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WILDFIRE FUELS MANAGEMENT: A NESTED ROTATION APPROACH APPLIED TO PONDEROSA PINE FORESTS

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Abstract

Vegetative fuels management for wildfire risk mitigation is increasing recognized as a crucial complement to suppression. We develop a nested rotation model to examine the fuel treatment timing in the context of a forest environment where part of the values at risk are standing timber to be harvested. Simulations are performed for a representative ponderosa pine forest, and implications of the model for policy issues are discussed, including 1) the effects of public suppression of wildfire on private fuel management incentives, 2) externality problems when non-timber values such as wildland-urban interface property is not accounted for in private fuel management decisions.

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Introduction

A policy of intensive wildfire suppression for almost a century has resulted in excessive accumulation of vegetative fuel loads and wildfires of increasing intensity and severity in many forest environments (Ingalsbee 2000; Prestemon et al. 2001). Over the last three decades, forest managers and researchers have increasingly called for greater emphasis on fuels management for wildfire risk mitigation. In response, the Healthy Forests Restoration Act of 2004, which includes substantial emphasis on fuels management, was recently approved by the US Congress and signed into law. Although fuels management treatments have long been advocated (Weaver 1943) and are gaining support as effective means of reducing fire hazard (Stephens 1998; Pollet and Omi 2002; Hof and Omi 2003; Rideout 2003; Martinson, Philip, and Omi 2003), further economic research is needed to better understand when, where, and how these risk mitigation approaches should be applied.

Vegetative fuels mature over time and wildfire risk changes with it. Therefore, one important element of the fuels management problem is the timing of fuel treatments. In this paper, we examine the fuel treatment timing issue in the context of a forest environment where at least part of the values at risk are standing timber to be harvested. We develop a rotation model in which fuel treatment interventions are nested within an encompassing timber harvest rotation. The model allows us to solve for the optimal number and timing of fuel treatments and timber harvest in a setting where wildfire risk changes over time, fuel treatments reduce wildfire risk, and wildfire suppression is costly.

Several studies have examined the economics of forest management under the risk of total destruction of forest value. Martell (1980) uses a stochastic discrete model

and applies dynamic programming techniques to obtain the optimal solution. In Routledge (1980), an extension of the Faustmann model is used to determine the optimal forest rotation. Later research by Reed (1984, 1987), Reed and Errico (1985, 1986), examined the long run effects of the risk of fire on rotation length and fire return interval. In Thorsen and Helles' (1998), the risk is considered as an endogenous variable; endogenous in the sense that the level of risk can be controlled by the management actions. All these papers found that the optimal rotation age decreases over time under the risk of wildfire. Yoder (in press) examines optimal rotation of prescribed fire treatments for reducing wildfire risk and providing forage or other benefits.

Our approach is unique in two ways: First, we present a model general enough to make use of the two general forms of fuel treatment (thinning and prescribed fire). Second, we propose a discrete nested rotation model for harvestable timber environments in which the pre-harvest intervention rotations are embedded in a harvest rotation. Although the treatment of fuel management as a rotation problem is similar in spirit to Yoder (in press), the analytical and numerical implementation of the problem is substantially different given the nested rotation problem. Reed (1987) examines optimal timber harvest and wildfire protection also, but treats protection activities as a continuous variable. In contrast, most fuel management activities are performed in a forest in a discrete rather than continuous manner, as we assume in this paper. This difference leads, again, to very different analytical approaches.

We apply our general model to simulations of both thinning and prescribed fire interventions for ponderosa pine forests, a prevalent forest type in the Western United

States. We also incorporate the costs of wildfire suppression into the model to examine the structure of the economic tradeoff between *ex ante* fuel management and *ex post* suppression. We then apply the model to a number of current policy issues. First, we formally examine the economic tradeoffs between fuel treatments and suppression efforts. Second, by parameterizing the model for a specific forest type, we are able to examine the effects of differences in potential damage (such as large potential damage along the urban fringe) on optimal intervention. Third, we examine the incentive effects of public wildfire suppression on private fuel management decisions.

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, by some policy implications discussion.

The nested rotation problem

Consider a succession of even-aged forest stands that are managed to maximize the expected net present value of the stand under the risk of wildfire. To mitigate the risk of destruction by fire, the manager chooses the timing of harvest and a number of pre-harvest interventions that affect the probability distribution of wildfire return, as well as a level of suppression given that a fire occurs. 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 valuable resources (such man–made structures). The time-path of wildfire risk is affected by fuel management interventions (*interventions* for short), and in the event of a preharvest wildfire, the extent of damage can be reduced by suppression effort.

Optimization in this context amounts to jointly maximizing over $n + 1$ choice variable, where n - 1 pre-harvest interventions, harvest (the nth intervention) and suppression effort. Solving the optimization problem requires a two step process: 1) conditional optimization for a set of feasible n, 2) selecting the $n \times 1$ vector that provides the highest expected net present value. $\mathbf{T}_n = [T_{n,1}, T_{n,2}, ..., T_{n,n}]'$ is a vector of interventions, where $T_{n,i}$ represents the time of intervention i given n interventions, measured in time since planting. These interventions are assumed to affect only the risk of wildfire. The conditional probability of wildfire occurring at anytime Z after any arbitrary number of intervention I is given that no fire occurred between $T_{n,i-1}$ and $T_{n,i}$ is

$$F\left(T_{n,i}, T_n\right) = \int_0^{T_{n,1}} f(t)dt + (1 - \int_0^{T_{n,1}} f(t)dt)\int_{T_{n,1}}^{T_{n,2}} f(t - T_{n,1})dt + \\ \cdots + (1 - \int_{T_{n,i-2}}^{T_{n,i-1}} f(t - T_{n,i-2})dt)\int_{T_{n,i}}^{Z} f(t - T_{n,i-1})dt$$

where $f(t)$ is the probability of a fire occurring at time t. Note that $F(T_{n,j}, \mathbf{T}_n)$ is a function of the intervention vector as well as the end-point, which is the time of the jth intervention, $T_{n,j}$, and that every intervention results is resetting the probability of destructive wildfire back to the initial state. Figure 1 illustrates the probability density function and cumulative density function for wildfires with and without fuel management interventions.

To find the optimal timing vector, the manager maximizes the expected net present value of the benefits given the uncertainty of fire occurrences. 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 $e^{-rT_{n,n}} V(T_{n,n})$. For simplicity we assume that *V(t)* is not a function of interventions, just time from planting.

2. If a wildfire occurs, the owner receives $e^{-rT_{n,n}} (1-g(s))V(T_{n,n})$ 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 $g''(s) > 0$. It is assumed that the remaining timber is left to grow to the optimal harvest date. So the financial loss from a wildfire in terms of timber value is realized at harvest time, not when the wildfire occurs.

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 $s \cdot \tau \cdot G(T_{n,n}, \mathbf{T}_n)$, where $G(T_{n,n}, \mathbf{T}_n)$ is a discounted version cumulative wildfire distribution function given fuel interventions, with the harvest date being the endpoint:

$$G(T_{n,i}, T_n) = \int_0^{T_{n,1}} e^{-rt} f(t)\,dt + (1 - \int_0^{T_{n,1}} e^{-rt} f(t)\,dt) \int_{T_{n,1}}^{T_{n,2}} e^{-rt} f(t - T_{n,1})\,dt \quad + \\ \cdots\cdots \quad + \quad (1 - \int_{T_{n,n-2}}^{T_{n,n-1}} e^{-rt} f(t - T_{n,i-2})\,dt) \int_{T_{n,n-1}}^{T_{n,n}} e^{-rt} f(t - T_{n,i-1})\,dt\,.$$

4. Damage may accrue beyond just the value of timber. To allow this, we introduce a constant *D* that represents potential damage to non-timber property such as homes and buildings. 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 value of any given intervention cost is $w \cdot G(T_{n,i}, \mathbf{T}_n)$.

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

$$
\begin{aligned}
EPV_n &= \frac{1}{1-e^{-rT_{n,n}}}\begin{pmatrix} E[\,PV\,(\text{timber value})\,] \\ -E[\,PV\,(\text{suppression costs+damage})\,] \\ -E[\,PV\,(\text{intervention costs})\,] \end{pmatrix} \\
&= \frac{1}{1-e^{-rT_{n,n}}}\begin{pmatrix} \left[e^{-rT_{n,n}}\,(1-F\,(T_n,T_{n,n})\,g\,(s))\,V\,(T_{n,n})\right] \\ -\left[\,G\,(T_n,T_{n,n})\,(\tau\,s+g(s)\,D)\right] \\ -\left[\,w\,I\,[n>1]\sum_{i=1}^{n-1} e^{-rT_{n,i}}\,(1-F\,(T_n,T_{n,i}))\right] \end{pmatrix}
\end{aligned}
\tag{1}
$$

Where, to summarize notation:

- EPV_n is the expected net present value given n interventions;
- r is the discount rate;
- $\boldsymbol{T_n}$ is an $(n \times 1)$ vector of $(n\text{-}1)$ intervention dates and a harvest date;
- $T_{n,i}$ is the time of the ith intervention; harvest is the nth intervention;
- $V\,(T_{n,n})$ is the timber's stumpage value at harvest time;
- $F(\mathbf{T}_n, T_{n,i})$ is the probability of wildfire occurring before time $T_{n,i}$ given the intervention vector $\mathbf{T}_n$;

- G ($\mathbf{T}_n$, $T_{n,i}$) is the discounted (present value) probability of wildfire occurring before time $T_{n,i}$ given the intervention vector $\mathbf{T}_n$;
- 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.
- $\boldsymbol{I}[\boldsymbol{n}>\mathbf{1}]$ is an indicator function such that when there is no pre-harvest intervention, $\boldsymbol{I}[\boldsymbol{n}>\mathbf{1}]=\mathbf{0}$, otherwise, $\boldsymbol{I}[\boldsymbol{n}>\mathbf{1}]=\mathbf{1}$.

The first term in brackets relates to the value of timber, the second term in brackets relates to the costs of wildfire, and the third term in brackets relates to the costs of intervention. The number of choice variables, and therefore the number of first-order conditions for the problem, depends on the number of interventions before harvest. We find the vector of arguments to maximize this function in two steps. First, the vector of optimal intervention times $\mathbf{T}_n$ and suppression effort s is chosen conditional on a specific number of interventions n. Conditional optimization is performed over feasible intervention sets n=1…m, to find the m conditionally optimal vectors $\mathbf{T}_1 \ldots \mathbf{T}_m$ and each of their associated values of optimal s**.** Second, from the m conditionally optimal vectors, we choose the vector [$\mathbf{T}_i$, s] that maximize EPV_n.

For illustration purpose, consider the first order conditions for a maximum for the case of n=2, so that the landowner chooses s_2 and the intervention schedule $T_2 = [T_{2,1}, T_{2,2}]$. The first-order condition for suppression is

$$(2) \qquad -g'(s_2)\left[\delta^a V(T_{2,2}) + D\right] = \tau \ ,$$

where $\delta^a = \left(e^{-rT_{2,2}} F(T_{2,1}, T_{2,2}) / G(T_{2,1}, T_{2,1})\right)$ is a probability weighted discount factor. This first-order condition implies that the expected marginal benefits from suppression in terms of damage foregone (and discounted to the expected time of the suppression expenditures) equal the marginal cost of suppression.

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

$$w\left(r\left[1 - F(T_{2,1})\right] + F'(T_{2,1})\right)e^{-rT_{2,1}} = g(s_2)V(T_{2,2})\left[e^{-rT_{2,2}}\left(1 - F(\mathbf{T}_2)\right)F'(T_{2,1})\right] + \left(Dg(s_2) + \tau s_2\right)\left[G'(T_{2,1})\left(1 - G(\mathbf{T}_2)\right)\right],$$

(3) or

$$\delta^b w = \delta^c g(s_2)V(T_{2,2}) + \delta^d\left(Dg(s_2) + \tau s_2\right)$$

marginal benefit of waiting = marginal cost of waiting

where the δ's again represent probability weighted discount factors. This condition implies that the expected present value of marginal intervention costs equals the expected costs of waiting one more period in terms of damage and suppression costs.

The forest manager harvests when the expected marginal increase in timber value from further growth (left hand side of equation (4)) equals the total marginal cost (right hand side of equation (4)). Assuming that the risk of damage from wildfire drops to zero at harvest, the first-order condition is

$$\left[1-F(\mathrm{T}_2,T_{2,2})\big(g(s_2)\big)\right]V'(T_{2,2}) = rEPV_2 + r\left(1-F(\mathrm{T}_{2,1},T_{2,2})(g(s_2))\right)V(T_{2,2})$$

(4) $$\delta^e\ V'(T_{2,2}) = r\left(EPV_2 + \delta^f V(T_{2,2})\right)$$

marginal benefit of waiting = marginal cost of waiting

Again, the δ's are probability weighted discount factors. This first-order condition is similar to a Faustmann result, and is of the same form as first-order conditions derived for timber harvest under wildfire threat in previous literature (e.g. Newman, 1988, p. 8).

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, nor do they usually pay the full price of suppressing wildfires on their land or to which they have contributed, because fire suppression services are generally provided for and funded through public agencies (Yoder et al. 2003).

To consider the first case, we choose a simple alternative for simulation comparisons that can be a reasonable representation of externality problems at 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, *D*. 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 positive *D*. The second case, that in which 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 τs must be removed from the second line of (1).

Second, because the landowner makes decisions based on the expectation that suppression will be performed in the event of a fire, this fact must be accounted for. We do that 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 (2) (given 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 (1) but with τs removed from the second line. It should be noted that it is highly unlikely that wildfire suppression activities satisfy first-order condition (2). They have almost unlimited but non-reallocable budgets for suppression, which would likely lead to over-suppression (see, for example, O'Toole 2002). There are a number of other incentive issues lurking within this problem as well, but we use first-order condition (2) as the constraint as a simple illustrative assumption.

Simulations Results and Discussion

For simulation purposes, the model must be specified completely. Fuel treatments to mitigate the risk of catastrophic fires in the Ponderosa Pine forest are a very controversial issue because of the growing human population in these areas. Understanding the

potential returns and liabilities associated with a reintroduction of fire in these type of forest is therefore of prime interest to the public and policy makers.

For a base case, we attempt to specify the 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.

To represent the growth in value of ponderosa pine, we use the modified Weibull function (see Yang, Kozak, and Smith 1978), which we estimated using data published in Oliver et al. (1978): $V(t) = 1536750\,(1 - e^{-0.00015t^{2.2}})$.

For the fire return interval representing wildfire probabilities, we use a Weibull distribution with location, scale, and shape parameters of a = 0, b = 30, c = 2, respectively, which is generally consistent with estimated fire return intervals for this forest type. (see Smith and Fischer 1997 for further discussion). These parameters result in a probability density function of $f(t) = 0.002t\,e^{-0.001\,t^2}$ 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), we use a suppression production function $g(s_n) = e^{-0.0055s_n}$, where suppression effort s_n is defined such that one unit of

suppression costs $\tau = 295$. The unit cost of one intervention is set at 130, and the interest rate *r* is set at 0.05. Finally, Non-timber values at risk are set to *D*=100,000 or zero (in the case of no non-timber values at risk, or no liability for lost non-timber values).

Six cases are shown in table 1 for comparison. For each case, the number and timing of interventions, the level of suppression given a wildfire, the harvest date, and the optimal objective function value are shown for two sub-cases, one in which the timber owner is liable for non-timber damage and one in which he or she is not. Cases 1 through 4 are based on the assumption that the timber owner pays for suppression as if it were one part of their operating expenses, and cases 4 and 5 assume public 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. Note that 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.

Private suppression

Case 1 can be considered a base case. All management options are performed, and suppression costs are borne directly by the timber owner. The expected net present value of the objective function is maximized with the application of 4 fuel management interventions whether or not liable for *D*. When liable for all costs including *D*, the harvest date is 33.7 years, expected suppression is 55.6 units, and the value of the objective function is 10,133. When the timber owner is not liable for *D,* the harvest date is later at 35.3 years, and expected suppression effort of 2.2 is substantially lower. Fuel

interventions are also shorter when the timber owner is liable for all potential damage. These results are intuitively plausible: When the full costs of damage are not borne by the timber owner, fuel management and suppression are not personally worth as much, so fuel management is delayed and suppression effort is reduced.

Case 2 represents a scenario in which suppression is restricted to equal zero, which we include for comparison. Here, the number and timing of the fuel management interventions and the harvest date are the only means of addressing wildfire risk. In comparison with case 1, the harvest dates are very similar, but the fuel management regimes are quite different, both between case 1 and case 2, and within case 2 with and without liability for non-timber damage. When liable, the number of fuel management interventions increases by one compared to case 1, but decreases by one when not liable. Thus, fuel management is altered substantially when suppression is restricted, and its optimal use changes dramatically when potential risks change.

In case 3 no fuels management regime is implemented, so suppression and timber harvest timing alone are relied upon as choice variables. In this case, the timber harvest dates are 29.5 and 32.4 and years when liable and not liable respectively respectively. In each case timber rotation lengths decrease 3 to 4 years compared to case 1. Interestingly, suppression levels are very similar to case 1, so most of the difference in expected damage given no fuel treatments is absorbed by changing the harvest dates.

Case 4 shows results when both fuel management and suppression are restricted to be zero and harvest date is chosen to maximize expected benefit. As one might expect,

harvests dates are the shortest of all cases, occurring at 25.7 and 29.2 years with and without liability for non-timber values, respectively.

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

Public suppression

Cases 5 and 6 are based on the assumption that, in the event of a wildfire, suppression is applied by the Forest Service optimally given private fuel accumulations. "Optimal" suppression in this case is second-best in the sense that fuel management will be sub-optimal from a societal perspective because timber owners are not bearing the full cost of wildfire risk.

Case 5 shows the result with private fuel management, harvest and public suppression provision. The simulation shows that public suppression of 146.8 and 147.3 units (with and without liability for *D*) is much higher than when suppression costs are borne by the timber owner (the next-highest suppression level is 55.6 in case 1). The harvest are pushed back slightly as compared to case 1, and when non-timber damage is not accounted for by the timber owner, the number of fuel interventions is reduced to three and the length of intervals between them increase. With public suppression and no liability for potential non-timber losses --- as arguably is the case in most of the United States, the timber owner has quite weak incentives to invest much wildfire prevention

through fuel management and harvest. When fuel management is not used at all, as in case 6, harvest dates are again shorter, but public suppression is at its highest of all.

Policy and Management strategies implications

The above simulation s 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 wildfire losses and suppression expenditures. 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, although the owners of land with flammable vegetation may contribute to the incidence and severity of wildfires, they tend not to face full 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. These results suggest that changes incentive structures may be called for. There are many such instruments to be considered, including altering legal liability rules, subsidization of fuel management projects, taxing fire risk contributions, or directly regulating fuel accumulations.

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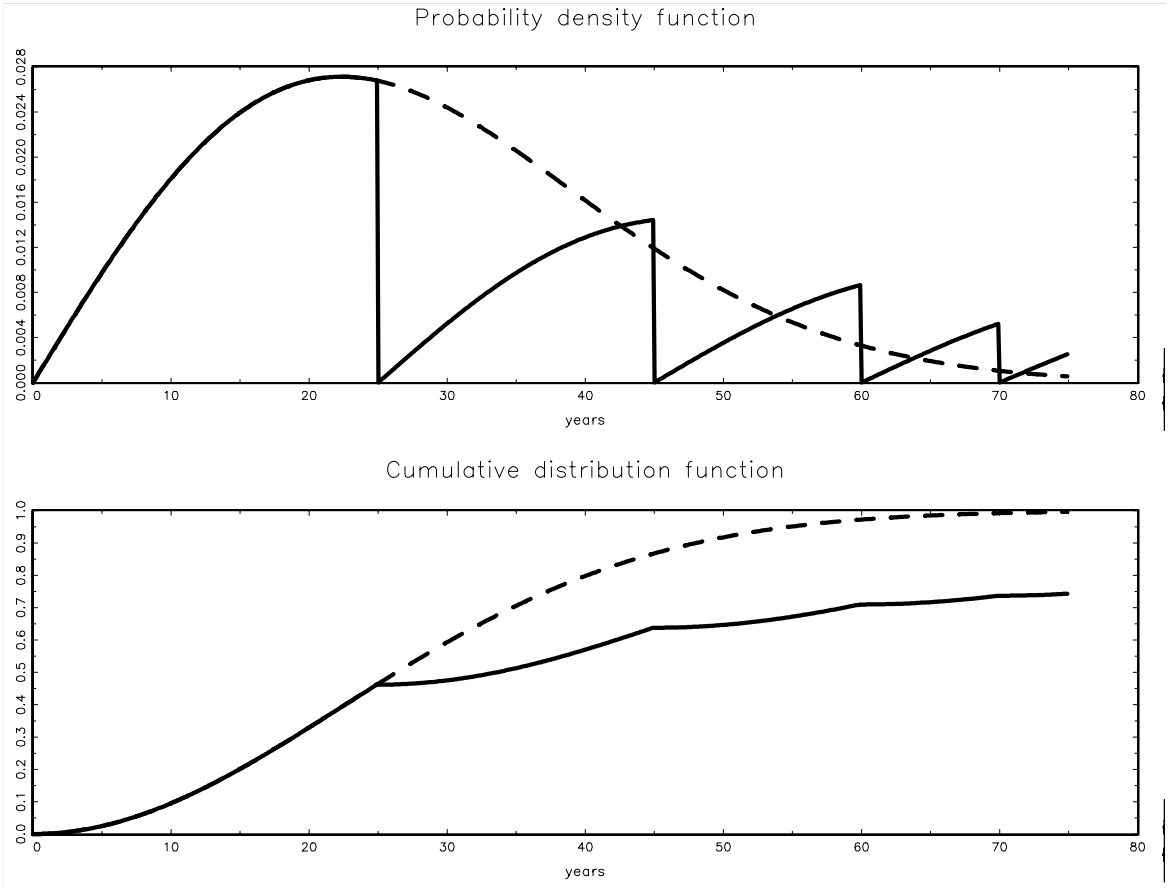

Figure 1. Wildfire probability distributions, with fuel management interventions (solid lines) and without interventions (dotted lines).

Table 1. Simulation results. Forest owner bears suppression costs.

Management strategies	Liability for D	Timing of interventions	# inter-ventions	harvest date	Suppress-ion units	Net Benefit
Case1: Private suppression	Liable	$x_{5,1}$=7.9 $x_{5,2}$=15.9 $x_{5,3}$=22.9 $x_{5,4}$=29.2	4	33.7	55.6	10,133
	Not liable	$x_{5,1}$=10.3 $x_{5,2}$=18.2 $x_{5,2}$=24.9 $x_{5,4}$=30.6	4	35.3	2.2	11,322
Case2: Fuel treatment only	Liable	$x_{6,1}$=7.8, $x_{6,2}$=14.9 $x_{6,3}$=21.0 $x_{6,4}$=27.0 $x_{6,5}$=30.9	5	33.4	.	10,009
	Not liable	$x_{4,1}$=7.8, $x_{6,2}$=20.2 $x_{4,3}$=28.0	3	35.0	.	11,319
Case3: Suppr. only	Liable.	.	.	29.5	36.5	6748
	Not liable	.	.	32.4	2.56	10,591
Case4: Harvest only	Liable	.	.	25.7	.	6376
	Not liable	.	.	29.2	.	10,586
Case5: Private treatment, public suppression.	Liable	$x_{5,1}$=10.3 $x_{5,2}$=20.5 $x_{5,3}$=28.6 $x_{5,4}$=32.2	4	34.7	146.8	10,734
	Not liable	$x_{4,1}$=13.4 $x_{4,2}$=23.3 $x_{4,3}$=30.4	3	35.8	147.3	11,533
Case 6: Public suppr. only.	Liable	.	.	32.7	155.6	9,320
	Not liable	.	.	34.1	157.3	11,303