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FIREFIGHTS AND FUEL MANAGEMENT: A NESTED ROTATION MODEL FOR WILDFIRE RISK MITIGATION

by

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ABSTRACT

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Scientists and policymakers are increasingly aware that wildfire management efforts should be broadened beyond the century-long emphasis on suppression to include more effective efforts at fuel management. Because wildfire risks change over time as vegetation matures, fuel management can be viewed as a timing problem, much like timber harvest itself. We develop a nested rotation model to examine the fuel treatment timing issue in the context of a forest environment with both timber value and non-timber valuesat-risk. Simulations are performed for a ponderosa pine forest and discussed with a focus on three important aspects of wildfire management: 1) the economic tradeoffs between fuel treatments, suppression, and timber harvest 2) the effects of public wildfire suppression on private fuel management incentives, 3) externality problems when non-timber values-at-risk such as wildland-urban interface property is not accounted for in private fuel management decisions.

Keywords: wildfire, fuels management, fire suppression, optimal rotation, wildfire economics.

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Abstract: Scientists and policymakers are increasingly aware that wildfire management efforts should be broadened beyond the century-long emphasis on suppression to include more effective efforts at fuel management. Because wildfire risks change over time as vegetation matures, fuel management can be viewed as a timing problem, much like timber harvest itself. We develop a nested rotation model to examine the fuel treatment timing issue in the context of a forest environment with both timber value and non-timber values-at-risk. Simulations are performed for a ponderosa pine forest and discussed with a focus on three important aspects of wildfire management: 1) the economic tradeoffs between fuel treatments, suppression, and timber harvest 2) the effects of public wildfire suppression on private fuel management incentives, 3) externality problems when non-timber values-at-risk such as wildland-urban interface property is not accounted for in private fuel management decisions.

1 Introduction

A century-long policy of intensive wildfire suppression has contributed to substantial accumulation of vegetative fuel loads and wildfires of increasing severity in many forest environments (Ingalsbee 2000, Prestemon et al. 2001). Over the last three decades, forest managers and fire researchers have increasingly called for greater emphasis on management of vegetative fuels for wildfire risk mitigation (Stephens 1998, Pollet and Omi 2002, Hof and Omi 2003, Rideout 2003, Martinson and Omi 2003). In response, the Healthy Forests Restoration Act of 2003 (HFRA) includes substantial emphasis on fuels management to address forest health and wildfire concerns. In principle, the Act calls for increases in the use of prescribed fire and mechanical thinning to reduce fuel loads, and it dictates that these efforts should concentrate primarily on the wildland urban interface. The precursor to the HFRA, George W. Bush's Healthy Forest Initiative, sparked off heated debate because environmental groups argued that it was an attempt to justify and facilitate commercial logging on federal land.

One of the major hurdles for addressing the controversy over the Healthy Forest Initiative is a poor scientific understanding of the effectiveness of fuel management for wildfire risk mitigation and of the economic and physical relationships between fuel management and suppression as wildfire risk mitigation alternatives. The theoretical economic foundations of wildfire suppression were initially developed early in the twentieth century as a simple cost minimization problem (Sparhawk 1925), and this cost-minimization perspective has been incorporated conceptually into the decision-making process of wildfire suppression efforts. However, the empirical understanding of the productivity of suppression for reducing damage is weak to nonexistent. The scientific understanding of fuel management for wildfire risk mitigation is also still at an early stage of development, especially research regarding political economy, property rights, and incentives for fuel management (Hesseln 2000). The relative effectiveness of commercial logging as a means of mitigating wildfire risk is unclear, especially in comparison to prescribed fire and pre-commercial thinning as alternatives (Carey and Schumann 2003, Sparhawk 1925, Stone et al. 2004). Finally, the economic relationship of fuel management and suppression as complements is only just now beginning to receive significant attention in the economics literature (Botti et al. 2004, Omi 2004, Prestemon et al. 2004).

We contribute to this nascent literature on the economic relationship between suppression and fuel management by developing a dynamic model and simulations to characterize and illustrate the fundamental tradeoffs involved in wildfire risk mitigation. We model fuel management as a timing problem in which fuel treatment rotations are nested within a timber harvest rotation. Wildfire occurrence is a stochastic variable whose probability distribution is altered by fuel treatment and truncated by harvest. The costs of wildfire include timber and non-timber property damage, as well as wildfire suppression costs. Choice variables in the model include the number and timing of fuel treatments, the timber harvest date, and wildfire suppression effort. We parameterize the general model and perform simulations for a representative ponderosa pine forest, a prevalent forest type in the Western United States in low elevation areas that are often populated by humans. The model allows a formal representation of the economic tradeoffs between wildfire damage and suppression, fuel treatment, and harvest, as well as analytical and numerical comparative statics analysis for changes in various model parameters, such as exogenous increases in values at risk, suppression costs, and fuel treatment costs.

We apply the model to examine some important institutional issues for private and public landowners and managers in wildfire prone environments. First, individual private landowners face relatively weak incentives for fuel management and suppression because they do not accrue all the benefits of these efforts; some accrue to neighbors in the region because wildfire moves through a landscape regardless of property boundaries. This externality problem is particularly acute in highly fragmented and high value areas such as at the wildland urban interface. Second, because wildfire suppression is generally provided by public agencies, the full cost of wildfire are not accrued by landowners and are not economically tied to fuel management activities. Public land managers also arguably face incentives that induce too much investment in suppression and too little in fuel management (Ingalsbee 2000, O'Toole 2002).

Numerous studies have focused on the economics of timber harvest under the risk of total destruction of forest value based on Faustmann-type analyses (Martell 1980, Routledge 1980, Reed 1984, Reed and Errico 1985 1986, Reed 1987, Thorsen and Helles 1998). Of these, our approach is perhaps most closely related to Reed (1987), which uses an optimal control framework to examine optimal timber rotation and continuous wildfire protection for a forest stand subject to sudden destruction by fire. Along different lines, Yoder (2004) examines the optimal rotation of prescribed fire treatments for reducing wildfire risk and providing forage or other benefits. Our approach is unique in three ways: First, we present a model general enough to make use of the two general forms of fuel treatment (thinning and prescribed fire). Second, although the treatment of fuel management as a rotation problem is similar in spirit to Yoder (2004), the analytical and numerical implementation of the nested rotation problem is substantially different and provides new insights into the relationships between treatments, harvest, and suppression. Third, we formally examine the impacts of externalities and public firefighting suppression on private fuel management incentives.

The next section describes the theoretical model and optimization routine. In section three the results of the simulations are presented and discussed, followed in section four concludes with some policy implications.

2 Wildfire Management as a Nested Rotation Problem

Consider a forest stand that is managed to maximize the expected net present value of an infinite series of harvests under the risk of wildfire. At any point in time during the maturation of the forest stand, a wildfire might occur that can impose damage on both the forest stand and other property such as homes. The time-path of wildfire risk (referred to as the *wildfire return* distribution in the fire sciences literature), is affected by fuel management interventions, and in the event of a pre-harvest wildfire, the extent of damage can be reduced by suppression effort. Thus, control variables include the number and timing of fuel management interventions, suppression effort in the event of a wildfire, and a timber harvest date.

Suppose that the timber rotation can be ended in one of two ways: by harvest, or by a wildfire, after which a salvage harvest is performed followed by replanting. Following Reed (1984), The duration of a rotation can then be thought of as a random variable whose distribution censored at the planned harvest date. This wildfire return distribution is affected by intra-harvest fuel management interventions. Let $\mathbf{T}_n = [T_1, T_2, ..., T_n]'$ be a $n \times 1$ vector of planned action dates. The last element, T_n, is the planned harvest date, and the previous elements T_i for $i < n$ are fuel management intervention dates. Every fuel management intervention T_i has the effect of setting the fuel load back to an initial state, thus shifting the fire return distribution out by the amount of time since the last fire or intervention. Figure 1 illustrates the probability density function and cumulative density function for wildfires with and without fuel management interventions Below we develop the wildfire return distribution conditional on fuel management interventions.

Let the "natural" wildfire return density function (as if it were uninterrupted by management interventions or harvest) be denoted $f(x)$, which satisfies the requirements of a probability density function for $x \in \Re^+$: $f(x) \geq 0 \; \forall \; x > 0$ and $\int_0^\infty f(x)\mathrm{d}x = 1$. The associated cumulative distribution function for wildfire occurrence in the absence of fuel management or harvest is $F(x)$, so that $F(T_i) = \text{Prob}[x < T_i]$. Let $S(T_i) = \text{Prob}[x \geq T_i] = [1 - F(T_i)]$ denote the survival function evaluated at intervention i, which equals the probability of applying intervention i of n prior to a wildfire event.[1] The probability of a wildfire occurring prior to each successive intervention is the recursive conditional set

$$
\begin{aligned}
F(\mathbf{T}_1) &= \int_0^{T_1} f(x)\mathrm{d}x = 1 - S(\mathbf{T}_1) \\
F(\mathbf{T}_2) &= S(\mathbf{T}_1) \int_{T_1}^{T_2} f(x - T_1)\mathrm{d}x = S(\mathbf{T}_1)F(T_2 - T_1) \\
F(\mathbf{T}_3) &= S(\mathbf{T}_2) \int_{T_2}^{T_3} f(x - T_2)\mathrm{d}x = S(\mathbf{T}_2)F(T_3 - T_2) \\
&\vdots \\
F(\mathbf{T}_n) &= S(\mathbf{T}_{n-1}) \int_{T_{n-1}}^{T_n} f(x - T_{n-1})\mathrm{d}x = S(\mathbf{T}_{n-1})F(T_n - T_{n-1}). \qquad (1)
\end{aligned}
$$

where the vector $\mathbf{T}_i = \begin{bmatrix} T_1 & T_2 \cdots & T_i \end{bmatrix}$ (in boldface) represents the dates of all interventions up to the i^{th} and T_i (no boldface) represent the date of i^{th} intervention. The wildfire return distribution is censored at T_n, and the probability of reaching harvest without a wildfire is

[1] The following framework follows the engineering literature on reliability and maintenance. See Kececioglu (1991) for an example of a more general treatment.

$S(\mathbf{T}_n) = 1 - F(\mathbf{T}_n)$.

The expected net present value of a timber rotation is made up of two primary components:

- The costs of fuel management interventions prior to harvest or wildfire.
- The net benefits accrued at the end of the rotation, which may be ended by wildfire or harvest.

The cost of a fuel treatment w is accrued at the time of each respective intervention, but a treatment will be performed only if a wildfire has not occurred prior to the planned treatment date, and only if one or more fuel treatments is optimal (that is, if $n > 1$ is chosen). Given that an intervention i is carried out, the discounted cost is $e^{-rT_i}w$, and the probability carrying out the intervention is $S(\mathbf{T}_i)$. The discounted expected value of intervention costs for one timber rotation can be written as

$$E[C] = I_{n>1}\left[w\sum_{i=1}^{n-1} e^{-rT_i}S(\mathbf{T}_i)\right] \tag{2}$$

where $I_{n>1}$ is an indicator variable that takes the value 1 if $n > 1$ and zero otherwise.

Now consider the benefits and costs that are accrued at the end of the rotation, which we will denote Y. Because the fire return distribution is censored at T_n, the expected net present value of Y can be written concisely as

$$E[Y] = E[Y|x < T_n] + E[Y|x = T_n]. \tag{3}$$

Let the function $V(t)$ denote the stumpage value of timber at any point in time since the end of the last rotation. For simplicity we assume that the stumpage value depends only on stand age (so that fuel treatments do not affect the growth or quality of standing timber), and we ignore replanting costs.[2] If the harvest date T_n is reached without a wildfire event

[2]Both of these simplifications are easily incorporated into the model, but clutter analytical results and are not of central interest in this paper.

$(x = T_n)$, the full value of timber $V(T_n)$ is recovered at harvest. Thus, the expected value from harvest at the planned date (the second element in equation 3) is

$$E[Y|x = T_n] = e^{-rT_n} V(T_n) \times \text{Prob}[x = T_n] = e^{-rT_n} V(T_n) S(\mathbf{T}_n). \tag{4}$$

If a wildfire occurs prior to the planned harvest date $(x < T_n)$, suppression effort s is exerted to reduce the fraction of value lost to the fire, and a salvage harvest for the remaining timber value is performed immediately.[3] Let suppression effort be denoted s with marginal cost τ. In the event of a wildfire, the fraction $g(s)V(x)$ is lost, so the remaining value is $(1 - g(s))V(x)$. The function $g(s)$ can be thought of as a suppression productivity function, with first and second derivatives $g'(s) < 0$ and $g''(s) > 0$.

Non-timber values can be very important in the context of wildfire management, especially in the Wildland Urban Interface. For expediency in simulating the consequences of externalities on risk mitigation decisions, we treat non-timber damage as distinct from timber losses. Let D represent non-timber values-at-risk from a wildfire, such that D is the total replacement value of non-timber property that would be lost given a wildfire *and* no suppression effort $(s = 0)$. We assume that suppression productivity is the same for both timber and non-timber values, so that total property losses for a given suppression level are $g(s)(V(t) + D)$. We also assume that the non-timber property is replaced immediately after the fire. Putting the above elements together, the net value accrued if and when a wildfire occurs before harvest is

$$h(x, s) = V(x) - g(s)\left(V(x) + D\right) - \tau s. \tag{5}$$

[3] There are other possible ways to model timber value loss and the timing of timber value accruals. If the fire damage is not uniform, such as if it completely destroys one part of the stand but leaves the remaining fraction unharmed, the manager may leave the remaining timber to grow until the planned timber harvest date $V(T_n)$. A complication with this scenario in the context of numerous timber rotations is that each time a fire occurs, the initial stand is effectively split by the fire into two stands of separate ages. Over the course of many rotations and many fires, the stand could be atomized into many small stands of various ages.

Given an interest rate of r, the expected net present value of the rotation at the end of each successive stage T_i is

$$
\begin{aligned}
E[Y|0 < x < T_1] &= \int_0^{T_1} e^{-rx}\ h_x(x,s)\ f(x)\mathrm{d}x \\
E[Y|T_1 < x < T_2] &= S(\mathbf{T}_1)\int_{T_1}^{T_2} e^{-r(x+T_1)}\ h_x(x,s)\ f(x-T_1)\mathrm{d}x \\
E[Y|T_2 < x < T_3] &= S(\mathbf{T}_2)\int_{T_2}^{T_3} e^{-r(x+T_2)}\ h_x(x,s)\ f(x-T_2)\mathrm{d}x \\
&\vdots \\
E[Y|T_{n-1} < x < T_n] &= S(\mathbf{T}_{n-1})\int_{T_{n-1}}^{T_n} e^{-r(x+T_{n-1})}\ h_x(x,s)\ f(x-T_{n-1})\mathrm{d}x. \qquad (6)
\end{aligned}
$$

and letting $T_0 = 0$,

$$E[Y|x < T_n] = \sum_{i=1}^{n} E[Y|T_{i-1} < x < T_i] \qquad (7)$$

where $h_x(x,s) = \partial h/\partial x = (1 - g(s))V_x$ represents the change in $h(x,s)$ over time, which amounts to the growth rate of the value of undamaged timber for a given s. Equation 7 is the first term in equation 3. The expected net present value of a single rotation equals equation 3 minus equation 2. Following Reed (1984), Englin et al. (2000) and others, the expected net present value of an infinite series of rotations is

$$E[\mathrm{NPV}] = \frac{E[Y] - E[C]}{1 - E[e^{-rT_n}]} \qquad (8)$$

where $E[e^{-rT_n}]$ is the expected discount factor such that

$$E[e^{-rT_n}] = \sum_{i=1}^{n}\left[S(\mathbf{T}_{i-1})\int_{T_{i-1}}^{T_i} e^{-r(x+T_{i-1})} f(x-T_{i-1})\mathrm{d}x\right] + e^{-rT_n}S(\mathbf{T}_n). \qquad (9)$$

where $S(\mathbf{T}_i)$ are defined in equation 1 and $S(\mathbf{T}_0) = 1$. The expectation on the discount factor for the series of infinite rotations is necessary because the rotation length itself is a random variable.

Given the necessary and sufficient curvature conditions in the economic region of the choice set, maximization of objective function (8) requires jointly maximizing over n choice variable, with $n-1$ pre-harvest fuel management interventions, harvest (the n^{th} action), and the expected suppression effort. Because the number of choice variables is endogenous, solving the optimization problem is performed with a two step process: 1) conditional optimization for a set of feasible n, and then 2) selecting the $n\times$ 1 vector that provides the highest expected net present value.

2.1 Selected analytical results

For illustration, consider the first-order conditions for the case of $n = 2$. The landowner chooses the intervention schedule $\mathbf{T}_2 = \begin{bmatrix} T_1 & T_2 \end{bmatrix}$, and the expected suppression effort s corresponding to $n = 2$. We begin by characterizing the analytical first-order conditions for the case in which the timber owner faces all costs and benefits. We then briefly discuss two extensions of the model: 1) the case in which some wildfire damage is external to the timber owner's decision process, and 2) the case in which suppression is provided by a public agency rather than the timber owner.

For clarity and intuition of the following analytical results, we temporarily assume a planning horizon of just one timber harvest rotation. The results are intuitively similar for an infinite series of timber harvests, but the analytical first-order conditions are complicated by elements that amount to Faustmann-like land rent components.[4] This assumption is dropped later (the simulations are based on an infinite set of timber harvest rotations).

In general, the first-order conditions for a choice variable $z \in \begin{bmatrix} T_1 & T_2 & s \end{bmatrix}$ is

$$\frac{\partial E[Y|0 \leq x < T_1]}{\partial z} + \frac{\partial E[Y|T_1 \leq x < T_2]}{\partial z} + \frac{\partial E[Y|x = T_2]}{\partial z} - \frac{\partial E[C]}{\partial z} = 0 \tag{10}$$

[4]The analytical results for an infinite series of timber rotations are available from the authors.

The first-order condition for suppression is

$$\int_0^{T_1} e^{-rt} f(t)\ h_s(t,s)\ \mathrm{d}t + S(T_1) \int_{T_1}^{T_2} e^{-r(t+T_1)} f(t-T_1)\ h_s(t,s)\ \mathrm{d}t = 0,$$

which is satisfied if

$$h_s(t,s) \equiv -g_s[V(t)+D] - \tau = 0. \tag{11}$$

This first-order condition implies that the marginal benefit of suppression in terms of damage foregone equals the marginal cost of suppression whenever a wildfire occurs.[5]

The first-order condition for fuel management is slightly more complex. Assuming (as we do in the simulations below) that a fuel management intervention restores the wildfire probability (at intervention time) to zero, the first order condition can be written as:

$$\int_{T_1}^{T_2} e^{-r(x+T_1)} h_x(x,s) \left[\left(S'(T_1) - rS(T_1)\right) f(t-T_1) - S(T_1) f'(t-T_1) \right] \mathrm{d}t$$
$$- e^{-rT_1} \left[h_{T_1}(T_1,s) + w \left(rS(T_1) - S'(T_1)\right) \right] = 0. \tag{12}$$

The first line of equation 12 corresponds to the marginal net gains from shortening the time between the fuel treatment and harvest. The second line corresponds to the marginal gains from extending the time until the first fuel intervention, which includes the present value of the change in the probability of expending w, and the marginal gains in $h(t,s)$ prior to T_1.

Finally, harvest is performed when the expected marginal increase in timber value from further growth equals the total expected marginal cost of waiting. Assuming again that the risk of damage from wildfire drops to zero at harvest, the first-order condition is:

$$\left\{ e^{-rT_1} S(T_1) f(T_2-T_1) h_{T_2}(T_2,s) \right\} + \left\{ S(T_1,T_2) \left[V'(T_2) + V(T_2)(S_{T_2}(T_1,T_2) - r) \right] \right\} = 0 \tag{13}$$

The first element in braces is the marginal net present expected benefit of delaying harvest

[5] This first-order condition is the same for an infinite series of rotations as well.

corresponding to the case in which an intervening wildfire occurs ($\partial \mathrm{E}[Y|T_1 < x < T_2]/\partial T_2$). The second element in braces is the marginal expected benefits corresponding to harvest prior to a wildfire event ($\partial \mathrm{E}[Y|x = T_2]/\partial T_2$).

2.2 Extensions: fuel-related externalities and public suppression

Two important aspects of the fuel management problem is that timber owners or managers often do not face the full costs of their contributions to wildfire risk to neighboring property, nor do they pay the full price of suppressing wildfires to which their vegetation has contributed, because fire suppression services are generally provided for and funded through public agencies.

Non-timber damage as an externality. To consider the effects of external wildfire damage, we choose a simple alternative for simulation comparisons that can be a reasonable representation of the wildland-urban interface. Suppose that the timber owner faces all of the timber losses associated with wildfire, but none of the non-timber values at risk, such that D might represent the value of homes in nearby wooded residential neighborhoods. Then the timber owner will make decisions about fuel management, harvest and perhaps suppression (if he or she were paying for it) as if D were equal to zero, even if it is not. Resource allocation decisions for this liability structure can then be compared to the case where the landowner is liable for all costs, including nonzero D.

Public rather than private suppression. The second case, where timber owners do not pay for suppression, can be examined by making two modifications to the forest owner's optimization problem. First, the suppression cost term $\tau\, s$ must be removed from $h(x, s)$ (equation 5), because the timber owner no longer pays these costs. Second, the landowner makes fuel management decisions based on the expectation that suppression will be publicly provided if a fire occurs. We account for this expectation by assuming that in the event of a fire, public suppression will be provided at an optimal level such that it satisfies first-order condition (11), conditional on the forest owner's pre-fire private fuel management decisions. This first order condition is therefore added as a constraint to the timber owner's optimization, which, again, is represented by equation (8) but with τs removed from the second line. Thus, public suppression levels are second-best in the sense that it is optimal given preexisting (suboptimal) fuel management outcomes by forest owners. It should be noted that it is highly unlikely that wildfire suppression activities satisfy first-order condition (11). They have almost unlimited but non-reallocable budgets for suppression, which would likely lead to over-suppression (O'Toole 2002). There are a number of other incentive issues lurking within this problem as well, but we use first-order condition (11) as the constraint as a simple illustrative assumption.

3 Simulations specification and results

For simulation, we parameterize our model to approximate ponderosa pine forest of the inland northwest region. We choose a ponderosa pine environment both because it is a common fire-prone environment with substantial human populations (Pollet and Omi 2002), and because there is relatively more known about ponderosa pine fire ecology compared to most other forest types. The specification is based on a per acre basis, but it is important to recognize that the structure and specification of any fuel management and wildfire system such as this is likely to be highly dependent on stand size.

To represent the growth in value of ponderosa pine timber, we use the modified Weibull function $V(t) = A(1 - e^{-\alpha\, t^{\beta}})$ described in Yang et al. (1978), where the coefficient A represents the stumpage value of the timber. Using a set of data collected by the Pacific Southwest Research Station and published in Oliver and Powers (1978), we estimated the growth function $V(t) = 128000(1 - e^{-0.0005t^2})$, given a site index 80 and a spacing of 10 feet. For the fire return interval representing wildfire probabilities, we use a Weibull distribution with location, scale, and shape parameters of a = 0.001, b = 30, c = 2, respectively, which is generally consistent with estimated historic fire return intervals for this forest type. (see Smith and Fischer (1997) for further discussion). These parameters result in a probability density function of $f(t) = 0.002te^{-0.001t^2}$and a cumulative distribution function of $F(t) = 1 - e^{-0.001t^2}$. The mean fire return interval for this distribution is approximately 26.6 years.

The productivity of suppression is defined in terms of the fraction of potential damage saved. Based on preliminary regressions using the National Interagency Fire Information Database NIFMID (2004) and simulation model calibration, we use a suppression production function $g(s) = e^{-0.5s}$, where suppression effort s is defined such that the fire suppression costs per acre is $\tau = 295$ (Schuster et al. 1997). Accordingly, the per acre cost of one fuel treatment intervention is set at $130 for U.S. Forest Service region 5, which corresponds to the area where the data were collected (see Schuster et al. (1997) for further discussion). Finally, the interest rate r is set at 0.05, and non-timber values at risk are set to D =100,000.

The numerical results for six management strategies are shown in Table 1. The simulations were performed using the software *Mathematica* (Wolfram Research 2002). For each case, the timing and number of interventions, the expected level of suppression given a wildfire, the harvest date, and expected net present values to both the timber owner and to society as a whole are shown. The difference between the timber owner's present value of expected net benefits and society's is the expected net present value of total external costs.

Cases 1 through 4 are based on the assumption that the timber owner pays for suppression as if it were a part of operating expenses. Cases 4 and 5 assume publicly provided suppression as discussed above. Cases 2 through 4 and 6 show the effects of restricting the use of one or more management alternative to zero. For each case, two sub-cases are shown: one in which the timber owner pays for non-timber damage, D, and one in which he or she does not. This comparison is important, because apart from some special cases, landowners are not generally liable for wildfires that move off their land onto the land of others.

A couple of general characteristics of the results in table 1 are worth noting. First, in all cases, fuel intervention intervals shorten over time within the harvest interval because the value of timber is growing and therefore the values at risk are higher later in the timber rotation. Second, it should be no surprise that the timber owner's private net present expected value is higher when he or she is *not* responsible for either non-timber value D or suppression costs, but the social net present expected value is lower due to the poor private timing of actions. Finally, the rotation lengths vary, but are not inconsistent with ponderosa pine rotations in similar environments (Fiedler et al. 1988)

3.1 Private suppression

In Case 1, all management options are performed, and suppression costs are borne directly by the timber owner. The results in table 1 show that the expected net present value of the objective function is maximized with the application of 6 fuel management interventions. When the timber owner is liable for all costs including D, the harvest date is 43.7 years; expected suppression is 87.2 units, and the value of private and social net benefit is \$9,223. Intervals between fuel interventions are shorter when the timber owner is liable for all potential damage. For case 1 with landowner liable for D, the expected time of a wildfire given the optimal intervention dates is $\mathrm{E}[x] = 42.8 < T_7$.

For case 1 given that the owner is *not* responsible for non-timber losses D, the harvest date is later 45.0 years. The probability of reaching harvest without a wildfire in this case is $S(\mathbf{T}_5) = 0.93$, whereas the probability of reaching $t = 45$ without fuel treatments is 0.81. Expected suppression effort of 6.13 is substantially lower because we are assuming private suppression effort for this case. Thus, as would be expected, when D is not accounted for privately, fuel management is delayed and suppression effort is reduced. Further, the timber owner's net benefit is higher than (\$9,325) than when D is internalized, but the net social value of the timber rotations is lower.

Figure 2 shows the relationship between the number of fuel treatment and optimal suppression effort (with optimal intervention timing conditional the number of treatments) for case 1 without landowner liable for D. As the number of treatments increases to $n - 1 = 4$, expected optimal suppression effort decreases. After $n-1=4$, expected suppression effort increases. Two things are happening here: 1) each additional treatment shifts the expected date of a wildfire out, and 2) the optimal harvest date shifts out, leading to larger values at risk because $V(t)$ is growing. Going from $n-1=4$ to $n-1=5$, the (diminishing) marginal value of a treatment in terms of risk reduction is more than offset by the higher marginal value product of suppression due to growth in $V(t)$, so higher suppression expenditures compensates for diminishing returns of fuel treatments.

Case 2 restricts suppression to equal zero and is included in table 1 for comparison with case 1. Here, the number and timing of the fuel management interventions and the harvest date are the only means of addressing wildfire risk. Compared to Case 1, fuel management and harvest dates are earlier, and when the timber owner is not liable for D, the number of fuel management interventions is higher by one compared to the case 1 analogue. Thus, earlier fuel treatments (and perhaps more of them), and earlier harvest, act as substitutes for suppression. Note also that both private and social net benefits are lower than in their comparable case 1 results.

In case 3, no fuels management regime is implemented, so suppression and timber harvest timing alone are relied upon as choice variables. Loosely speaking, this case might represent the general approach followed by the U.S. forest service throughout most of the 20^{th} century. Timber harvest dates are 31.9 and 33.3 years when liable and not liable for D, respectively. In each case, timber rotation lengths decrease approximately 8 years compared to case 1. Suppression levels are lower than case 1 (25.6 and 4.7 when liable for D or not, respectively). Thus, most of the effect of ignoring fuel treatments as an option is accounted for by reductions in harvest dates, and given that harvest rotations are short, timber-values at risk are lower at the expected wildfire date, and so the marginal value product function of suppression is lower, so less suppression is used.

Case 4 assumes both fuel management and suppression are restricted to be zero, so the timber harvest date is the only choice variable. As one might expect, harvests dates are the shortest of all cases, occurring at 26.3 and 30.2 years with and without timber-owner liability for non-timber values, respectively.

It is of particular interest to note that of all management regimes so far, those in which fuel management is restricted provide the lowest expected net present value (cases 3 and 4, liable for D) both to the forest owner and to society. This result is supportive of the increasingly fervent calls for the importance of fuels management in fire-prone environments.

3.2 Public suppression

Cases 5 and 6 are based on the assumption that in the event of a wildfire, a public agency applies suppression optimally, given private fuel accumulations up until the date of the fire. Therefore, "optimal" suppression in this case is second-best in the sense that private fuel management will be inefficient because timber owners are not bearing the suppression component of the costs of wildfire, and will therefore alter their fuel management regimes relative to case 1 (the efficient case).

Case 5 shows the result with publicly provided suppression and private fuel management. The simulation shows that public suppression of 89.6 and 91.9 units (with and without landowner liability for D, respectively) is higher than any case in which suppression costs are borne by the timber owner. When the timber owner does not account for non-timber damage, the harvest date of 46.2 years and net private benefit of $9,351 are the highest of all scenarios. The number of fuel interventions is reduced to 2, and the lengths of intervals between them increases.

With public suppression and no fuel management, as in case 6, harvest dates are again shorter, but public suppression is at its highest of all (99.9 and 105.5). Given the assumption that harvest and fuel treatments mitigate fire risk, and regardless of potential non-timber losses internalization, this case provides lower social benefits ($7,604 and $7,570) compared to case 5, where fuel treatments are applied.

Of all the cases presented, these last two scenarios with public suppression and no liability for potential non-timber damage are perhaps the most similar to the incentives of private landowners in most of the United States. Weak incentives to invest in wildfire prevention through fuel management and long harvest rotations lead to very high public suppression expenditures. These results are consistent with the increasing suppression costs and wildfire severity observed over the past decades. In effect, since fire suppression expenditures are supported almost entirely by public agencies, there is little private incentive to invest in preventive actions such as fuel treatments. This ultimately lead to more catastrophic fires and to increasing public firefighting expenditures.

Although the above simulations provide insights into the trade-offs between suppression and fuel treatments that cover a broad range of wildfire issues, they are based on just one set of underlying physical relationships between timber growth, wildfire risk, fuel management, harvest, costs, and benefits. There are many ways in which the model could be respecified to better fit a given situation. For example, we have applied the same suppression productivity function to timber and non-timber values, but it is likely that approaches to protecting homes are different than approaches to protecting timber, implying that the suppression productivity function would differ. We have also assumed that the timber stumpage value is not a function of the treatments' timing, when in fact it is likely that thinning and prescribed fire activities also often augment timber growth. Finally, the optimistic assumption of second-best public firefighting effort almost certainly grossly underestimates the level of suppression effort exerted by firefighting agencies.

4 Policy and Management implications

Wildfire fuels and values at risk change over time, so wildfire risk management is in part a timing problem. In this article, we embed the wildfire management problem in a setting that captures many of the important elements affecting incentives for private and public wildfire risk mitigation, and many of the most pressing policy questions as well.

Fuel management provides positive externalities to the extent that it reduces the contribution of a landholding to regional wildfire risk. Although there are good reasons for public provision of wildfire suppression services, one consequence of public firefighting services is that the private marginal costs of waiting to invest in fuel management are not fully internalized by the landowner or forest manager. The result of these two incentive problems is "too little, too late" private fuel management, and public suppression expenditures that are substantially higher than they might otherwise be. A century of this combination of incentives may be a major contributor to the apparent substantial increases in suppression costs and wildfire severity in recent years.

The legal and regulatory environment frames private incentives for fuel management. There is a small but growing number of public programs and laws pertaining to wildfire fuel management that arguably tries to address the incentive problems illustrated in this paper. A few states have cost-share programs for fuel reduction on private land, and laws have been proposed in several state legislatures to direct the funding needs for suppression at forest owners specifically. As these laws develop, it is important that they be designed to affect fuel management choices at the margin for individual forest owners.

One interesting legal conundrum relates to prescribed fire, which is often the least-cost method of wildfire as a fuel management option.[6] Although legal liability for prescribed fire use is relatively clearly established in statutory and common law, legal liability for accumulation of excessive fuel loads is notYoder et al. (2003). If a wildfire starts or flows through a landholding, the landowner is usually not at risk of liability for excessive fuel loads.[7] But if a prescribed fire started for fuel management purposes escapes and turns into a wildfire, the person performing the prescribed fire faces relatively well-developed negligence law Yoder et al. (2003). Thus, although the full expected costs of prescribed fire may be

[6] On the wildland-urban interface, it is also important to balance the incentives of forest owners with the incentives of homeowners. "Moving to the hazard" and homeowner incentives are an important element of this problem, but because the focus of this paper focuses on timber owners specifically, we leave these issues aside.

[7] A few states do have statutory negligence laws for individuals who do not attempt to stop a fire from spreading from their land.

approximately accounted for, the costs of leaving the fuel alone may not.[8]

The relationship between wildfire and timber harvest is also a contentious issue. George W. Bush's precursor to the Healthy Forests Restoration Act of 2003, The Healthy Forest Initiative, discusses fuel management at length, but environmentalists attacked the initiative as a politically motivated attempt to open the door for increased timber harvest.
Furthermore, many fire ecologists claim that timber harvest, particularly old growth, is usually not an effective means of reducing wildfire risk. The structure of our model elucidates a couple of dimensions of this issue. First, the *type* of property at risk matters. If timber values are at risk, it makes sense to harvest earlier in areas with high wildfire risk, preempting wildfire losses by extracting value. For non-timber values, altering timber harvest timing is a form of fuel management for wildfire risk reduction. If timber harvest is ineffective at reducing wildfire risk to non-timber values, then shortening timber harvests makes little economic sense in terms of reducing non-timber losses.[9] On the other hand, if harvest does reduce the risk of nontimber damage, then shorter rotations make economic sense. This last point is illustrated by the harvest date differences between the scenarios in which the timber owner is responsible for non-timber values and those in which the timber owner is not responsible for nontimber values.

As is the case with much of the recent wildfire management literature, the emphasis of the Healthy Forests Restoration Act of 2003 is on the spatial distribution of wildfire risk mitigation, with explicit directives to focus spatially on the wildland-urban interface. Nonetheless, the fuel management is a dynamic temporal problem as well. Although the model presented in this paper is modelled as a single fire-prone forest stand, a useful further development would be to incorporate the dynamic model into a broader spatially explicit

[8] In four states, however, landowners or contractors can be found liable for *activity fuels* such as timber slash, where a specific activity, such as timber harvest, can lead to substantially increased wildfire risk. The characteristic of being able to pinpoint a specific action (e.g. the creation of timber slash) is helpful for clearly assigning liability and negligence through the courts; at the margin, it is likely more difficult to pinpoint a threshold of negligence with respect to natural fuel accumulation.

[9] In simulations examined in this article we assume that both harvest and wildfire interventions reduce wildfire risk to zero, but the model can easily be specified to differentiate between the two activities and allow for incomplete risk reduction in either case.

model of wildfire risk management.

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Table 1: Simulations Results. Cases 1-4: Private owners bear the costs of suppression. Cases 4-6: Suppression provided by a public agency.

Management Strategies	Owner responsible for D	fuel treatments (n-1)	dates	Harvest Date	Suppression units	Net Private Benefit	Net Social Benefit
Case 1:	Yes		13.7				
Private			21.0				
suppression			26.8				
and fuel			32.2				
treatments			37.0				
		6	41.2	43.7	87.2	9,223	9,223
	No		22.3				
			33.8				
			39.2				
		4	42.7	45.0	6.13	9,325	9,201
Case 2:	Yes		13.1				
Fuel			19.9				
treatments			25.7				
only			31.3				
			35.7				
		6	38.6	40.6		9,094	9,094
	No		17.4				
			25.5				
			32.2				
			36.6				
		5	40.8	44.6		9,239	7,290
Case 3: Private	Yes			31.9	25.6	7,711	7,711
suppression only	No			33.3	4.7	7,808	7,418
Case 4: No Suppression or treatments	Yes			26.3		3,228	3,228
	No			30.2		6,936	2,472
Case 5: Public	Yes		16.2				
suppression and			28.5				
private treatments			37.1				
		4	41.8	45.1	89.6	9,211	8,750
	No		32.1				
		2	41.9	46.2	91.9	9,351	8,216
Case 6: Public	Yes			40.5	99.9	9,164	7,604
suppression only	No			45.6	105.5	9,331	7,570

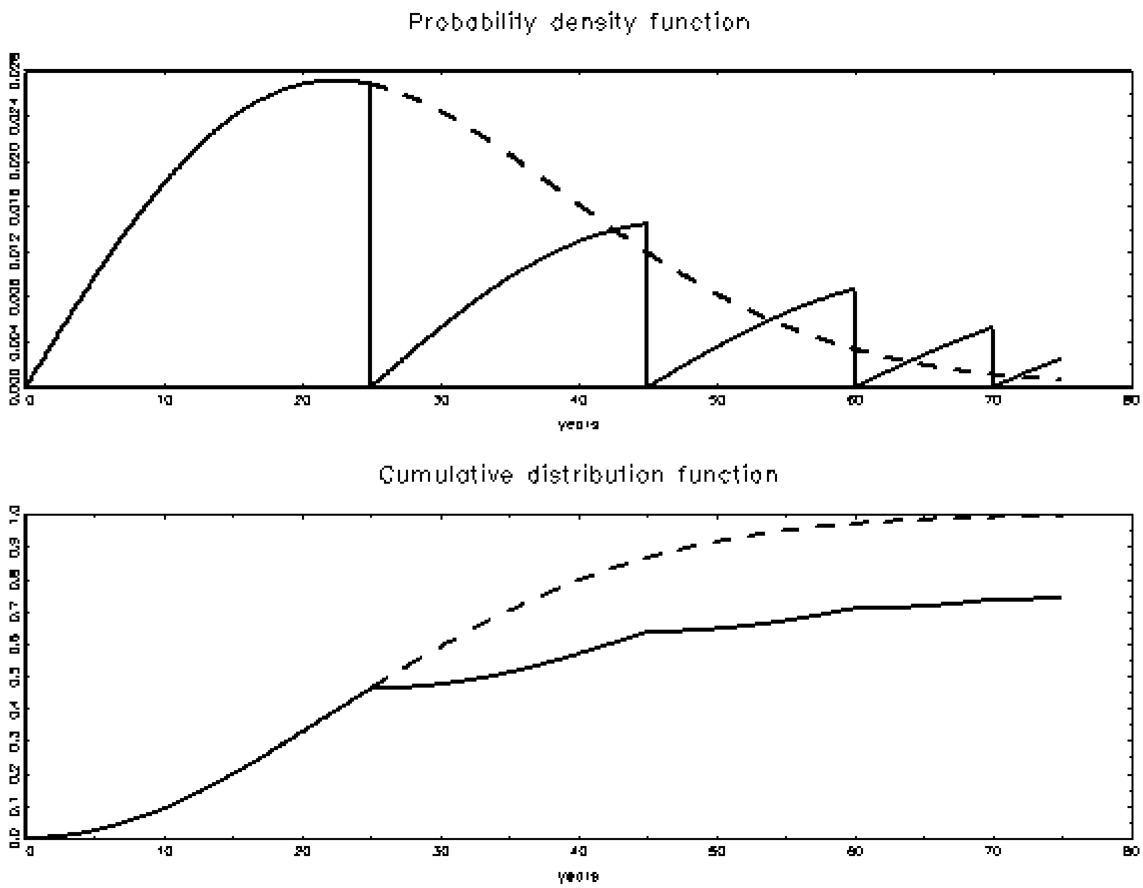

Figure 1: Wildfire probability distributions, with fuel management interventions (solid lines) and without interventions (dotted lines). Interventions are shown to be applied at increasing frequency as is optional when timber value grows over time.

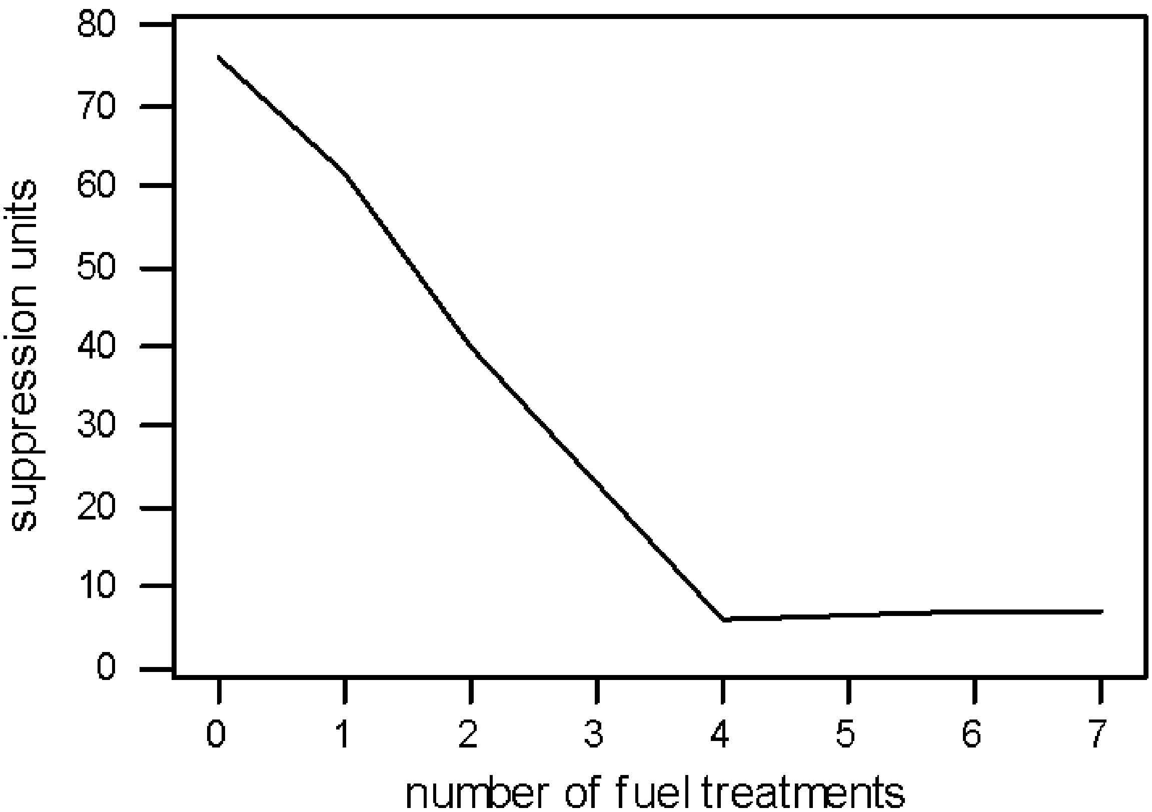

Figure 2: Substitution between the number of (conditionally optimal) fuel interventions and the amount of suppression effort. Case 1 (landowner not liable for D; optimal number of treatments = 4).