Reducing Social Losses from Forest Fires

Gregory S. Amacher, Arun S. Malik, and Robert G. Haight

ABSTRACT. *We evaluate two financial incentives to encourage nonindustrial forest landowners to undertake activities that mitigate fire losses: sharing of fire suppression costs by the landowner and sharing of fuel reduction costs by the government. First and second best outcomes are identified and compared to assess the effectiveness of these incentives in reducing social losses and fire suppression costs, under various assumptions about landowner behavior and information. We find that while cost sharing of fire suppression by the landowner invariably reduces social losses, this is not always true for government cost sharing of landowner fuel reduction. However, cost sharing of fuel reduction can yield larger reductions in social losses when fire risk is high. Both policies tend to induce larger reductions in both social losses and fire suppression costs when landowners engage in fuel reduction. We find that improving a landowner's information about fire risk and fuel reduction can yield substantial reductions in social losses.* (JEL Q23, Q54)

I. INTRODUCTION

Forest fires often arise from forces beyond the control of landowners, such as lightning strikes or fire fronts originating elsewhere. Nevertheless, the substantial recent losses from forest fires in the United States and in Europe have been blamed, in part, on landowners who ignore or are not aware of the importance of fuel reduction in limiting fire damage (FAO 2003; SAF 2000, 2002; *The Economist* 2003). In the United States alone, financial losses due to recent fires have reached billions of dollars per year. In 2003, the government spent approximately 2.7 billion dollars on suppression activities in the fire-prone Southwestern part of the country alone (*Salt Lake Tribune* 2004).

Fire losses to landowners and suppression costs incurred by the government could be reduced considerably if landowners were to employ higher levels of fuel reduction in their forests. Fuel reduction includes activities such as prescribed burning and some forms of thinning and pruning. It is widely accepted among fire experts that fuel reduction protects stands from damage in the event of fire, since it reduces the fuel loadings present in a stand. However, fuel reduction is costly, and this invariably means that the incentive for private landowners to engage in fuel reduction may not coincide with the government's desire for them to do so. Governments may be spending more on fire suppression as a result.[1]

These observations raise the question of whether governments should employ financial incentives to encourage landowners to undertake fuel reduction. Doing so could

Land Economics • August 2006 • 82 (3): 367–383
ISSN 0023-7639; E-ISSN 1543-8325

The authors are, respectively, professor, College of Natural Resources, Virginia Polytechnic Institute and State University, associate professor, Department of Economics, George Washington University, and research forester, USDA Forest Service, Northern Research Station, St. Paul, Minnesota. The authors would like to thank the U.S. Forest Service, North Central Research Station, for financial support, Christian Crowley, Melinda Vokoun, and Amy Osorio for research assistance, and two anonymous reviewers and seminar participants at George Washington University for helpful comments. All remaining errors are our own.

[1] This type of problem arises in many other natural hazard reduction settings, such as coastal zone damage. Coastal zone landowners can make decisions that affect wetland quality and condition, such as leaving buffer strips. The size and condition of these natural buffers are important determinants of protection from flooding associated with severe storms. The government shares in some cost of restoration after severe storms, and this cost depends on decisions landowners have previously made regarding buffers. Absent any regulations, coastal zone owners will not make management decisions consistent with public costs of restoration.

reduce the social losses associated with forest fires.[2] One possibility is for the government to compensate landowners for fuel reduction (Nelson 2000). Another possibility is to have landowners share in the cost of fire suppression, thereby increasing their incentive to undertake fuel reduction. Governments have used financial incentives to encourage other types of forestry activities; a common example is cost sharing of tree planting activities.[3]

Our objective in this paper is to evaluate alternative financial incentives for encouraging fuel reduction by nonindustrial private forest landowners. The focus on nonindustrial landowners is important, as these landowners hold most of the forest land susceptible to fire risk in the United States. We examine two types of financial incentives—both cost-sharing policies. The first is a traditional policy under which the government pays a share of the landowner's costs of fuel reduction; the second is a non-traditional policy under which the landowner pays a share of the government's fire suppression costs if a fire occurs. We examine the effectiveness of these policies in reducing social losses, as well as fire suppression costs, in various scenarios. Among other things, our simulation results illustrate that the existence of fuel reduction cost sharing does not ensure a landowner will engage in fuel reduction.[4]

An important factor when choosing and targeting policies is the information held by landowners when making decisions. For example, nonindustrial landowners are unlikely to have perfect information about the probability of fire occurrence. A landowner who is poorly informed is likely to make erroneous planting and fuel reduction decisions. These mistakes could lead to larger losses and higher government fire suppression costs in the event of fire (SAF 2000, 2002). We therefore consider how information held by a landowner influences the effectiveness of the cost-sharing policies.

In addition to considering the effects of imperfect information about fire risk, we consider the possibility of a landowner who simply does not engage in fuel reduction. This is not uncommon among nonindustrial landowners (SAF 2000, 2002), and could be due to high idiosyncratic costs of undertaking fuel reduction (as might be true for absentee landowners), or the mistaken belief that fuel reduction has no effect on fire losses. The latter can be thought of as an extreme case of imperfect information.

The basic model used for our analysis is the repeating rotations framework of landowner decision making under fire risk employed by Reed (1984), Englin, Boxall, and Hauer (2000), and Amacher, Malik, and Haight (2005). Reed presented the first infinite rotations model of landowner behavior under fire risk. Englin, Boxall, and Hauer (2000) extended their model to include nontimber benefits, and Amacher, Malik, and Haight (2005) introduced fuel reduction decisions. Our approach is closely related to that in Amacher, Malik, and Haight (2005), accordingly, in this paper we only elaborate on our extensions of their model.

We extend Amacher, Malik, and Haight's model in three ways to evaluate the cost-sharing policies described above. First, we explicitly introduce a government that chooses the level of fire suppression effort. This allows us to characterize first-best and second-best solutions, and to identify social losses resulting from the divergence between landowner and government incentives.[5]

[2] As we make clear formally later, social loss in this article refers to the decrease in maximum rents to the landowner, net of fire suppression costs, when the landowner makes decisions without regard to the government's costs of suppression, versus the case where the landowner internalizes these costs.

[3] See Amacher, Conway, and Sullivan (2003) and Boyd and Hyde (1986) for discussions of these programs.

[4] Landowner non-participation has been noted for other forestry cost sharing programs, such as tree planting (Boyd and Hyde 1986).

[5] Amacher, Malik, and Haight (2005) examine only the second-best solution for our model here, taking government fire suppression effort as exogenous. They do not characterize the socially optimal mix of fuel

Unlike other work in the forest economics literature dealing with uncertainty, our model is structured as a Stackelberg game played between the landowner and government. Second, using a simulation, we compare the ability of the two types of cost-sharing policies to reduce social losses and fire suppression costs. Third, we show how differences in the information available to a landowner influence the effectiveness of the cost-sharing policies. Unlike Amacher, Malik, and Haight (2005), we omit nontimber benefits in order to simplify our simulations. Amacher, Malik, and Haight found nontimber benefits to have only a modest effect on landowner choices.[6]

The rest of the paper proceeds as follows. First, we present our model, making explicit the divergence in incentives between the landowner and government with regard to fuel reduction. Second, we present a simulation of the two cost-sharing policies under various assumptions about the information held by the landowner. Third, we discuss the policy implications of our findings, and, finally, we offer some concluding remarks.

II. FIRE ARRIVAL

As in Amacher, Malik, and Haight (2005), our analysis relies on a specific assumption about fire arrival (occurrence) and the resulting losses suffered by a forest landowner should fire arrive before the rotation age is reached. Specifically, we assume that fuel reduction limits stand damage once fire arrives but does not affect the probability that a stand ignites. Most fires in fact arrive on an individual landowner's land regardless of whether fuel reduction is undertaken or not. Consider a lightning strike on a specific tree, or a fire arriving on the landowner's forest through flying embers or root systems from a burning adjacent area.

However, it is well known that fuels affect the severity of damage once a stand ignites. A recent survey concluded there is evidence that preventative burning of fuels (an important fuel reduction activity) can play an important role in reducing stand damage once fire arrives, but its effect on overall fire risk is not conclusive (Fernandes and Botelho 2004). The same study suggests that there is not enough evidence to claim that burning has any significant effect on the probability of fire arriving in a stand. Further, Graham, McCaffrey, and Jain (2004) review the general fuel reduction literature, arguing there is enough evidence to conclude that fuel reduction and planting density choices can reduce the likelihood of a "benign" (ground) fire developing into a severe damaging (crown) fire, because fuel deposition and structure determines fire behavior, such as temperature and flame length, once the stand ignites. Our assumption is also consistent with research comparing fire ignition and damage factors (Wade and Lundsford 1990), and it is the basis of private fire insurance on forest properties, according to a recent U.S. Forest Service report (USFS 2003).[7]

To model fire arrival, we follow the existing literature (Reed 1984, 1987; Englin, Boxall, and Hauer 2000; Amacher, Malik, and Haight 2005) and assume that fires occur randomly over time according to a Poisson process with parameter λ. This parameter represents the average fire arrival rate, that is, it is the probability that

reduction and fire suppression, nor do they evaluate policies for reducing social losses.

[6] The inclusion of nontimber benefits can result in non-concavities in the objective function, making it more difficult to identify global maxima given the complexity of our simulation. We found that the usual approach of modeling nontimber benefits as a function of stand age but not stand density (e.g., Swallow, Parks, and Wear 2003; Englin, Boxall, and Hauer 2000; and Amacher, Malik, and Haight 2005) generated unrealistic results in a few scenarios. Specifically, at high fire risk levels, optimal solutions occasionally called for not planting any trees yet reaping nontimber benefits.

[7] This assumption is not that important to the simulation results. If in fact fuel reduction does reduce fire arrival probabilities, then the suppression costs avoided by the government due to landowner fuel reduction would be even greater, which implies that social losses associated with landowners ignoring the effect of fuel reduction on suppression would be larger.

fire occurs in any given time period. A Poisson arrival process can be interpreted as one where the forest stand can ignite due to local events such as weather (lightning), arson, or a wildfire arriving as a "fire front" from outside a landowner's stand. The fire arrival rate is constant over the life of a stand.

With the Poisson probability distribution, the time between fire arrivals is an exponential random variable, X, having a cumulative distribution function $(1 - e^{-\lambda X})$. The probability density function for X is then $\lambda e^{-\lambda X}$. This implies that, given any rotation age T, the probability that a fire arrives before the end of a rotation is Pr $(X < T) = (1 - e^{-\lambda T})$. The probability the stand grows to the rotation age without a fire occurring is Pr $(X = T) = e^{-\lambda T}$.

III. GOVERNMENT'S PROBLEM

The interaction between the landowner and the government is captured by an infinitely repeated Stackelberg game. The landowner moves first, at the beginning of each rotation, by choosing the rotation age (T), planting density (d), level of fuel reduction (z), and the stand age at which fuel reduction is undertaken (s). The landowner makes these choices with knowledge of how the government will respond with fire suppression effort, denoted by g, should fire arrive before the end of a rotation.

When a fire arrives, the government chooses fire suppression effort, taking the landowner's decisions as given. The government maximizes net social benefits at the time of fire. The cost of fire suppression incurred by the government is given by $h(g)$, which is an increasing function of g.[8] Since we assume, consistent with the previous literature (Reed 1984; Englin, Boxall, and Hauer 2000; and Amacher, Malik, and Haight 2005), that the landowner plants the stand and begins a new rotation after a fire, the government's problem is simply,

$$Max_{g|\Gamma}\ k(z,d,g)pV(X,d) - h(g),\ \forall X \geq s, \qquad [1]$$

where $k(z,d,g)$ is a salvage (recovery) function for the landowner, p is the timber price taken exogenously by the landowner and government, $V(X,d)$ is the timber volume of the stand at the time of fire, s is the time the landowner undertakes fuel reduction (see below), and Γ denotes the information set available to the government when making decisions. For $X < s$, that is, arrival of fire before fuel reduction is taken, we would have [1] with $k(0, d, g)$ in place of $k(z,d,g)$.

Given the fact that a fire need not destroy the entire stand, the salvage function represents the proportion of the stand that can be harvested after a fire. Fuel reduction increases the proportion of salvageable timber, $\frac{\partial k(.)}{\partial z} \geq 0$, but there is, plausibly, some salvage even when no fuel reduction is undertaken.[9] Planting at higher densities could possibly increase fire severity and reduce salvageable timber, so we assume $\frac{\partial k(.)}{\partial d} \leq 0$. Fire suppression effort expended by the government increases salvageable timber, $\frac{\partial k(.)}{\partial g} \geq 0$. To reflect diminishing returns, $k(.)$ is a concave function of fuel reduction and government fire suppression effort, and a convex function of planting density.

The cross-partial derivative of $k(.)$ is assumed to be negative so that g and z are imperfect substitutes in the salvage func-

[8] There may be economies of scale associated with fire suppression if one were to consider $h(g)$ over a large area consisting of multiple landowners. This would not alter the basic nature of the problem or results here. Returns to scale captured by a government but not the landowner would lessen the effect of the externality discussed below, but the inefficiencies we uncover from the landowner ignoring the cost of suppression when making decisions would remain.

[9] Without this assumption, the government's problem in [1] would imply that it would never engage in fire suppression if the landowner had not undertaken fuel reduction prior to the fire arriving. This is hardly reasonable.

tion. This implies that the government will engage in less suppression on land on which greater fuel reduction has been undertaken. This assumption is plausible for a range of suppression and fuel reduction levels, given recent calls to encourage landowners to undertake fuel reduction as a means of reducing the government's expenditures on fire suppression (Nelson 2000).

The concave timber volume function in [1] depends positively on both rotation age and planting density, $\frac{\partial V(.)}{\partial X} > 0$ and $\frac{\partial V(.)}{\partial d} > 0$. Little is known about whether forest volume depends on fuel reduction. Given that fuel reduction encompasses activities such as brush removal and burning of surface fuels, a safe assumption for our purposes is that it does *not* affect forest stock at harvest time. In fact, any link between prescribed burning of surface fuels and yield has been deemed inconclusive at best (Waldrop et al. 1987; Waldrop 1997). We therefore assume that $V(.)$ does not depend on z.

As noted above, the government does not choose the level of fire suppression effort (g) when the landowner makes his decisions. Choosing suppression effort at this point would result in a value of g that is suboptimal given that fire occurrence is random. More precisely, the government's choice of fire suppression effort would not be time consistent if it were made at the same time that the landowner chooses T, z, d, and s. Thus, [1] is solved each time a fire arrives in any rotation to determine the value of g that maximizes timber salvage net of suppression costs, conditional on the decisions made by the landowner. The presence of the costs of fire suppression in [1] and its absence from the landowner's problem, described below, is the reason for the divergence in incentives to undertake fuel reduction.[10]

The first order condition for the problem in [1] is straightforward and can be solved to obtain a reaction function that describes how the government's choice of fire suppression effort depends on the landowner's decisions and stand age at which fire occurs. Recalling that Γ denotes the information set available to the government, which we assume is accurate, the reaction function can be represented as: $\hat{g}_\Gamma = G(z,d,s,X|\Gamma)$. Given the assumption that z and g are imperfect substitutes in the "production" of salvageable timber, the level of suppression effort chosen by the government is a decreasing function of the level of fuel reduction (if any) undertaken by the landowner. Moreover, given the assumption that timber volume is an increasing function of stand age and planting density, the government's suppression effort is also increasing in these two variables. Obviously, suppression effort is set equal to zero if the landowner completes a rotation without a fire arriving, $X = T$.

IV. LANDOWNER'S PROBLEM

The landowner moves first and makes his forest management decisions conditional on the government's reaction function and on information he has about the magnitude of the fire arrival rate. Denote the landowner's information set by Δ. In making his decisions, although the landowner recognizes the government's reaction function, he evaluates it using his potentially inaccurate information set. The government's reaction function as perceived by the landowner is therefore written $\hat{g}_\Delta = G(z,d,s,X|\Delta)$. The landowner solves the following infinite rotations problem,[11]

$$Max_{d,z,s,T|\Delta} R(d,z,s,T|\Delta) \equiv \frac{E(e^{-rX}Y^{sb})}{(1 - E(e^{-rX}))} - c_I(d), \quad [2]$$

[10] In some cases, the government may allow landowners to deduct a percentage of fire losses from their income tax payments for that year. This would further diminish the incentives for a landowner to undertake fuel reduction, and therefore the magnitude of the externality inherent in the landowner ignoring the government's fire suppression costs would increase.

[11] As [2] shows, the government's problem above is embedded into each rotation of the landowner's infinite rotations problem. In both the first- and second-best

where the "*sb*" superscript denotes this as the second best case, r is the discount rate, and $c_1(d)$ is the planting cost incurred at the beginning of the first rotation (planting costs for subsequent rotations are included in Y^{sb}). Note that this differs slightly from Amacher, Malik, and Haight (2005), who omit the initial stand's planting costs (captured by the last term in [2]).

In [2], Y^{sb} is a random variable representing current value of net benefits to the landowner in each period. Y^{sb} can take on three possible forms depending on the timing of fire arrival and fuel reduction. First, if a fire arrives before fuel reduction is undertaken, $X < s$, then the landowner salvages a portion, $k(.)$, of the forest stock, even though he does not engage in fuel reduction ($z = 0$), and incurs a cost of establishing a new forest for the next rotation,

$$Y_1^{sb} = pk(0,d,\hat{g}_\Delta)V(X,d) - c_2(d) \text{ if } X < s, \quad [3]$$

where $c_2(d)$ is the cost of planting on burned land.

When fire arrives after fuel reduction is undertaken but before the rotation age is reached, $s \leq X < T$, the landowner salvages a portion of the forest stock and incurs the compounded cost of fuel reduction previously incurred at time s, in addition to the cost of establishing a new forest,

$$Y_2^{sb} = pk(z,d,\hat{g}_\Delta)V(X,d) - c_2(d) - c(z)e^{r(X-s)} \text{ if } s \leq X < T, \quad [44]$$

where $c(z)$ is the cost of fuel reduction incurred at time s.

Finally, when the rotation age T is reached without a fire, the landowner harvests all existing forest stock, incurs the cost of establishing a new forest, and incurs the compounded cost of fuel reduction paid at time s,

$$Y_3^{sb} = pV(T,d) - c_1(d) - c(z)e^{r(T-s)} \text{ if } X = T, \quad [5]$$

where, as before, $c_1(d)$ is the cost of planting on unburned land. The expressions in [3] and [4] reflect the assumption, stated earlier, that a new rotation is started after a fire. Therefore, X, the time between fire arrivals, also represents stand age and is distinct from the rotation age, T.

Let $\{d^{sb}, z^{sb}, s^{sb}, T^{sb}\}$ denote the solution to the landowner's problem. The present value of the landowner's *anticipated* expected rents at this second-best outcome are given by $R^{sb}(d^{sb}, z^{sb}, s^{sb}, T^{sb}|\Delta)$, while his *actual* expected rents are given by $R^{sb}(d^{sb}, z^{sb}, s^{sb}, T^{sb}|\Gamma)$. The government's actual choice of suppression effort at the second best outcome is given by $G(z^{sb}, d^{sb}, s^{sb}, X|\Gamma)$.

V. FIRST-BEST PROBLEM

In the decision problem specified in [2], the landowner ignores the government's costs of fire suppression, $h(g)$—they do not appear in the landowner's objective function.[12] The first-best, or socially optimal, choices of the landowner's decision variables can be derived by modifying [2] to account for the government's cost of suppression and by removing any imperfect information about the fire arrival rate. The government's costs of fire suppression are easily accounted for by replacing Y_1^{sb} with $Y_1^{fb} = pk(0,d,\hat{g}_\Gamma)V(X,d) - c_2(d) - h(\hat{g}_\Gamma)$, and Y_2^{sb} with $Y_2^{fb} = pk(z,d,\hat{g}_\Gamma)V(X,d) - c_2(d) - c(z)e^{r(X-s)} - h(\hat{g}_\Gamma)$, where "*fb*" denotes the first-best case. Note that $Y_3^{fb} = Y_3^{sb}$, because in this case fire does not arrive before the rotation age is reached

cases, the government chooses the level of fire suppression only when a fire occurs. This happens only once during any given rotation given that after each fire the landowner salvages timber and begins a new rotation. Embedding the reaction function into the landowner's problem captures the fact that, each time a fire occurs, the government will choose the level of fire suppression that solves the problem in [1], and this will be conditional on choices the landowner has made prior to the fire. The timber salvaged by the landowner is also determined in part by the level of fire suppression effort chosen by the government for the fire that occurred.

[12] The costs of fire suppression still indirectly influence the landowner's welfare, however, since they determine the level of fire suppression undertaken by the government.

(see equation [5]), so there is no fire suppression. The landowner's potentially imperfect information is eliminated by replacing the information set Δ of the second best case with the government's accurate information set Γ.

Let $NR(d,z,s,T|\Gamma)$ denote the modified objective function obtained by using Y_1^{fb}, Y_2^{fb}, and Y_3^{fb} in [2]; $NR(.)$ captures the present value of expected rents net of fire suppression costs given perfect information about the fire arrival rate. These "net rents" are our measure of social welfare. The first-best solution, denoted $\{d^{fb}, z^{fb}, s^{fb}, T^{fb}\}$, is obtained by solving this modified problem using the same approach as that used to derive the second-best solution. The corresponding first-best choice of fire suppression effort is given by $G(z^{fb},d^{fb},s^{fb},X|\Gamma)$.

Social Losses

By moving first, the landowner is able to take advantage of the fact that government fire suppression is an imperfect substitute for fuel reduction in the salvage function; from the landowner's perspective, it is a costless substitute. The reduction in social welfare at the second-best outcome can be determined by substituting the landowner's choices into the first-best objective function and comparing the resulting net rents to those at the first-best outcome. The difference in net rents captures the social loss associated with the second-best outcome:

$$SL = NR(d^{fb},z^{fb},s^{fb},T^{fb}|\Gamma) - NR(d^{sb},z^{sb},s^{sb},T^{sb}|\Gamma). \quad [6]$$

The magnitude of the social loss depends on the divergence between the first- and second-best solutions. The solution to the first-best problem presumably calls for greater fuel reduction and lower fire suppression effort compared to the second-best solution. The magnitude of the social loss will also depend on information available to the landowner when making decisions. We return to these issues later in the simulation.

Cost-Sharing Policies

The two cost-sharing policies described earlier can potentially reduce the social losses associated with the landowner's choices. A cost-sharing policy that has the government pay a share of the landowner's fuel reduction costs can be modeled by replacing the terms $c(z)e^{r(X-s)}$ and $c(z)e^{r(T-s)}$ in [4] and [5] with $(1-\beta)c(z)e^{r(X-s)}$ and $(1-\beta)c(z)e^{r(T-s)}$, respectively, where β is the share paid by the government. The resulting reduction in the marginal cost of fuel reduction incurred by the landowner induces a higher level of fuel reduction to be chosen, and increases the present value of expected rents given the higher current value of rents Y_2^{sb} and Y_3^{sb}.

The alternative cost sharing policy that has the landowner pay a share of the costs of fire suppression can be modeled by subtracting the term $\alpha h(\hat{g}_\Delta)$ from Y_1^{sb} and Y_2^{sb} in [3] and [4], respectively. The parameter α is the share of fire suppression costs paid by the landowner. Imposition of this policy will affect the landowner's fuel reduction choice and will likely affect other choices as well, because it partially internalizes the costs of fire suppression. Unlike the fuel reduction policy, it will invariably reduce the present value of expected rents enjoyed by the landowner.

Finally, we can consider how the accuracy of the landowner's information about fire risk affects the magnitude of social losses at the second best outcome, and the ability of the two cost-sharing policies to reduce these losses. Nonindustrial landowners are likely to underestimate the magnitude of fire risk, as captured in our model by the magnitude of the average fire arrival rate, λ.

VI. SIMULATION RESULTS

As indicated earlier, we consider two types of landowners (as in Amacher, Malik, and Haight 2005): a *full-prevention landowner* who undertakes some fuel reduction in addition to making rotation age and planting density choices; and a *partia-prevention landowner* who does not under-

TABLE 1
FUNCTIONAL FORMS AND PARAMETER BASE VALUES

Type	Function	Assumed Form
Timber volume	$V(X,d)$	$e^{\alpha-\frac{\beta_1}{dX}-\frac{\beta_2}{XS}-\frac{\beta_3}{X^2}-\frac{\beta_4}{S^2}}$
		($\beta_1 = 3418.11$, $\beta_2 = 740.82$, $\beta_3 = 34.01$, $\beta_4 = 1527.67$, $\alpha = 9.75$, $S = 80$)
Costs of fuel reduction	$c(z)$	$c_3 + c_4 z$ ($c_3 = 4$, $c_4 = 0.06$)
Planting costs (burned and unburned)	Unburned land	$c_1 d$ ($c_1 = 0.42$)
	Burned land	$c_2 d$ ($c_2 = 0.30$)
Costs of fire suppression	$h(g)$	$c_5 g$ ($c_5 = 0.5$)
Timber salvage	$k(z,d,g)$	$(1 - k_4 e^{(-\frac{k_0(k_1 z + k_2 g + k_3 gz)}{d})})$
		($k_0 = 0.05$, $k_1 = 20$, $k_2 = 20$, $k_3 = 0.2$, $k_4 = 1$)

take fuel reduction, choosing only rotation age and planting density ($z = 0$ for this landowner). The partial-prevention landowner is arguably representative of many, if not most, nonindustrial private landowners in the United States.

All functional forms and base parameter values relevant to the simulation are presented in Table 1.[13] These were chosen to be consistent with the model described above and available published evidence. The tree species chosen for the simulation is loblolly pine, a tree prevalent in the southeastern United States, where nonindustrial land ownership is common. Previous literature provides adequate guidance for the volume function and planting costs. Marginal costs for establishing trees on burned and unburned land follow Dubois et al. (2001). The marginal cost of replanting burned land is less than the marginal cost of replanting unburned land because less soil preparation is involved (Dubois et al. 2001; Smith 1986). Stumpage prices net of harvesting costs per thousand board feet for pine sawtimber were obtained from TimberMart South for the same time period (TMS 2000). Our loblolly pine volume function was taken from the existing Faustmann-based policy literature (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. The landowner's discount rate was assumed to be 3%.

No published information was available for some functions needed, so we proceeded by choosing functional forms with plausible shapes that gave reasonable baseline values for decision variables, rents, fuel reduction costs, and fire suppression costs. This was especially true for the timber salvage function $k(.)$. Here, our choice of functional form was restricted by the requirement that the function be bounded by zero and one, regardless of the values of its arguments. This led us to an exponential form (see Table 1), strictly concave in fuel reduction and fire suppression effort, and strictly convex in planting density (reflecting diminishing returns). For the functional form and parameters assumed, Figure 1 shows the fraction of timber salvaged as a function of fuel reduction and fire suppression over the range of values obtained in our simulations; planting density is held fixed at 200 trees per acre, a typical value obtained in the simulations. As the level curves in Figure 1 indicate, fuel reduction and fire suppression are imperfect substitutes. The parameters of the salvage function were chosen so that this substitution

[13] The program used for the simulation is MATLAB version 6.1, with optimal values identified using two global search algorithms: Matlab's built in *fminsearch* routine, which employs a simplex search routine, and the public domain plug-in for Matlab, *glbsolve*, which relies on Lipschitzian optimization (see Jones, Pettunen, and Stuckman 1993).

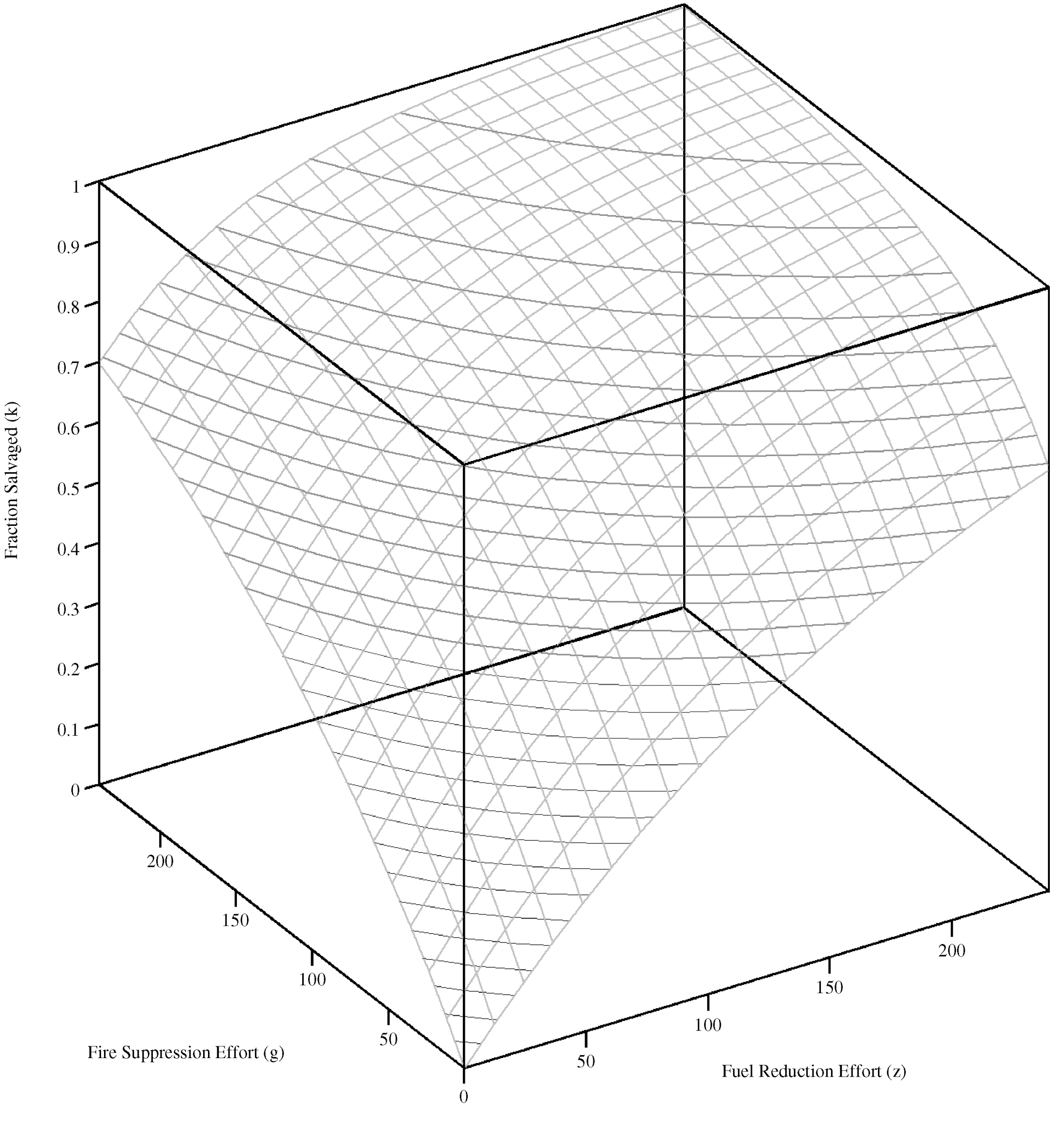

FIGURE 1
FRACTION SALVAGED AS A FUNCTION OF FUEL REDUCTION AND FIRE SUPPRESSION
(PLANTING DENSITY HELD FIXED AT D = 200)

held over the relevant range, and to generate values of the decision variables and fire suppression costs that were plausible.

In the simulations, the magnitude of *k(.)* is an increasing function of stand age, since the level of fire suppression effort chosen by the government increases as the stand ages and becomes more valuable. For a fire arriving at the rotation age, the value of *k(.)* ranged from 0.70 for a partial prevention landowner who underestimated fire risk, to a maximum of 0.94 for a full prevention landowner who received cost sharing for fuel reduction.

The cost of fire suppression effort, $h(g)$, was assumed linear in g so that the government's reaction function could be solved for analytically. In the simulations, the present value of suppression costs ranged from \$2.8 per acre at a first-best outcome to \$32 per acre for a partial-prevention landowner who underestimated fire risk. The current value of fire suppression costs for a single fire ranged up to \$144 per acre. For stands less than approximately 12 years of age, no fire suppression effort was exerted. This is consistent with the forest not having enough value to justify incurring suppression costs.[14]

The cost of fuel reduction was assumed to have both variable and fixed components to reflect labor and equipment needs. Total costs of fuel reduction in the simulation ranged between \$10 and \$21, with larger values resulting at higher levels of fire risk. This range is consistent with per acre costs of activities such as burning of surface fuels in the southeastern United States (Dubois et al. 2001).

The results of the simulations are presented in Tables 2 through 5. All results are presented on a per acre basis. Table 2 presents the first-best and second-best solutions when landowners have perfect information about fire risk (i.e., the magnitude of the fire arrival rate). In this scenario, social losses stem entirely from the fact that the landowner does not bear the cost of fire suppression. The second column in Table 2 gives the true magnitude of the fire arrival rate, λ; recall that λ captures the probability of fire occurrence in a given year. The third through sixth columns give the optimal values of decision variables, while the seventh column gives the total fuel reduction costs incurred (if any) in each rotation in current value terms. The column labeled "Fire Suppression Costs" reports the *present value* of expected fire suppression costs for the stand in perpetuity. The column labeled "Net Rents" gives the present value of expected rents net of fire suppression costs. In the case of the second-best solutions, recall that these are calculated by substituting the landowner's choices into the net rent function, $NR(d, z, s, T; \Gamma)$. Finally, the entries in the column labeled "Social Loss" are computed using [6]. If the elements in this column are added to those in the "Net Rents" column, one obtains net rents at the first-best outcome.

Examining the first-best results we see that fuel reduction is socially desirable at the two higher fire arrival rates, but not at the lowest one ($\lambda = 0.01$). This finding is, of course, sensitive to the assumed costs of fuel reduction—with lower costs, fuel reduction could be desirable even at the lowest fire arrival rate. Comparing the results for the full-prevention landowner to the first-best solution, we see that the full-prevention landowner also does not engage in fuel reduction at the lowest arrival rate, again given the assumed costs of fuel reduction. For this arrival rate, the full-prevention landowner behaves just like a partial-prevention landowner. For all three arrival rates, the full prevention landowner's choice of rotation age differs little from the first-best choice. The same is true with regard to the timing of fuel reduction. However, the full-prevention landowner's choice of fuel reduction effort is roughly half of the socially optimal level at the two higher arrival rates.

Turning to the partial prevention landowner, who by definition does not undertake fuel reduction, we see that this landowner's choice of rotation age is also similar to the first-best solution. At the highest arrival rate, this landowner mitigates fire risk by reducing planting density to a level below the socially optimal one. Unlike the full-prevention landowner, who can undertake more fuel reduction as fire risk increases, the partial-prevention land-

[14] Government suppression cost in the simulation is bounded above by the maximum land rent for an acre. It is worth noting that in practice fire suppression might be undertaken for young non-merchantable stands if valuable structures were present on the property, or there was an intention to prevent spread to neighboring valuable parcels. In this regard, suppression costs could also be higher; they are sometimes reported as high as \$300 per acre. It is likely that the costs of fire suppression for a given acre without structures and not affecting nearby communities would be considerably lower than the average reported in the literature.

owner can only increase salvage by reducing planting density. But reductions in planting density, unlike increases in fuel reduction, reduce timber volume at harvest, limiting this landowner's incentive to undertake such reductions in the face of fire risk.

From the last column in Table 2, we see that social losses are small at the lowest arrival rate but rise as fire risk increases. The losses are substantially larger for the partial prevention landowner, ranging up to $28 per acre.

Table 2 also shows the present value of fire suppression costs for the government. For the first-best solution, the costs are quite modest and fall with increasing fire arrival rates because of the sharp increase in fuel reduction. Except at the lowest arrival rate (for which no fuel reduction is undertaken in any of the three cases), suppression costs are at least twice as high for the full-prevention landowner and at least three times higher for the partial-prevention landowner compared to the first-best solution. The very high suppression costs for the partial-prevention landowner explain the finding that the rents earned by this landowner are not much lower than those earned by the full-prevention landowner—the government compensates for the partial-prevention landowner's lack of fuel reduction effort by increasing fire suppression effort.

Table 3 presents the effects of the two cost-sharing policies when the landowner has perfect information about fire risk; again, both full- and partial-prevention landowners are considered. A 50% cost share of fuel reduction and a 50% cost share of fire suppression are simulated. In what follows, these will be called the "fuel reduction policy" and "fire suppression policy," respectively. Note that the fuel reduction policy is relevant only for the full-prevention landowner.

The column in Table 3 labeled "Fuel Reduction Costs" gives the *total* costs associated with fuel reduction and not just the landowner's share of these costs. Similarly, the column labeled "Fire Suppression Costs" reports the present value of *total* fire suppression costs and not just the fire suppression costs borne by the government. The last two columns in the table present the changes in total fire sup-

TABLE 2

First-Best and Second-Best Solutions Given Perfect Information about Fire Risk

Model	λ	T*	d*	s*	z*	Fuel Reduction Costs	Fire Suppression Costs	Rents	Net Rents	Social Loss
First-Best Solution										
	0.01	24.7	222	—[a]	—[a]	—[a]	10.3	125.6	115.3	0
	0.02	27.1	200	10.4	187	15.2	6.6	86.9	78.8	0
	0.04	30.6	162	10.5	280	20.8	4.8	29.0	24.2	0
Full-Prevention Landowner										
	0.01	25.5	225	—[b]	—[b]	—[b]	11.1	126.0	114.9	0.4
	0.02	27.1	210	10.3	99	9.9	13.8	89.6	75.8	3.0
	0.04	30.2	177	9.7	154	13.3	14.1	32.9	18.8	5.4
Partial-Prevention Landowner										
	0.01	25.5	225				11.1	126.0	114.9	0.4
	0.02	26.6	200				19.5	88.3	68.8	10.0
	0.04	29.6	154				27.9	23.9	−4.0	28.2

[a] Socially optimal not to undertake fuel reduction.
[b] Landowner chooses a corner solution at which no fuel reduction is undertaken.

TABLE 3

Effects of Cost Sharing when Landowners Have Perfect Information about Fire Risk

Model	True λ	T*	d*	s*	z*	Fuel Reduction Costs	Fire Suppression Costs	Rents	Net Rents	Social Loss	Change in Suppression Costs	Change in Social Loss
Full Prevention Landowner												
50% Cost-Sharing of Fuel Reduction												
	0.01	25.8	232	9.3	112	10.7	7.6	127.7	112.5	2.8	−3.5	2.4
	0.02	27.0	217	8.3	192	15.5	9.2	98.3	77.6	1.2	−4.6	−1.7
	0.04	29.9	186	8.3	280	20.8	7.3	44.5	21.7	2.5	−6.8	−2.9
50% Cost-Sharing of Fire Suppression												
	0.01	25.1	223	–[b]	–[b]	–[b]	10.7	120.5	115.2	0.1	−0.4	−0.3
	0.02	27.0	205	10.3	141	12.4	10.7	83.5	78.1	0.7	−3.0	−2.3
	0.04	30.3	169	10.1	221	17.3	8.3	27.4	23.3	1.0	−5.8	−4.4
50% Cost-Sharing of Fire Suppression												
	0.01	25.1	223				5.3	120.5	115.2	0.1	−5.7	−0.3
	0.02	25.8	196				9.1	78.9	69.9	8.9	−10.4	−1.0
	0.04	28.2	144				11.9	11.0	−0.9	25.1	−16.0	−3.1

[b] Landowner chooses a corner solution at which no fuel reduction is undertaken.

pression costs and social losses resulting from each policy.

Comparing the choices of the full-prevention landowner in Table 3 and Table 2, we see that the fuel reduction policy only induces small changes in rotation age and planting density. However, it induces a large increase in fuel reduction effort. At the lowest arrival rate, the fuel reduction policy results in the full-prevention landowner now undertaking fuel reduction. At the two higher arrival rates, the level of fuel reduction effort is now slightly higher than at the first-best solution. The fuel reduction policy also lowers the stand age at which fuel reduction is undertaken, albeit by a small margin. Neither of these effects is surprising given the lower effective fuel reduction cost faced by the landowner.

Turning to the fire suppression policy, we see that at the lowest arrival rate the full-prevention landowner continues not to undertake fuel reduction. At higher arrival rates, this policy induces a smaller but still substantial increase in fuel reduction effort; this effort is delayed and applied at a stand age closer to the socially optimal one. The policy also induces a lower planting density, one that is quite close to the socially optimal density.

The last column in Table 3 shows the change in social losses associated with the two policies relative to the no-policy outcomes in Table 2. With one exception, both policies reduce social losses, and the reductions increase with fire risk. The exception occurs with the fuel reduction policy at the lowest fire risk. At this risk level, the fuel reduction policy *increases* social losses, which implies that the fuel reduction effort induced by the policy is socially undesirable.

For the full-prevention landowner, reductions in social losses are larger with the fire suppression policy (−0.3 to −4.4 versus 2.4 to −2.9). This is not altogether surprising. The fire suppression policy directly targets the cause of the inefficiency we model, namely the externality resulting from the landowner not bearing the costs of fire suppression. In contrast, the fuel reduction policy only targets the externality indirectly. This is manifested by the finding that the fuel reduction policy actually increases social costs at the lowest arrival rate. It can also be appreciated if we consider the extreme case of a fire suppression policy that requires the landowner to bear *all* the costs of fire suppression. Then, given perfect information, there would be no difference between the first-best outcome and the full-prevention outcome. In contrast, although a suitably chosen fuel reduction cost share could induce a level of fuel reduction identical to that at the first-best solution, in general, this cost share would not induce the landowner to choose the socially optimal age at which to undertake this effort, or to choose the socially optimal planting density.

Whether a given fire suppression policy does in fact yield lower social costs than a fuel reduction policy will depend on the precise levels of the cost shares and on the level of fire risk. For example, we can show that if the landowner is only required to bear 1% of the cost of fire suppression, then a 50% cost share of fuel reduction yields a much larger reduction in social loss at the higher arrival rates.[15]

Turning to the results in Table 3 for the partial-prevention landowner, we see that the fire suppression policy induces small reductions in both the rotation age and planting density. Social losses are consistently reduced, with the reductions increasing with arrival rates. However, the reductions in social losses are smaller in magnitude than those for the full-prevention landowner (at the higher arrival rates). This can be attributed to the partial prevention landowner having fewer choices that can be "corrected" by internalizing the externality.

The next to last column in Table 3 shows the effects of the policies on total fire suppression costs. For the full-prevention landowner, we see that both policies reduce total fire suppression costs, with the reductions being larger for the fuel reduction policy given its ability to induce larger increases in fuel reduction effort. The reductions in suppression costs are even larger for the partial-prevention landowner. These reductions are due to the lower planting densities and rotation ages.

Tables 4 and 5 present the effects of the two cost-sharing policies under an assumption that the landowner underestimates the fire risk parameter λ by 50%. The first set of results in each table (labeled "No Cost Sharing") shows the outcome without any government intervention. For these results, the entries in the last two columns give the change in total fire suppression costs and social losses, respectively, relative to the perfect information setting with no government intervention (Table 2). In Table 4, which presents the results for the full-prevention landowner, the first set of results show that the landowner now only undertakes fuel reduction at the highest arrival rate. Interestingly, at the two lower arrival rates, the landowner now behaves no differently than a partial-prevention landowner. The entries in the last column indicate that a poorly informed landowner results in an increase in social losses ranging from \$0.6 to \$13.9 per acre.

The second and third sets of results in Table 4 show the effects of the two policies on the imperfectly informed full-prevention landowner. The last two columns report the change in suppression costs and social losses, respectively, relative to the scenario in which there is no government intervention but the landowner has imperfect information about fire risk (i.e., the first set of results in the same table). At the lowest risk level, we see that the fuel reduction policy now does not induce the landowner to undertake fuel reduction. Thus, the landowner's behavior is unaffected by the policy. At this risk level, the fire suppression policy also does not induce the landowner to undertake fuel reduction, but it does induce the landowner to slightly reduce both rotation age and

[15] Intuition might suggest that the larger reduction in social losses with the fire suppression policy is a function of discounting and the fact that fire suppression expenditures may be incurred later in a rotation than fuel reduction expenditures. However, we found that a lower discount rate (1% instead of 3%) did not diminish the advantage of the fire suppression policy over the fuel reduction policy.

TABLE 4

FULL PREVENTION LANDOWNER WHO UNDERESTIMATES FIRE RISK BY 50%

Model	True λ	T*	d*	s*	z*	Fuel Reduction Costs	Fire Suppression Costs	Net Rents	Social Loss	Change in Suppression Costs[a]	Change in Social Loss[a]
No Cost-Sharing											
	0.01	25.0	239	—[b]	—[b]	—[b]	11.2	114.3	1.0	0.1	0.6
	0.02	25.5	225	—[b]	—[b]	—[b]	21.7	66.5	12.3	7.9	9.3
	0.04	27.1	210	10.3	99	9.9	22.6	4.9	19.3	8.4	13.9
50% Cost-Sharing of Fuel Reduction											
	0.01	25.0	239	—[b]	—[b]	—[b]	11.2	114.3	1.0	0.0	0.0
	0.02	25.8	232	9.3	112	10.7	13.8	74.4	4.4	−7.9	−7.9
	0.04	27.0	217	8.35	192	15.5	15.1	13.0	11.2	−7.5	−8.1
50% Cost-Sharing of Fire Suppression											
	0.01	24.8	238	—[b]	—[b]	—[b]	11.0	114.5	0.8	−0.2	−0.2
	0.02	25.1	223	—[b]	—[b]	—[b]	19.4	67.3	11.5	−2.3	−0.8
	0.04	27.0	205	10.26	141	12.4	17.6	12.1	12.1	−5.0	−7.2

[a] For the no cost-sharing scenario, changes are relative to the perfect information scenario (Table 2); for the cost-sharing scenario, changes are relative to the no cost-sharing scenario given the underestimate of fire risk.

[b] Landowner chooses a corner solution at which no fuel reduction is undertaken.

planting density. This yields a small reduction in social loss. At the higher risk levels, the fuel reduction policy achieves larger reductions in social losses than the fire suppression policy. This is particularly true at the intermediate arrival rate ($\lambda = 0.02$), because the fuel reduction policy induces the landowner to undertake fuel reduction, whereas the fire suppression policy does not. This result differs from that obtained when the landowner is perfectly informed. As before, reductions in suppression costs are larger with the fuel reduction policy at the higher arrival rates.

TABLE 5

PARTIAL PREVENTION LANDOWNER WHO UNDERESTIMATES FIRE RISK BY 50%

Model	True λ	T*	d*	Fire Suppression Costs	Net Rents	Social Loss	Change in Suppression Costs[a]	Change in Social Loss[a]
No Cost-Sharing								
	0.01	25.0	239	11.2	114.3	1.0	0.1	0.6
	0.02	25.5	225	20.1	66.5	12.3	0.6	2.3
	0.04	26.6	200	31.6	−14.0	38.2	3.8	10.0
50% Cost-Sharing of Fire Suppression								
	0.01	24.8	238	11.0	114.5	0.8	−0.2	−0.2
	0.02	25.1	223	19.4	67.3	11.5	−0.7	−0.8
	0.04	25.8	196	29.5	−11.3	35.5	−2.1	−2.7

[a] For the no cost-sharing scenario, changes are relative to the perfect information scenario (Table 2); for the cost-sharing scenario, changes are relative to the no cost-sharing scenario given the underestimate of fire risk.

Table 5 presents results for the partial-prevention landowner. We can see from the first set of results in the table that imperfect information increases social losses by $0.6 to $10 per acre. This increase is smaller than for the full-prevention landowner. Imperfect information also increases total fire suppression costs; the increases are, once again, smaller than for the full prevention landowner. The second set of results in the table shows that the fire suppression policy reduces social losses by $0.2 to $2.7 per acre. Compared to the full-prevention landowner, there is no difference in the results for the two lower arrival rates, since the full-prevention landowner behaves like a partial-prevention one. But at the highest fire arrival rate, the fire suppression policy achieves a smaller reduction in social loss for the partial-prevention landowner. A similar conclusion holds for the reduction in fire suppression costs.

VII. POLICY IMPLICATIONS

Our model, like other stand-level models in the literature that incorporate fire risk, is obviously a very stylized one. It relies on simplifying assumptions about the interaction of fuel reduction, planting density, and fire suppression on timber salvage. Given these limitations, the simulation results we obtain need to be interpreted with caution. The results do, however, offer some important qualitative insights relevant to the design of government policy.

The results for the full-prevention landowner demonstrate that neither of the policies considered consistently dominates the other. When the landowner is perfectly informed, the fire suppression policy yields larger reductions in social loss for all arrival rates. However, this is not true when the landowner is imperfectly informed: in this case, at higher arrival rates, the fuel reduction policy may be preferable.

Our results also point out a pitfall of employing the fuel reduction policy: it can actually result in higher social losses by inducing the landowner to undertake fuel reduction when it is not socially desirable to do so. This occurred at the lowest fire arrival rate with the perfectly informed landowner. This possibility was not observed with the fire suppression policy, either for the results presented here or for sensitivity analyses we conducted (available upon request) in which we varied parameters of the salvage function and the cost of fuel reduction. We believe that this finding is not specific to our model. As argued above, the fire suppression policy directly targets the externality, and, in a first-best setting, introduction of this policy would reduce social losses regardless of the level of the cost share.[16] Thus, the fire suppression policy may be considered a "safer" policy to the extent that it will not result in higher social losses.

Another argument in favor of the fire suppression policy is that it can influence the behavior of a partial-prevention landowner, that is, a landowner who does not engage in fuel reduction. Furthermore, as our results reveal, the fire suppression policy can influence the behavior of a full-prevention landowner in situations in which the fuel reduction policy does not. Recall that in the case of an imperfectly informed full-prevention landowner, at the lowest arrival rate, the fuel reduction policy did not induce the landowner to engage in fuel reduction, leaving the landowner's behavior unchanged (see Table 4). When facing the fire suppression policy, the same landowner reduced his rotation age and planting density.

A comparison of the reductions in social losses achieved by the fire suppression policy for the full- and partial-prevention landowners reveals that larger reductions are consistently achieved with the full-prevention landowner. This is true regardless of whether landowners are perfectly or imperfectly informed. This suggests that when faced with a choice of targeting only one of the two types of landowners, governments can achieve larger social gains by

[16] In a second-best setting in which there are additional distortions (beyond the fire suppression cost externality), the fire suppression policy need not reduce social losses given the theory of second best.

targeting full-prevention landowners.[17] Although we found these conclusions also held in the sensitivity analyses we conducted, we conjecture that this result may not be robust to alternative specifications of the salvage function. Intuition suggests that if salvage is very sensitive to changes in planting density and relatively insensitive to changes in fuel reduction, then reductions in social losses may be just as large for a partial-prevention landowner.

Other results regarding the merits of targeting informed versus imperfectly informed landowners are mixed. No clear-cut conclusions can be drawn as to whether larger reductions in social losses are achieved by targeting informed landowners versus imperfectly informed landowners, even if the government could distinguish them. The results in Tables 3, 4, and 5 reveal that the relative magnitude of the reductions in social losses depends on the policy instrument and on the precise level of fire risk. This finding was also borne out in our sensitivity analyses.

Finally, our results reveal the importance of information about fire risk in determining the magnitude of social losses and "excess" fire suppression costs. The first set of results in Tables 4 and 5 imply that correcting imperfect information about fire risk would generate reductions in social losses and fire suppression costs that are similar in magnitude to those achieved by the two cost-sharing policies.

Another dimension of information may be of equal, if not greater, importance. If a partial-prevention landowner does not undertake fuel reduction because of imperfect information about the benefits of doing so, correcting such misinformation could yield the largest social gains. The differences in social losses between the partial- and full-prevention landowners in Table 2 (or Tables 4 and 5) are as large as $20 per acre at the highest arrival rate. These findings suggest that more attention should be given to policies aimed at improving the information held by landowners.

VII. CONCLUDING REMARKS

Our analysis opens up several new features of landowner-based modeling that could be extended to further understand the fire economics problem. There are three obvious policy design problems that merit further study. First, the mechanism of targeting cost-sharing policies to achieve certain social cost reductions remains a fruitful area for further work. We found that in some cases the first-best solution does not necessarily involve fuel reduction. Thus, it may not be optimal to have cost sharing for every landowner, especially where fire risk is low or landowners are of a certain type. Second, we have assumed, as is conventional in the regulatory literature, that government collections of revenues under the fire suppression policy are pure transfers. These collections therefore do not appear as "earmarked" funds in the government's objective function. Earmarked cost sharing has not been considered before in the resources literature, so we have no priors for what might come from its application. But earmarking would lead to a different problem than the one here, and it would be useful to contrast the fuel reduction policy with the fire suppression policy in the presence of earmarking.

It would also be interesting to consider further complexities in fuel reduction and fire damage modeling at the landowner level. It is possible that tree age affects salvage since older trees are often more fire resistant. It would also be worth introducing a decay in the effectiveness of fuel reduction, because the effectiveness of this treatment in preventing fire losses declines over time. An analysis of multiple landowners on a landscape, where adjacent landowner fuel reduction has implications for fire arrival on a given landowner's stand, is also an unstudied problem. Current large scale models of fire suppression do not incorporate individual landowner

[17] Targeting these landowners is no small task given that partial prevention landowners and imperfectly informed full prevention landowners (willing to undertake fuel reduction) are observationally equivalent if the full

decisions about fuel reduction, but our analysis shows there is much to be gained by understanding this layer of the problem.

References

Amacher, Gregory, Richard Brazee, and Tom Thompson. 1991. "The Effects of Forest Productivity Taxes on Optimal Rotation Age and Initial Stand Investment." *Forest Science* 37 (Aug.): 1099–1118.

Amacher, Gregory, M. Christine Conway, and Jay Sullivan. 2003. "Econometric Analysis of Nonindustrial Forest Landowners: Is There Anything Left To Do?" *Journal of Forest Economics* 9 (Dec.): 137–64.

Amacher, Gregory, Arun Malik, and Robert Haight. 2005. "Not Getting Burned, the Importance of Fire Prevention in Forest Management." *Land Economics* 81 (May): 284–302.

Boyd, Robert, and William F. Hyde. 1986. *Forestry Sector Intervention*. Ames Ia.: Iowa State University Press.

Chang, Sun J. 1984. "A Simple Production Function Model for Variable Density Growth and Yield Modeling." *Canadian Journal of Forest Research* 14:783–88.

Dubois, M., K. McNabb, T. Straka, and W. Watson. 2001. "Costs and Cost Trends for Forestry Practices in the South." *Forest Farmer* 60:25–31.

The Economist. 2003. "Heat and Light." http://economist.com/science/displayStory.cfm?story_id=2035208

Englin, Jeffrey, Peter Boxall, and Gordon Hauer. 2000. "An Empirical Examination of Optimal Rotations in a Multiple Use Forest in the Presence of Fire Risk." *Journal of Agricultural and Resource Economics* 25 (1): 14–27.

Fernandes, P., and H. Botelho. 2004. "A Review of Prescribed Burning Effectiveness in Fire Hazard Reduction." *International Journal of Wildland Fire* 12 (2): 117–28.

Food and Agriculture Organization of the United Nations (FAO). 2003. "Fires Are Increasingly Damaging the World's Forests." www.fao.org/english/newsroom/news/2003/21962-en.html. September.

Graham, Russell, T., S. McCaffrey, and T. Jain. 2004. "Science Basis for Changing Forest Structure to Modify Wildfire Behavior and Severity." General Technical Report RMRS-GTR-120. Fort Collins, Col.: USDA Forest Service, Rocky Mountain Research Station.

Jones, D., C. Perttunen, and B. Stuckman. 1993. "Lipschitzian Optimization Without the Lipschitz Constant." *Journal of Optimization Theory and Applications* 79 (1): 157–81.

Nelson, Robert H. 2000. "Restoring Forest Health and Restoring Forest Health on Federal Lands. Testimony to the Task Force on Natural Resources and the Environment." House Budget Committee, September 13.

Reed, William. 1984. "The Effects of the Risk of Fire on the Optimal Rotation of a Forest." *Journal of Environmental Economics and Management* 11 (2):180–90.

———. 1987. "Protecting a Forest Against Fire: Optimal Protection Patterns and Harvest Policies." *Natural Resource Modeling* 2 (1): 23–53.

Salt Lake Tribune. 2004. "Fed Fire Spending Burns Holes in Pockets." May 12, 2004.

Smith, David M. 1986. *The Practice of Silviculture*. 8th ed. NewYork: Wiley Press.

Society of American Foresters (SAF). 2000. "Managing the Impact of Fires on Communities and the Environment: Report to the President in Response to the Wildfires of 2000." http://www.safnet.org/policyandpress/firereport.pdf.

———. 2002. "Wildfire Season Heats Up Debate in Washington." *Forestry Source* (Oct.).

Swallow, Steven, Peter Parks, and Dave Wear. 1993. "Spatial Interactions in Multiple-Use Forestry and Substitution and Wealth Effects for the Single Stand." *Journal of Environmental Economics and Management* 25 (1):103–20.

Timber Mart South (TMS). 2000. *Market Newsletter* 1st–4th Qtrs 6 (May).

USDA Forest Service (USFS). 2003. "Fire and Aviation Management Briefing Paper." Washington, D. C.: USDA Forest Service.

Wade, D., and J. Lundsford. 1990. "Fire as a Forest Management Tool: Prescribed Burning in the Southern United States." *Unasylva* 41: 28–38.

Waldrop, Tom. 1997. "Four Site Preparation Techniques for Regenerating Pine-Hardwood Mixtures in the Piedmont." *Southern Journal of Applied Forestry* 21:116–22.

Waldrop, T., D. Van Lear, F. Thomas, W. Harms. 1987. "Long Term Studies of Prescribed Burning in Loblolly Pine Forests of the Southeastern Coastal Plain." General Technical Report GTR SE-45. USDA Forest Service Southeastern Experiment Station.