation lengths shorten as the timber rotation progresses starting with

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[4] A number of states, including the state of Washington, have statutory law imposing liability for activity fuels, but not for other types of undisturbed vegetation.

the first, at 4.8 years, and the last (ending at harvest) of 2.8. The reason for this is that the potential loss from wildfire grows as timber value grows, so it makes economic sense to reduce wildfire risk more frequently as timber value grows. Now consider what happens when potential damage increases by 200,000. Suppression effort increases from just fewer than two units to over 16 units, and the timber harvest date is earlier. Interestingly, the number of interventions drops from five to three, and the length of time between interventions increases. This is undoubtedly at least partly due to the very large increase in suppression expenditures.

When fuel management intervention is used exclusively and suppression is not (case 2), the number of interventions jumps back up to five and six, with and without external damage, respectively. With no damage, the optimal rotation length is slightly shorter than when suppression is used. Furthermore, though the differences are subtle, the interventions are postponed slightly and bunched up nearer the end of the timber rotation in comparison to the results for case 1. Thus, intuitively, fuel interventions are used to substitute for suppression more frequently when timber values are highest. When external damage is involved, the timber rotation drops by more than two years, and the number of interventions increases by one, to six.

In case 3, no fuels management regime is implemented, and suppression and timber harvest timing alone are relied upon as choice variables. In this case, the timber harvest dates are strikingly lower, at 13 and 7 years, respectively.[5] Interestingly, with no fuels management and no potential non-timber damage, the result is that wildfire risk is dealt with entirely by shortening the timber rotation length, rather than relying on suppression. When non-timber damage is set to 200,000, however, suppression jumps to over 14 units.

Implications for Wildfire risk Management in a Forest Setting

The above simulation results shed some light on the tradeoffs between *ex ante* fuels management and the incentive effects of both high potential damage and incomplete liability for fuels management incentives. The tradeoffs between fuels management for wildfire risk mitigation and suppression can be seen in the different scenarios presented above, which illustrate that fuels management, and even timber harvest, can be used as a means to reduce suppression. If potential damage from wildfires is large, such as on the wildland-urban interface, it makes sense to alter fuel management interventions and harvest accordingly by either increasing the number of interventions and/or increasing the timber harvest frequency, even when suppression is used in the event of a wildfire. Finally, even though the owners of land with flammable vegetation may contribute to the incidence and severity of wildfires, they tend not to face liability for those contributions. For this and other reasons, incentive for fuels management on private land is relatively weak. If suppression costs are also borne by public agencies, these incentives to reduce wildfire risks associated with their land are even weaker.

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[5] Again, these timber harvest ages are exceedingly low, but the case illustrates the main implications of the model.

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