Not Getting Burned: The Importance of Fire Prevention in Forest Management

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ABSTRACT. *We extend existing stand-level models of forest landowner behavior in the presence of fire risk to include the level and timing of fuel management activities. These activities reduce losses if a stand ignites. Based on simulations, we find the standard result that fire risk reduces the optimal rotation age does not hold when landowners use fuel management. Instead, the optimal rotation age rises as fire risk increases. The optimal planting density decreases. The level of intermediate fuel treatment, but not its timing, is sensitive to the magnitude of fire risk. Cost-sharing is shown to be an effective instrument for encouraging fuel treatment.* (JEL Q23)

I. INTRODUCTION

Recent forest fires around the world have focused attention on programs to encourage non-industrial forest landowners to reduce the risk of property damage from wildfires (SAF 2000, 2002; FAO 2003; *The Economist* 2003). These programs recommend fuel treatment activities, such as thinning and prescribed burning, with the aim of reducing fire damage if a stand ignites. In addition to these activities, which are undertaken during a rotation, landowners can undertake fuel management activities at the time of stand establishment that are also likely to reduce the intensity of fire and its rate of spread. One such activity is installation of artificial fire breaks; another is planting at reduced densities.

In addition to reducing potential financial losses suffered by landowners, fuel management may reduce a government's costs of fire suppression by reducing fire intensity and rate of spread. Fire suppression costs severely affect government budgets. It is estimated that U.S. federal agencies spent $1.6 billion on wildland fire suppression in 2002 (NIFC 2003). Because nonindustrial landowners do not bear fire suppression costs completely, there may be a divergence between landowner decisions about fuel management and decisions a government would make if it could control landowner behavior directly. As a result, understanding landowners' fuel management decisions is important to improving government fire prevention policy.

The implications of fire risk for landowner behavior have been studied in a Faustmann-type framework under the assumption that landowners choose only stand rotation age (Reed 1984, 1987; Yin and Newman 1996) and value both timber and non-timber benefits (Englin, Boxall, and Hauer 2000). In an effort to better understand the behavior of nonindustrial private forest landowners in the presence of fire risk, we build on this work by developing a model of landowner behavior that captures several features of the fire problem that have received little attention in the existing literature. Most importantly, our model recognizes that landowners can mitigate fire losses by undertaking intermediate fuel treatment and by varying initial planting density. Fuel treatment increases the salvage value of timber if a stand ig-

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nites, and the same is true of lower planting densities. Our model also recognizes that the average fire arrival rate may vary with stand age, and we consider the possibility of an arrival rate that is constant, rising, or falling with stand age. Finally, we recognize that landowners may value nontimber uses of their forestland.

Our objective is to determine how fire risk influences the fuel management decisions of nonindustrial private landowners and how these decisions affect their welfare.[1] As we show, incorporating fuel management decisions yields results that differ markedly from those derived using models that consider only rotation age. For instance, the main result in the existing empirical literature is that fire risk reduces the optimal rotation age, with rotation age falling as fire risk increases. We find this to be true only in special cases of our model. In the more general versions, rotation ages are larger in the presence of fire risk and increase in magnitude as fire risk increases. We also find that the level of fuel treatment, but not its timing, is sensitive to the magnitude of fire risk.

Our work is related to a paper by Reed (1987) on optimal fire protection expenditures for commercial forests.[2] However, our objectives and the structure of our model differ from his. Reed considers a setting in which fire protection effort is undertaken at each point in time. The landowner's decision variables are the level of fire protection expenditures and rotation age. The assumption of continuous fire protection effort is plausible for commercial forests, but not for forests owned by nonindustrial landowners, who manage their stands only occasionally. It also does not capture fuel management activities such as prescribed burning, which are generally undertaken only once during a rotation by most landowners. Furthermore, Reed assumes that fire protection influences the probability of fire arrival and not the volume of timber salvaged in the event of fire (there is no salvage in his model). In contrast, we assume, for reasons discussed below, that prevention efforts in the form of fuel management do not influence the probability of fire arrival, but do influence the volume of timber salvaged after a fire. Finally, given his focus on commercial forests, Reed does not consider nontimber benefits, and he restricts attention to fire risk that is constant or decreasing with stand age.

The rest of this paper proceeds as follows. First, we present a theoretical model of nonindustrial landowner behavior in the presence of fire risk. Second, we conduct simulations, based on the theoretical model, to analyze landowner behavior. Third, we examine the effectiveness of alternative policies for inducing landowners to undertake higher levels of intermediate fuel treatment. Finally, in the last section of the paper, we summarize our main findings and discuss some policy implications of our work.

II. LANDOWNER DECISION MODEL

Consistent with previous stand-level models with fire risk, our model of landowner behavior assumes an infinite series of rotations, and known and stationary prices and costs. The landowner is risk-neutral and values timber returns fully, but may or may not value nontimber benefits. In addition to rotation age, T, the landowner has three new decision variables. The first is planting density, d, which affects fuel loadings as the stand grows. A lower planting density is assumed to reduce fuel loadings and the damage caused by fire if the stand ignites.[3] The second decision variable is the level of intermediate fuel treatment, z, such as thinning (or pruning) trees and removing (or burning) surface fuels during a rota-

[1] Nonindustrial landowners hold over 70% of forested area in most eastern and midwestern states of the United States. They own similar land holdings in northern and central Europe.

[2] In his earlier, and seminal, paper on fire risk, Reed (1984) briefly considers fire prevention in the form of a discrete reduction in the average fire arrival rate that entails a fixed cost at each point in time.

[3] We cannot accurately model installation of fire breaks in our single-acre model since this activity effectively removes some land from production.

tion.[4] The variable z is best viewed as an index of intermediate (fuel) treatment effort. Intermediate treatment is also assumed to reduce the damage caused by fire. The third decision variable, s, is the stand age at which intermediate treatment is undertaken. We assume intermediate treatment is undertaken only once during a rotation, as is plausible for a private nonindustrial landowner.

Fire Risk and Timber Volume

Following Reed (1984), we assume the occurrence of fires is governed by a Poisson process with parameter λ. This parameter captures the probability that a stand ignites in a given year; it is also referred to as the average fire arrival rate. A stand can ignite from local events like lightning or arson, or from a wildfire front originating elsewhere.

We consider three possibilities regarding the behavior of λ: that λ is a constant, or that λ is either increasing or decreasing with stand age X, $\lambda = \lambda(X)$.[5] This specification assumes that the probability of stand ignition depends only on stand age and not on the level of fuel treatment. Fuel treatment reduces the severity of fire once it arrives (Moore, Smith, and Little 1955; Cumming 1964; Van Wagtendonk 1996; Brose and Wade 2002; Outcalt and Wade 2004).

The Poisson nature of fire arrivals together with the assumption that a new stand is planted if a fire occurs implies that the time between stand "destructions," by fire or by harvesting, is a random variable, X, with a mixed distribution. For $0 \leq X < T$, where T is the rotation age, X is distributed exponentially with cumulative distribution function $(1 - e^{-m(X)})$, where

$$m(X) \equiv \int_0^X \lambda(t)dt. \qquad [1]$$

Therefore, the probability that the stand is destroyed by fire before reaching the rotation age is

$$\Pr(X < T) = (1 - e^{-m(T)}). \qquad [2]$$

When $X = T$, the stand reaches the rotation age without being harmed by fire and is instead "destroyed" by harvesting. The probability of this event is

$$\Pr(X = T) = 1 - \Pr(X < T) = e^{-m(T)}. \qquad [3]$$

The term $m(X)$ represents the sum, from the time of stand establishment to the time of fire arrival, of the probability of fire arrival in each period. We refer to $m(X)$ as the "aggregate level of fire risk." Note that $m(X)$ is not bounded above by one since it is the sum of probabilities of independent events. Since $\frac{dm}{dX} = \lambda(X)$, the probability density function for X over the interval $0 \leq X < T$ is $\lambda(X)e^{-m(X)}$.

The net economic rents captured by the landowner depend on the timing of fire, as well as on the nature and timing of the landowner's decisions during a rotation. If a fire occurs, we assume that the landowner harvests any salvageable timber, and then replants and begins a new rotation. With the exception of Reed (1984), who considers random salvage independent of a landowner's choices, previous landowner decision models have assumed that no timber is salvaged in the event of fire.[6] This assumption is unlikely to be true when intermediate treatment is undertaken. Indeed, recommendations for intermediate treatment are typically justified in terms of reducing losses if a fire occurs (Mason et al. 2003; USDA 2003).

[4] Some forms of thinning, such as juvenile spacing, can raise fire risk by increasing the amount of flammable debris on the forest floor. Reed and Apaloo (1991) consider the implications of this increased risk for the desirability of juvenile spacing.

[5] When λ varies with stand age, the Poisson process is non-homogenous. Reed (1984, 1987) considers a non-homogenous fire arrival process. Aside from his work, a constant arrival rate has been assumed in other forest landowner decision models in which the Poisson distribution is used (Englin, Boxall, and Hauer 2000; Fina, Amacher, and Sullivan 2001).

[6] Stainback (2002) allows for salvage in the event of catastrophic events such as fire, but he does so in the context of the economics of carbon sequestration.

Forest timber volume per acre is assumed to be a concave function of stand age and planting density, $V(X, d)$, where $\frac{\partial V(.)}{\partial X} > 0$ and $\frac{\partial V(.)}{\partial d} > 0$.[7] In general, little is known about how intermediate fuel treatment affects forest volume. However, given that it comprises activities such as brush removal and prescribed burning, it is safe to assume that most intermediate fuel treatments would not affect yield at harvest time.[8] Thus, our model assumes that $V(.)$ does not depend on z.

We assume the fraction of timber volume salvaged in the event of fire is given by a concave function of planting density and intermediate treatment, $k(d,z)$.[9] Higher levels of intermediate treatment increase salvageable timber, $\frac{\partial k(.)}{\partial z} \geq 0$. On the other hand, higher planting densities potentially increase the severity of fire once it occurs, reducing salvageable timber, $\frac{\partial k(.)}{\partial d} \leq 0$. The latter assumption recognizes that higher densities entail greater fuel loadings over time as the stand naturally thins itself.

To be conservative, and to render comparable results derived in versions of our model with and without intermediate treatment, we assume that no timber is salvaged if a fire occurs before intermediate treatment is applied: $k = 0$ for $X < s$, where, as before, s is the treatment age. A positive fraction is salvaged only after treatment is applied: $k > 0$ for $X \geq s$. We also assume that salvage by the individual landowner does not affect market harvest price, which is equivalent to assuming that the landowner is a price taker.[10]

Nontimber Benefits

We follow the Hartman (1976) convention and define nontimber benefits valued by the landowner to be a function of: (1) the weight the landowner attaches to these benefits, and (2) calendar time for periods in which there is no harvesting. Also, see Jackson (1980). Although there is qualitative evidence that intermediate treatment can enhance some types of nontimber benefits (e.g., see Cushwa and Redd 1966; Haines, Busby, and Cleaves 2001), there is little, if any, quantitative information about this relationship. We therefore assume that nontimber benefits do not depend on z. (Allowing for such dependence would further strengthen our findings regarding the economic benefits of intermediate treatment.) Assuming no harvesting between time zero and time X, the present value of nontimber benefits, $B(t)$, is given by

$$\delta \int_0^X B(t) e^{-rt} dt, \quad [4]$$

where r is the rate of time preference and δ is the weight attached to nontimber benefits by the landowner. We will consider both the case where a landowner does not value nontimber benefits, $\delta = 0$, and the case where he values them fully, $\delta = 1$.

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[7] It is also possible that site quality affects volume at harvest. The results in this paper would then hold within each site quality class, because we could define an acre of uniform site quality within each class.

[8] For example, studies of the effects of prescribed burning on forest growth are inconclusive (see Smith 1986; Waldrop et al. 1987; Waldrop 1997; Marino et al. 2001). The use of some forms of forest thinning as a fuel reduction treatment is also relatively unstudied. However, other studies, unrelated to fire risk, that have considered thinning have also assumed that thinning does not affect forest volume growth for the residual stand at harvest time, or they have assumed that heavier forms of thinning can be modeled as a price effect at harvest time (Cawrse, Betters, and Kent 1984; Betters, Steinkamp, and Turner 1991).

[9] Timber salvage also depends on the level of fire suppression effort deployed when a fire occurs. This effort is likely to be undertaken by the government and not the landowner. An individual landowner would take government fire suppression effort as exogenous. Hence we do not make it explicit in $k(\cdot)$; it is subsumed in the parameters of the function.

[10] Some work has shown that salvage can be important to markets and harvest prices when fire occurs on a large scale (Prestemon and Holmes 2000). In our problem, with a price-taking individual landowner, salvage is too small to affect harvest prices, and the landowner would act accordingly.

Landowners' Problem

Using the model elements described above, we can identify the landowner's net economic rents from a rotation. These rents depend on whether or not a fire arrives during a rotation, and on whether it arrives before or after intermediate treatment is undertaken. Let Y_i denote the landowner's current net rent in state of the world i. There are three possible states to consider: (1) fire arriving before intermediate treatment is applied, $X < s$; (2) fire arriving after intermediate treatment is applied but before the rotation age, $s \leq X < T$; and (3) the rotation age being reached without a fire, $X = T$.

Let $C_1(d)$ and $C_2(d)$ denote the cost of planting on unburned and burned land, respectively. If a fire occurs before intermediate treatment is applied, the landowner does not salvage any of the timber stock but incurs the cost of re-establishing a new forest. Hence, in this state of the world, net rents at time X are given by

$$Y_1 = e^{rX}\delta\int_0^X B(t)e^{-rt}dt - C_2(d); \quad X < s. \qquad [5]$$

If a fire occurs after intermediate treatment has been applied but before the rotation age is reached, the landowner salvages a portion of the timber stock, k, incurs the cost of re-establishment, and incurs the compounded cost of intermediate treatment previously incurred at time s. Net rents at time X are therefore

$$Y_2 = pk(d,z)V(X,d) + e^{rX}\delta\int_0^X B(t)e^{-rt}dt - C_2(d) - C_3(z)e^{r(X-s)}; \quad s \leq X < T, \qquad [6]$$

where p is stumpage price, and $C_3(z)$ is the cost of intermediate treatment.

Finally, if the rotation age T is reached without a fire, the landowner harvests all the timber, and incurs the cost of establishing a new forest, as well as the compounded cost of intermediate treatment paid at time s. In this state of the world, net rents at time T are

$$Y_3 = pV(T,d) + e^{rT}\delta\int_0^T B(t)e^{-rt}dt - C_1(d) - C_3(z)e^{r(T-s)}; \quad X = T. \qquad [7]$$

Following the analysis of Reed (1984), the landowner's problem can be written as

$$Max_{d,z,s,T}\,\frac{E(e^{-rX}Y)}{(1 - E(e^{-rX}))}, \qquad [8]$$

where the expectation (E) is taken with respect to the underlying random variable X.[11] An expression for the expected value in the numerator of [8] can be obtained by making use of [5]–[7] and the probability distribution of X. This distribution can also be used to derive an expression for the expected value in the denominator of [8].[12] Doing so, [8] can be written as

$$\frac{\int_0^s \lambda(X)e^{-m(X)}e^{-rX}Y_1dX + \int_s^T \lambda(X)e^{-m(X)}e^{-rX}Y_2dX + e^{-m(T)}e^{-rT}Y_3}{r\int_0^T e^{-m(X)-rX}dX} \qquad [9]$$

The first-order conditions for this problem are complicated, and deriving comparative static results analytically is generally infeasible.[13] We therefore make use of simulations.

III. SIMULATION MODEL

Our primary interest in conducting simulations is to determine the effect of fire risk and traditional forest policy instruments on landowner behavior and welfare.

[11] For consistency with previous literature (Reed 1984, 1987; Englin, Boxall, and Hauer 2000), we assume there are no initial (time zero) planting costs.

[12] The denominator in [9] is obtained from that in [8] by making use of the probability distribution of X: $E[e^{-rX}] = \left\{\int_0^T e^{-rX}\cdot\lambda(X)e^{-m(X)}dX\right\} + e^{-rT}e^{-m(T)}$. Integrating the expression in braces by parts yields $E[e^{-rX}] = 1 - r\int_0^T e^{-m(X)-rX}dX$.

[13] Reed (1984) and Englin, Boxall, and Hauer (2000) found this to be true in much simpler models in which rotation age was the only choice variable.

Various versions of the model are simulated. We start with the basic Faustmann model in which the landowner chooses only rotation age and planting density; fire risk and intermediate treatment are omitted, as are nontimber benefits.[14]

We then simulate four extensions of the Faustmann model: (1) a "no prevention" model in which the landowner does not engage in intermediate treatment and does not choose planting density—it is fixed at the optimal level for the Faustmann model; in this model, no timber is salvaged in the event of a fire ($k = 0$); (2) a "partial prevention" model in which the landowner does attempt to mitigate losses by varying planting density, but here again no timber is salvaged in the event of a fire; (3) a "full prevention" model in which the landowner mitigates losses by varying planting density *and* engaging in intermediate treatment; in this model, some fraction of timber is salvaged if a fire occurs after intermediate treatment has been undertaken ($k > 0$ for $X \geq s$); and (4) a version of the "full prevention" model in which the landowner values nontimber benefits ($k > 0$ for $X \geq s$ and $\delta = 1$). In all the simulations, the landowner's rate of time preference is assumed to be 3% ($r = 0.03$). The program used for the simulations is MATLAB version 6.1, with optimal values determined using a search algorithm applied to the appropriately defined objective functions.[15]

The tree species we model in our simulations is loblolly pine (*pinus taeda*). This is a species for which there is substantial information in the literature. Functional forms and parameter values used in the simulation are presented in Table 1. The functions were chosen to capture properties suggested by both theory and available empirical evidence. For timber volume, planting costs, and nontimber benefits, existing literature provided adequate guidance on the choice of functional forms and parameter values. The loblolly pine volume function we employ has been used before to simulate the effects of forest taxes on optimal rotation ages and planting densities (e.g., Chang 1984; Amacher, Brazee, and Thompson 1991). Referring to Table 1, a base age 25 site index of 80 feet ($S = 80$) was used for the volume function, which gives volume in boardfeet.

Given the nature of available cost data, we assume planting costs on both burned and unburned land are linear in planting density. Per-acre costs of establishing trees on burned and unburned land are taken from Dubois et al. (2001). The cost of planting on burned land is lower than that of planting on unburned land because less soil preparation is required (Waldrop 1997; Dubois et al. 2001). Stumpage prices for pine sawtimber are taken from Timber Mart-South for the same time period (TMS 2001). For our baseline simulations, a price of \$80 per thousand boardfeet is used.

The nontimber benefit function in Table 1 is similar to ones used in previous studies of forest landowner behavior (e.g., Swallow, Parks, and Wear 1990; Swallow and Wear 1993; Swallow, Talukdar, and Wear 1997; Vincent and Boscolo 2000). The value of the parameter b_1 was chosen so that nontimber benefits peak at a stand age of 60 years. In the case of loblolly pine, this is consistent with benefits associated with red-cockaded woodpecker habitat (Rudolph and Conner 1991). The value of the scale parameter b_0 was chosen so that the maximum value of nontimber benefits is \$2.94 per acre per year. This figure is consistent with estimates in the literature for nontimber benefits that take the form of hunting leases on private forest land. The recent Southern Forest Assessment undertaken by the U.S. Forest Service for the South,

[14] The Faustmann model solution provides a check of the simulation's validity. The simulation results were also checked against the first-order-condition-based model solutions derived in Reed (1984). The value of the objective function in the Faustmann version of the model is consistent with Conservation Reserve Program signup data for the southern United States, where payments average \$30–\$300 per acre for enrolled land (FSA 2003, 9–12).

[15] Rather than deriving the very unwieldy first-order conditions and numerically solving them, we used Matlab's simplex-based, global search algorithm *fminsearch*. For each basic scenario, we verified that the solutions obtained were in fact global maxima by conducting sensitivity analyses and by plotting the objective function in each choice variable.

TABLE 1
FUNCTIONAL FORMS AND BASE VALUES OF PARAMETERS USED IN SIMULATIONS

Type	Function	Assumed Form
Timber volume	$V(X,d)$	$e^{\alpha - \frac{\beta_1}{dX} - \frac{\beta_2}{XS} - \frac{\beta_3}{X^2} - \frac{\beta_4}{S^2}}$ ($\beta_1 = 3418.11$, $\beta_2 = 740.82$, $\beta_3 = 34.01$, $\beta_4 = 1527.67$, $\alpha = 9.75$, $S = 80$)
Average fire arrival rate function	Constant average arrival rate, λ	$\frac{t_0}{t_b - t_a}$ ($t_a = 0$, $t_b = 50$)
	Rising average arrival rate, $\lambda(X)$ with $\lambda' > 0$	$2t_0\frac{(X - t_a)}{(t_b - t_a)(t_c - t_a)}$ ($t_a = 0$, $t_b = t_c = 50$)
	Falling average arrival rate, $\lambda(X)$ with $\lambda' < 0$	$2t_0\frac{(t_b - X)}{(t_b - t_a)(t_b - t_c)}$ ($t_a = t_c = 0$, $t_b = 50$)
Nontimber benefits	$B(t)$	$b_0 t e^{-b_1 t}$ ($b_0 = 8/60$, $b_1 = 1/60$)
Planting costs	$C_1(d)$, unburned land	$c_1 d$ ($c_1 = 0.42$)
	$C_2(d)$, burned land	$c_2 d$ ($c_2 = 0.30$)
Timber salvage	$k(d,z)$	$k_0(1 - e^{\frac{-k_1(k_2+z)}{d}})$ ($k_0 = 0.9936$, $k_1 = 2/3$, $k_2 = 1$)
Cost of intermediate fuel treatment	$C_3(z)$	$c_0 + c_3 z$ ($c_0 = 5$, $c_3 = 0.04$)

which is the relevant region for the tree species we model, employs a value of $3 per acre for hunting leases (Wear and Greis 2002).[16]

As noted earlier, the average fire arrival rate, λ, represents the probability that the stand ignites in a given year. There is no quantitative information on how λ varies with stand age, X. We refer to the relationship between λ and X as the "fire arrival path," and make the simple assumption that the arrival path is linear, that is, the probability of stand ignition varies linearly with stand age. This linear relationship is modeled using the density function for the triangular distribution (Freund and Walpole 1980, 243–44). The shape of this density function can be suitably altered by varying its parameters (see Table 1). Specifically, the parameters can be chosen so that λ is either constant (constant arrival rate), linearly increasing (rising arrival rate), or linearly decreasing (falling arrival rate) with stand age. As shown in Table 1, a scale parameter, t_0, is introduced in the fire arrival rate function to simulate shifts in the fire arrival path. Since t_0 enters the function multiplicatively, changes in t_0 are directly and linearly related to changes in the average arrival rate. Thus, a doubling of t_0 results in a doubling of the average fire arrival rate for each stand age. For the constant arrival case, an increase in t_0 results in a parallel shift up of the fire arrival path since the path has a zero slope. For the rising arrival rate case, the arrival path has a positive slope, and an increase in t_0 rotates the path up, making it steeper. The same is true for the falling arrival rate case, except that the arrival path has a negative slope. Given

[16] We also considered peak ages of 10 years and 100 years for nontimber benefits, while maintaining the maximum value of nontimber benefits at $2.94. These variations resulted in only minor changes in our simulation results.

the definition of aggregate fire risk $m(X)$, changes in t_0 directly and linearly affect this variable as well (see equation [1]).

The relationship between planting density, fuel treatment, and timber salvage, as represented by $k(d,z)$, is also not well known. However, there is strong evidence that a regular program of prescribed burning reduces tree mortality in southern pine stands that are struck by a severe wildfire (Moore, Smith, and Little 1955; Cumming 1964; Outcalt and Wade 2004). For example, following a severe wildfire in 1998 in Florida, the tree mortality rate averaged 89% in pine plantations where fuel treatments had not been used, which was more than twice the average mortality rate in stands where fuel treatments had been applied (Outcalt and Wade 2004). We proceed with a functional form for $k(d,z)$ that has plausible characteristics and produces reasonable values of the decision variables, expected rents, and treatment costs.[17] The functional form employed (see Table 1) is strictly concave in its arguments to reflect diminishing returns and is bounded by zero and one to represent a fraction of the volume of the stand. The function was calibrated to take values in the interval 0.6–0.9, when optimal levels of intermediate treatment are employed.

The available literature also offers little guidance on the cost function for intermediate treatment, $C_3(z)$. For simplicity, a linear specification is used: $C_3(z) \equiv c_0 + c_3 z$, with c_0 and c_3 chosen so that the value of $C_3(z)$ at optimal treatment levels is within the range of intermediate treatment costs reported in the literature. These range from \$11/acre for prescribed burning and \$27/acre for brush clearing to \$45/acre for precommercial thinning (Dubois et al 2001).[18] The bulk of these costs are variable in nature; only precommercial thinning incurs substantial fixed costs. Accordingly, the fixed cost parameter, c_0, was assigned a value of \$5 to reflect the typically modest fixed costs associated with intermediate treatment.

IV. BASELINE SIMULATION RESULTS

Table 2 presents the baseline simulation results for versions of our model that exclude intermediate treatment and nontimber benefits. Units of measurement are years for rotation age (T), and number of trees per acre for planting density (d). The entries in the expected rents column are in dollars per acre and capture the present value of maximum expected rents, that is, the value of the landowner's objective function when evaluated at the optimal values of the decision variables.

The first row in Table 2 presents results for the Faustmann version of our simulation model. The results obtained for this model are identical to those derived from the standard Faustmann formula evaluated at a planting density of 408 trees per acre. Subsequent rows in the table contain results for versions of the simulation model that incorporate fire risk. For each of the three fire arrival paths, the magnitude of the average fire arrival rate was varied in order to examine the effects of increased fire risk. This was accomplished using the scaling parameter, t_0, introduced in the function for $\lambda(X)$ (see Table 1).

No Prevention Model

The first three rows under the heading "no prevention" in Table 2 contain results for the scenario in which the fire arrival rate is assumed to be constant over time. The first of these rows ($t_0 = 1$) presents results when the average arrival rate takes on a value of 1/50 ($\lambda = t_0/50$), that is, a fire arrives on average every 50 years. The subsequent rows show the results for average arrival rates of 2/50 and 3/50. These arrival rates are similar to those used by Reed (1984)

[17] We conducted sensitivity analyses of our choice of parameter values for this function and the intermediate treatment cost function. With one exception, noted in the discussion of the results for the full prevention model, we found our results were not sensitive to these choices. The sensitivity analysis results are available from the authors upon request.

[18] The costs are for the coastal plain of the southeastern United States, a region in which loblolly pine is a dominant species. The thinning costs are for stands established on bare land, as is assumed in our model.

TABLE 2

Optimal Choices and Rents for Models without Intermediate Treatment

Model	t_0	$m(T^*)$	T^*	d^*	Expected Rents
Faustmann			23.2	408	301
No Prevention[a]					
Constant Arrival	1	0.42	21.2	408	152
	2	0.79	19.8	408	20
	3	1.12	18.7	408	−101
Rising Arrival	3.2	0.42	18.0	408	121
	8.4	0.79	15.3	408	−50
	14.7	1.12	13.8	408	−187
Falling Arrival	0.6	0.42	22.4	408	162
	1.17	0.79	21.6	408	35
	1.7	1.12	20.9	408	−77
Partial Prevention					
Constant Arrival	1	0.43	21.5	308	163
	2	0.84	20.9	228	62
	3	1.08	21.6	149	7
Rising Arrival	3.2	0.43	18.3	313	131
	7.8	0.84	16.4	221	10
	10.2	1.08	16.3	170	−26
Falling Arrival	0.61	0.43	22.8	305	171
	1.19	0.84	23.0	223	74
	1.5	1.08	23.7	182	34

[a] Planting density held fixed at the Faustman level of 408 trees per acre.

and Englin, Boxall, and Hauer (2000); the values they use range from 0.5/50 to 2.5/50.[19]

We can see from the table that the presence of fire risk lowers the rotation age relative to the Faustmann rotation age. The reduction becomes larger as the average fire arrival rate increases, and ranges from 2.0 to 4.5 years. These results mirror the simulation results obtained by Reed (1984, 1987) and by Englin, Boxall, and Hauer (2000). The last column in the table shows that expected rents fall sharply as the fire arrival rate rises. Expected rents are in fact negative when λ takes on a value of 3/50.

The third column in Table 2, labeled *m(T*)*, captures aggregate fire risk from time zero to the optimal rotation age for the case being considered (see (1)). Examining the first three entries in this column, notice that $m(T^*)$ increases with the scaling parameter t_0. It is important to note, however, that the observed changes in the value of $m(T^*)$ reflect both the increase in t_0 and the change in T^*. This explains why, for example, a doubling of t_0 from one to two does not result in a doubling of $m(T^*)$—the doubling of t_0 is partially offset by the resulting fall in T^*.

The next three rows under the heading "no prevention" contain results for the scenario in which the average fire arrival rate is rising with stand age. In order to be able to compare the results for this scenario with those for the constant arrival rate scenario,

[19] Precise information on arrival rates for specific areas of the country or specific tree species are not readily available. Coarse-scale spatial data developed by the Forest Service indicate that in much of the southern United States fires arrive on average every 0–35 years (Schmidt et al. 2002). Data for 37 counties in northern Florida, comprising a mix of forest types including southern pine, indicate the average annual risk of fire was 1% during the period 1981–2001. Some areas in this region may have higher than average risk because of their proximity to people, who are the primary source of ignition (Prestemon 2003).

the value of the scaling parameter t_0 was chosen so that the value of $m(T^*)$ was approximately the same as for the corresponding constant arrival rate scenario. Not choosing t_0 in this manner would imply that the aggregate level of fire risk over a rotation would differ for the two scenarios. This would make it difficult to attribute changes in the optimal values of the decision variables to changes in the shape of the arrival path alone; changes would also be due to differences in the aggregate level of fire risk. As can be seen from the table, for this rising arrival rate scenario, rotation ages also decline monotonically with t_0. However, the rotation ages are approximately 3–5 years smaller than for the constant arrival rate scenario. Expected rents are also smaller, and turn negative at a lower aggregate risk level.

The last three rows under the heading "no prevention" are for the falling arrival rate scenario. Following the procedure used for the rising arrival rate scenario, the value of the scaling parameter t_0 was chosen so that the value of $m(T^*)$ was the same as for the corresponding constant arrival rate scenario—allowing, once again, a fair comparison of the results for the two scenarios. Here again, rotation ages fall monotonically with t_0. However, they are approximately 1–2 years *larger* than for the constant arrival rate scenario, though still smaller than the Faustmann rotation age. Expected rents are also larger than they are for the constant arrival rate scenario. The observed increase in rotation ages is easily explained: a falling average arrival rate implies that the expected marginal cost of continuing a rotation falls over time, because fire risk is decreasing, thus inducing the landowner to choose a higher rotation age.

Partial Prevention Model

The next set of results in Table 2 is for the "partial prevention" model. Recall that in this model the landowner chooses planting density but does not undertake intermediate treatment. Consider, first, the results for the constant arrival rate scenario. Note that the values of t_0 used in this scenario are the same as in the "no prevention" model, but the aggregate risk levels differ slightly because of differences in rotation age. As can be seen, rotation ages are once again smaller than for the Faustmann model. More striking, though, is the decline in planting density: it falls by 25% to 60% relative to the optimal density in the Faustmann model. Two reasons can be offered for this decline. The first is the decrease in rotation age, which reduces the expected marginal benefit of higher forest stocking. The second is the absence of any possibility of salvage, which implies that higher planting densities result in lower expected returns if a fire occurs within a rotation.

Examining the rotation ages more closely, we can see that the rotation age no longer declines monotonically with t_0; instead, it falls and then rises as t_0 increases. Moreover, the variation in rotation ages is much smaller than in the "no prevention" model. By adding planting density as a decision variable, the landowner can engage in loss prevention by lowering planting densities instead of lowering rotation ages. The entries in the last column show that this substitution renders the landowner substantially better off. Now, expected rents are positive even at the highest arrival rate ($t_0 = 3$, $\lambda = 3/50$).

Turning to the results for the rising arrival rate scenario, we find less variation in rotation ages in this scenario as well. But unlike the case for the previous scenario, increases in t_0 consistently reduce the optimal rotation age. Planting densities, on the other hand, are similar to those for the constant arrival rate scenario, and continue to decline monotonically with increases in t_0. The same behavior is exhibited by expected rents, but these are substantially smaller than for the previous scenario, turning negative for the largest value of t_0. These results can be explained as follows. A rising arrival rate and no salvage in the event of fire imply that the expected marginal net benefit of waiting to harvest falls more rapidly as a stand ages than when the fire arrival rate is constant; this induces the landowner to choose a lower rotation age. For this species, a lower rotation age in this range also

TABLE 3

OPTIMAL CHOICES AND RENTS FOR FULL PREVENTION MODEL WITHOUT NONTIMBER BENEFITS

Model	t_0	$m(T^*)$	T^*	d^*	s^*	z^*	$k(d^*,z^*)$	$C_3(z^*)$	Expected Rents
Constant Arrival	1	0.49	24.7	300	9.9	498	0.67	24.9	173
	2	1.10	27.6	244	9.6	680	0.84	32.2	103
	3	1.83	30.5	200	9.9	673	0.89	31.9	44
Rising Arrival	2.2	0.49	23.7	322	10.3	669	0.75	31.8	189
	4.27	1.10	25.4	294	9.8	883	0.86	40.3	144
	6.45	1.83	26.6	274	9.5	932	0.89	42.3	103
Falling Arrival	0.65	0.49	25.2	294	9.7	428	0.62	22.1	170
	1.34	1.10	28.7	227	9.6	596	0.82	28.8	90
	2.06	1.83	33.2	169	10.3	550	0.88	27.0	22

implies lower volume at harvest time, thus reducing maximum expected rents. Planting densities remain similar as fire risk increases and rotation age falls, because there is some substitution between rotation age and planting density in terms of volume harvested.

The last three rows under the "partial prevention" heading show the results for the falling arrival rate scenario. We once again find that rotation age does not vary much with t_0. However, the rotation age now *rises* as t_0 increases. For the highest value of t_0, the rotation age is now larger than the Faustmann age. This is the opposite of what was observed in the rising arrival rate scenario. However, as was true for the latter scenario, planting density does not differ much relative to the constant arrival rate scenario, but expected rents are slightly higher. The difference in the behavior of rotation age in this scenario can be explained by noting that a falling arrival rate implies that fire risk decreases as the stand matures. As a result, the expected marginal net benefit of waiting to harvest may be increasing with stand age, or not decreasing as fast as in the rising arrival rate scenario.

Full Prevention Model

Table 3 presents results for the 'full prevention' model without nontimber benefits. The landowner now chooses the level of intermediate treatment and its timing, in addition to rotation age and planting density. The treatment ages (s) reported in the table are in years. The units of the intermediate treatment variable are arbitrary, since z represents an index of effort. The table also reports the fraction salvaged in the event of fire, $k(d^*,z^*)$, along with the costs of intermediate treatment, $C_3(z^*)$, in dollars.

As before, for the rising and falling arrival rate scenarios, the values of t_0 were chosen so that aggregate fire risk was the same as for the corresponding constant arrival rate scenario. Note that aggregate risk levels are now higher than in the "no prevention" and "partial prevention" models due to the higher rotation ages. Therefore, comparisons across models need to be made carefully.

The results for this model differ markedly from those for the previous models. Examining the rotation ages, we can see that in all three scenarios rotation age now rises monotonically with t_0. Furthermore, the rotation ages are consistently higher than for the previous models. For the largest values of t_0, rotation ages are up to ten years higher than for the Faustmann model.

With two exceptions, planting densities for the "full prevention" model are similar to those for the "partial prevention" model. The exceptions occur in the rising arrival rate scenario when fire arrival rates are high: planting densities are much higher in this case, despite the higher aggregate risk levels in this model. For all three scenarios, planting density still declines monotonically as t_0 increases. Since rotation age exhibits the opposite behavior (rising as t_0 increases), an inverse relationship is observed between rotation age and planting density.

Turning to the two new decision variables, we can see that the level of intermediate treatment effort increases and then drops slightly for the constant and falling arrival rate scenarios. For the rising arrival rate scenario, it always increases. Moreover, for this scenario, treatment levels are substantially higher. The costs of intermediate treatment range from about $22 to $42 per acre, with larger values observed for the two higher values of t_0.

The age at which treatment is undertaken does not vary much across the three scenarios, ranging from 9.6 to 10.3 years. This range corresponds quite closely to treatment ages recommended in practice for activities such as brush removal and prescribed burning (Wade and Lundsford 1990). This correspondence between our simulated treatment ages and actual treatment ages lends plausibility to our representation of intermediate treatment costs and timber salvage in the event of fire.

As can be seen from the table, the fraction of timber salvaged in the event of fire increases with t_0, but the fractions for the two larger values of t_0 are very similar. Examining the entries in the last column, and comparing them to those in Table 2, it is evident that undertaking intermediate treatment substantially improves landowner welfare. This is not surprising: a landowner who can undertake intermediate treatment is able to defend himself against fire risk. The resulting improvement in welfare is most easily seen in the constant arrival rate scenario, but it can also be seen in the other two scenarios when aggregate risk levels are similar. For instance, for the falling arrival rate scenario of the "partial prevention" model in Table 2, expected rents for an aggregate risk level of 0.84 ($t_0 = 1.19$) are $74 per acre; in the corresponding scenario of the "full prevention" model in Table 3, for a higher aggregate risk level of 1.10 ($t_0 = 1.34$), expected rents are $90 per acre.

A comparison of expected rents across the models also reveals, rather strikingly, that with no prevention or partial prevention, the landowner is better off with a falling fire arrival rate; whereas with full prevention, he is better off with a rising fire arrival rate. This finding can be explained as follows. Giving the landowner additional decision variables in the form of intermediate treatment and its timing can only improve the landowner's welfare. However, the expected benefit of having these additional decision variables is greatest with a rising arrival rate (as reflected in the larger values of z for this scenario). With a falling arrival rate, if the landowner undertakes intermediate treatment early in a rotation, when fire risk is higher, the present value of treatment costs is high. If, instead, treatment is undertaken late in the rotation, its expected benefit is limited due to the falling arrival rate. In contrast, with a rising arrival rate, undertaking treatment later in the rotation is desirable since the risk of fire is higher then. This differential in the benefit of intermediate treatment dominates the "natural" benefit of a falling arrival rate observed in the "no prevention" and "partial prevention" models.

The observed increase in rotation age in all three scenarios can be attributed to two factors. The first is the presence of intermediate treatment costs, which are incurred in each rotation unless a fire arrives before the treatment age. These costs push up the rotation age, because increasing the rotation age reduces the present value of the infinite series of treatment costs (this effect is analogous to the well-known effect of higher planting costs on the optimal rotation age). The second factor is the landowner's ability to use intermediate treatment to reduce the potentially larger expected losses associated with higher rotation ages (a higher rotation age invariably increases the probability that a fire will destroy the stand before harvest). In essence, intermediate treatment enables the landowner to reduce the expected marginal cost of extending a rotation. This is beneficial because a longer rotation offsets the effect of reduced planting densities on timber volume at harvest. Reduced planting densities continue to be desirable, despite intermediate treatment, because they increase salvage in the event of fire.

TABLE 4
OPTIMAL CHOICES AND RENTS FOR MODELS WITH NONTIMBER BENEFITS

Model	t_0	$m(T^*)$	T^*	d^*	s^*	z^*	$k(d^*, z^*)$	$C_3(z^*)$	Expected Rents
Hartman			23.9	407					338
Full Prevention									
Constant Arrival	1	0.52	25.8	295	10.7	533	0.70	26.3	210
	2	1.16	29.1	239	10.6	707	0.86	33.3	140
	3	1.96	32.7	192	11.4	690	0.90	32.6	81
Rising Arrival	2.15	0.52	24.6	319	10.7	706	0.77	33.3	225
	4.16	1.16	26.5	292	10.1	913	0.87	41.5	180
	6.32	1.96	27.9	273	9.9	957	0.90	43.3	138

The above results demonstrate the importance of incorporating intermediate treatment effort into fire risk models if landowner behavior and welfare is to be properly understood. This does not imply, however, that intermediate treatment is always desirable. Its desirability depends on its costs and its effectiveness in increasing timber salvage, as well as on the magnitude of fire risk. The values we employ for these parameters in the simulations described here are such that it is always optimal for the landowner to undertake intermediate treatment. We can show this is not true when the average fire arrival rate is low and the effectiveness of intermediate treatment is sufficiently low or its costs are sufficiently high. In such cases, expected rents are higher when the landowner does not undertake intermediate treatment (see footnote 17).

Nontimber Benefits

Table 4 presents simulation results for versions of our model in which the landowner values nontimber benefits. The first row in the table contains the results for a Hartman model. Comparing this row to the first row in Table 2, we see that nontimber benefits raise the optimal rotation age slightly.[20] This is consistent with the findings in Swallow, and Wear (1993) given that the stand age at which nontimber benefits peak (60 years) is larger than the Faustmann rotation age. Expected rents are now larger than before only because of the addition of nontimber benefits.

The rest of Table 4 presents results for the "full prevention" model with nontimber benefits included. For the sake of brevity, we do not consider the "no prevention" and "partial prevention" models; we also do not consider the falling arrival rate scenario. The constant and rising arrival rate scenarios are arguably more likely to be observed in practice. Note that the aggregate risk levels in Table 4 are quite similar to those in Table 3, facilitating comparison of the results for the two models. Such a comparison reveals that the addition of nontimber benefits does not alter the *direction* of the relationships between t_0 and the landowner's optimal choices; the relationships identified in Table 3 continue to hold when nontimber benefits are included.

As for the impact of nontimber benefits on the landowner's optimal choices, we see that the effect on rotation ages is identical to that observed in the Hartman model: the addition of nontimber benefits raises the rotation age for both scenarios. Planting densities and intermediate treatment levels exhibit only minor changes. Intermediate treatment is delayed in all cases, with a delay of up to 1.5 years observed in the constant arrival rate scenario.

[20] The changes in rotation age are small due to our conservative assumption about the magnitude of nontimber benefits (they are at most $2.94 per acre). We obtained bigger changes in rotation age when we allowed for larger nontimber benefits.

TABLE 5
Summary of Key Findings from Baseline Simulations

Model	Rotation Age (T)	Planting Density (d)	Intermediate Treatment (z)	Expected Rents
No Prevention	Falls with fire risk; smaller than Faustmann rotation age	N/A; fixed at Faustmann level	N/A	Highest in FAR scenario; fall sharply with fire risk; negative at high risk levels
Partial Prevention	Falls with fire risk only in RAR scenario; larger than Faustmann rotation age in FAR scenario	Falls with fire risk; lower than Faustmann level	N/A	Highest in FAR scenario; fall less sharply with fire risk; negative only in RAR scenario
Full Prevention	Rises with fire risk; larger than Faustmann rotation age	Falls with fire risk but slowly in CAR and RAR scenarios; lower than Faustmann level	Rises with fire risk only in RAR scenario, highest levels for this scenario	Highest in RAR scenario; fall much less sharply with fire risk; always positive
Full Prevention with Nontimber Benefits	Rises with fire risk; larger than Hartman rotation age	Falls slowly with fire risk in CAR and RAR scenarios; lower than Hartman level	As above	As above

Note: RAR = rising (average fire) arrival rate; FAR = falling (average fire) arrival rate; CAR = constant (average fire) arrival rate.

Turning to the last three columns in Table 4, we see that the fractions salvaged in the event of fire are very similar in magnitude to those in Table 3. The same is true for intermediate treatment costs. This is not surprising because planting densities and intermediate treatment levels are largely unchanged. The entries in the last column for expected rents continue to behave as we would expect—falling as t_0 rises. As was true when nontimber benefits were absent, the landowner is better off with a rising arrival rate.

We summarize the main findings of our baseline simulations in Table 5. Note that the table does not include a discussion of treatment ages, s, since these were found to vary little across our models.

V. POLICY SIMULATIONS

When fires occur in practice, governments devote considerable sums to putting them out. Landowners do not bear these costs, and therefore cannot be expected to make decisions that recognize the fire suppression costs incurred by governments. This creates an incentive for governments to implement policies that encourage landowners to undertake intermediate treatment, to the extent that such treatment reduces losses in the event of fire and may therefore reduce governments' fire suppression costs. Historically, numerous forms of government interventions aimed at modifying landowner planting behavior have been employed (Boyd and Hyde 1986), examples include cost sharing and reforestation tax credits expensed against harvest income. Similar policy instruments could be considered for intermediate treatment. For instance, the government could share the costs of undertaking intermediate treatment. In our model, this type of cost sharing would be captured by a reduction in $C_3(z)$. Alternatively, the landowner could receive an income tax exemption at harvest, effectively increasing the net price of timber. This

TABLE 6
EFFECTS OF 50% DECREASE IN INTERMEDIATE TREATMENT COSTS IN FULL PREVENTION MODEL WITH NONTIMBER BENEFITS

Model	t_0	ΔT^*	Δd^*	Δs^*	Δz^*	$\Delta k(d^*,z^*)$	$\Delta C_3(z^*)$	ΔExpected Rents
Constant Arrival	1	0.4	19.1	−1.9	345.4	0.14	−6.3	22.8
		1.4	*6.5*	*−17.6*	*64.8*	*20.6*	*−23.8*	*10.9*
	2	−0.2	28.0	−1.9	315.0	0.06	−10.3	26.5
		−0.5	*11.7*	*−17.9*	*44.5*	*7.1*	*−31.1*	*18.9*
	3	−0.6	31.9	−2.3	289.3	0.04	−10.5	23.9
		−1.8	*16.7*	*−19.8*	*41.9*	*4.0*	*−32.3*	*29.4*
Rising Arrival	2.15	0.9	24.2	−1.6	413.9	0.11	−8.4	30.0
		3.6	*7.6*	*−14.6*	*58.6*	*14.9*	*−25.1*	*13.3*
	4.16	0.9	35.0	−1.5	424.0	0.06	−12.3	37.8
		3.6	*12.0*	*−14.9*	*46.4*	*6.7*	*−29.6*	*21.1*
	6.32	1.5	39.3	−1.5	425.7	0.04	−13.1	41.0
		5.5	*14.4*	*−14.9*	*44.5*	*4.9*	*−30.3*	*29.8*

Note: Fixed cost of intermediate treatment reduced from 5 to 2.5 and marginal cost reduced from 0.04 to 0.02. Resulting changes in values of variables from the baseline values in Table 4 are presented, with percentage changes in italics.

would increase the value function $pV(X,d)$ in equations. [6] and [7]. We briefly consider how these policy interventions affect landowner behavior in the "full prevention" model with nontimber benefits (our most general model). Cost sharing of intermediate treatment is examined in Table 6, while an increase in net price, through a tax exemption, is examined in Table 7. We restrict attention to the more plausible constant and rising arrival rate scenarios. Each table reports changes in the values of variables from the baseline values in Table 4, with percent changes presented in italics. It is worth noting that these results are based on an infinite-horizon model; therefore they are best interpreted as capturing the effect of a permanent introduction of each policy instrument.

The cost sharing results in Table 6 assume that the government covers 50% of the total costs of intermediate treatment. Examining the table, it is clear that cost sharing has only modest impacts on rotation age and planting density. In nearly all cases, the change in rotation age is under one year. Planting density increases in all cases, by 6%–17%. As one would expect, the most significant impact of the subsidy is on the level of intermediate treatment, which rises by 40%–65%. The stand age at which this treatment is undertaken is reduced by roughly two years.

The large increases in intermediate treatment levels, together with the modest increases in planting density, result in larger fractions salvaged in the event of fire. These fractions increase in absolute value by 0.04–0.14, with the largest increases observed for the lowest values of t_0. The costs of intermediate treatment borne by the landowner are reduced by the subsidy even though intermediate treatment levels are higher. The reductions range from about \$6 to \$13 per acre, with larger reductions observed in the rising arrival rate scenario. As the last column in the table reveals, expected rents rise by approximately 10%–30%, with the largest absolute, and relative, increases observed when the fire arrival rate is rising and large in value.

Together, these results suggest that cost sharing can be an effective means of encouraging landowners to undertake intermediate treatment effort without substantially distorting their other choices. It can be shown that much of the effect of cost sharing is due to the reduction in the marginal cost of intermediate treatment. The reduction in fixed cost only has a minor effect on the landowner's behavior and welfare.

TABLE 7

Effects of 25% Increase in Stumpage Price in Full Prevention Model with Nontimber Benefits

Model	t_0	ΔT^*	Δd^*	Δs^*	Δz^*	$\Delta k(d^*,z^*)$	$\Delta C_3(z^*)$	ΔExpected Rents
Constant Arrival	1	−2.2	55.0	−1.2	87.9	−0.01	3.5	92.6
		−8.4	*18.6*	*−11.5*	*16.5*	*−1.0*	*13.4*	*44.1*
	2	−2.9	52.4	−1.3	140.1	0.00	5.6	75.7
		−10.0	*21.9*	*−12.7*	*19.8*	*−0.6*	*16.8*	*54.0*
	3	−4.0	53.8	−1.8	172.4	−0.01	6.9	59.8
		−12.1	*28.1*	*−16.3*	*25.0*	*−0.6*	*21.2*	*73.7*
Rising Arrival	2.15	−2.0	56.9	−0.9	80.0	−0.02	3.2	99.8
		−8.3	*17.8*	*−8.6*	*11.3*	*−2.5*	*9.6*	*44.4*
	4.16	−2.4	54.0	−0.9	141.2	−0.01	5.6	91.2
		−8.9	*18.5*	*−9.0*	*15.5*	*−0.8*	*13.6*	*50.8*
	6.32	−2.7	53.0	−0.9	180.8	0.00	7.2	84.0
		−9.5	*19.4*	*−8.9*	*18.9*	*−0.1*	*16.7*	*61.0*

Note: Stumpage price increased from $80 to $100 per thousand board feet. Resulting changes in values of variables from the baseline values in Table 4 are presented, with percentage changes in italics.

The results in Table 7 for a net price increase of 25% exhibit a rather different pattern. The price increase induces larger changes in rotation age and planting density: rotation age falls by two to four years, while planting density rises by 18%–28%. The larger relative (but smaller absolute) changes in planting density are observed in the constant arrival rate scenario at high average arrival rates.

The higher planting densities induce an increase in intermediate treatment, the increases range from about 11%–25%, with larger relative increases observed in the constant arrival rate scenario; in absolute terms, the increases are approximately equal for the two scenarios. The stand age at which intermediate treatment is undertaken falls by approximately one to two years.

Given the form of the salvage function, the roughly equal relative increases in planting density and intermediate treatment imply that fraction salvaged is virtually unchanged. The costs of intermediate treatment go up by about $3–$7 per acre given the higher levels of treatment. Expected rents go up substantially as a result of the 25% price increase, rising by 44%–74%.

The above results suggest that a tax exemption is not a particularly desirable means of inducing more intermediate treatment. It results in relatively small increases in treatment, while altering rotation age and planting density choices to a fair degree.

VI. CONCLUSIONS

Our simulations reveal that the effects of fire risk on landowner behavior and welfare critically depend on: (1) the landowner's ability to mitigate losses, and (2) the relationship between fire arrival rates and stand age. If we eliminate planting density and intermediate treatment as decision variables, leaving the landowner to choose only rotation age (our "no prevention" model), we obtain results that are qualitatively identical to those in the existing literature. Specifically, we find that the optimal rotation age is smaller than in a standard Faustmann model, with the optimal rotation age declining as fire risk increases. The largest reductions in rotation age are observed when the average fire arrival rate rises with stand age, and the smallest when it falls.

These reductions in rotation age do not necessarily occur when we consider a modest extension of the "no prevention" model and allow the landowner to choose planting density (our "partial prevention" model). The effect of fire risk on the optimal rotation age then depends on the relationship between the average fire arrival rate and stand age. We find that the rotation age declines monotonically with fire risk only if the fire arrival rate rises with stand age. If the arrival rate falls with stand age, the rotation age rises as fire risk increases, rising above the Faustmann rotation age. With a constant arrival rate, the rotation age first falls and then rises. Planting densities in this model are substantially lower than in a Faustmann model. Moreover, planting density consistently falls as fire risk increases. The landowner's ability to vary planting density results in higher rents earned, especially when the average fire arrival rate is high.

Most striking are the results for our "full prevention" model, in which the landowner chooses the level and timing of intermediate treatment along with planting density and rotation age. In this model, rotation ages are consistently larger than the Faustmann rotation age and invariably rise as fire risk increases. Planting densities continue to be much smaller than in the Faustmann model, declining as fire risk increases. The level of intermediate treatment undertaken depends on the relationship between arrival rates and stand age, with the highest levels observed when the arrival rate is rising and the lowest when it is falling. The timing of this treatment varies little across the scenarios, ranging from 9.5 to 10.3 years.

We use our "full prevention" model with nontimber benefits to examine the effects of two plausible policies for inducing landowners to undertake higher levels of intermediate treatment: cost-sharing of 50% of intermediate treatment costs and a tax exemption that raises net stumpage price by 25%. At the subsidy level considered, we find cost-sharing to be an effective means of inducing a landowner to undertake higher levels of intermediate treatment. It achieves this without markedly distorting the landowner's other choices. A tax exemption appears to be less desirable: though it induces increases in intermediate treatment, it also results in much larger changes in the landowner's other choices.

Collectively, our results indicate that the optimal behavior of a landowner in the presence of fire risk is considerably more complex than suggested by the existing literature. This complexity implies that government policies intended to improve landowners' responses to fire risk need to be designed, and targeted, with considerable care. A simple prescription that might have been derived from the existing literature is for landowners to reduce rotation ages in the face of fire risk, with the reduction in rotation age increasing with fire risk. Our results suggest, however, that such a prescription is valid only if landowners do not undertake any intermediate treatment. And even in this case, it is valid only if fire risk rises with stand age. If landowners do undertake intermediate treatment, our results indicate that rotation ages should actually be increased, with the magnitude of the increase rising with fire risk.

Our results also indicate that the greatest gains from intermediate treatment, in terms of landowner welfare, are obtained in settings where fire risk is rising with stand age. When fire risk is constant or falling, large gains are observed only when fire risk is high. In these scenarios, if fire risk is low, intermediate treatment may not be desirable, depending on its costs and efficacy. These results imply that government efforts to encourage use of intermediate treatment need to be targeted carefully, focusing on forestland where fire risk is likely to be increasing with stand age or where fire risk is likely to be high.

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