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Nonindustrial private landowners, fires, and the wildland–urban interface

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Abstract

We estimate the value to a non-industrial forest landowner of information about the magnitude of fire arrival rates. A simulation based on a model from Amacher et al. [Amacher, G., Malik, A., Haight, R., in press. Not getting burned: the importance of fire prevention in forest management. Land Economics] is used to assess the cost of mistakes made by a landowner when stand management decisions are made without perfect knowledge of the fire arrival probability. These costs are reflected in the higher losses incurred by a landowner if fire arrives during a rotation. The representative landowner studied in the simulation is assumed to value nontimber benefits, and to make rotation age, planting density and fuel reduction decisions. We find that the value of information about the overall magnitude of fire risk is more than twice as high when the landowner underestimates fire risk, rather than overestimating it.

Keywords: Uncertainty; Non-industrial forest landowners; Information; Fuel reduction; Salvage

1. Introduction

The many recent forest fires in the U.S. along the wildland–urban fringe have precipitated discussion regarding government efforts to encourage landowners to reduce fuels on their properties. Information landowners have regarding the probability of fire arrival plays a role in their fuel reduction decisions. This suggests that information dissemination about the risk of fire could play a role as a potential policy mechanism. Landowners with improved information would realize the value of fuel reduction efforts aimed at minimizing losses should fire occur on their property (Society of American Foresters [SAF], 2000, 2002). For example, planting at lower densities may reduce fire loss through reduction in the spread of fire, or landowners could engage in burning of surface fuels, pruning, and clearing of underbrush, most of which do not yield merchantable timber. Often landowners make fuel and other decisions with an imperfect understanding of these probabilities (SAF, 2000, 2002). This may lead to fire losses that are higher than socially optimal.

In this paper, we estimate the value of improved information about fire arrival rates to a private forest

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landowner. We make use of a model based on Amacher et al. (in press).[1] Their work modifies Reed (1984) and Englin et al. (2000) by introducing fuel reduction as a landowner decision. They also show how to model the value of information about various fire–stand relationships a landowner must understand to make informed decisions. Value of information is defined as the additional rents obtained by having the information and making better-informed forest management and fuel reduction decisions. These better decisions are reflected in greater protection to forest assets (lower fire losses) should fire arrive during a rotation.

We specifically consider a representative private forest landowner assumed to value nontimber benefits in accordance with the types of landowners found on the wildland–urban fringe (e.g., see Pattanayak et al., 2002; Conway et al., 2003; Amacher et al., 2003; Kuuluvainen et al., 1996 for more discussion of these types of landowners).[2] Knowing the value of having better information about fire arrival probabilities for these landowners will be important in designing policies to ensure fuel reduction decisions are made in ways that reduce expected fire losses. This in turn could reduce the suppression costs paid by the government to control fires once they arrive. As the wildland–urban fringe continues to develop, an understanding of how landowner fuel reduction decisions are affected by information the landowner has will clearly be important to policy makers.

2. Simulation approach

We will not present details of the model from Amacher et al. (in press), but rather we will discuss the important aspects needed for our problem here. Further details of the model appear in Appendix A. The model of landowner behavior is a modification of the uncertainty-based multiple repeating rotations framework of Reed (1984) and others, and is applied on a per acre scale. The model could apply to landowners who either maximize rents captured in markets through forest management decisions, or to landowners who maximize both market and nonmarket rents by assuming, as we do, that nontimber benefits can be a part of the landowner's objective function. The model extends Reed's approach to include, as forest management decisions, planting density (d), rotation age (T), the level of fuel reduction effort (z) and the time during the rotation that fuel reduction is undertaken (s). Fuel reduction is not assumed to result in merchantable timber, and should fire arrive after z is employed at time s, the landowner is able to salvage more timber beyond what the landowner would salvage if fuel reduction was not used earlier. If fire does arrive and fuel reduction has not yet been employed, then we assume that nothing is salvaged.[3] Examples of fuel reduction comprising z include brush removal, burning of surface fuels, and even some forms of thinning such as pruning. In this model, a new rotation is started, and cost of planting incurred, whenever either fire arrives or the rotation age is reached without a fire.

To make perfectly informed decisions, the landowner in this framework would need to know the fire probability realized at each year during the rotation. We assume, like others have, that fire arrival follows a Poisson process. The Poisson distribution allows for multiple fire events during a rotation, and there is independence across events. The arrival rate (or

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[1] This paper focuses on several types of landowners and mainly other types of information or landowner mistakes. We focus more on information regarding the fire arrival probability in this paper, which is more relevant for the wildland–urban fringe.

[2] Decoster (1998) notes that landowners who either do not understand forestry practices for small lots or choose not to engage in forestry practices are becoming increasingly more important as land becomes fragmented through urban-induced parcelization. Others have also shown or argued this (Conway et al., 2003; Amacher et al., 2003). It is worth noting that our approach could apply in its simplest form to these landowners by assuming that the landowner captures only nontimber benefits and does not capture rents from any forest management.

[3] This assumption was used to avoid an ad hoc guess of salvage possibilities. While it means that damage from fire in our model could be overstated, other assumptions we employ imply that the importance of fuel reduction and the value of information we compute are understated. For example, as we discuss later, given the absence of any rigorous evidence we did not assume that there were any positive effects to nontimber benefits from fuel reduction (there could be), nor did we assume that fuel reduction affords any positive effects to tree growth (again, there could be positive effects).

probability) of fire is assumed to be constant over stand age.[4]

The assumption that fuel reduction increases salvageable timber makes sense given that fuel reduction is often advocated in fire risk situations in order to reduce the loss if fire occurs (Wade and Lundsford, 1990). Formally, salvage possibilities are assumed to be influenced by both fuel reduction and planting density, so that the salvageable fraction of timber is described by a concave function, $k(z,d)$ with $\frac{\partial k(.)}{\partial z} \geq 0, \frac{\partial k(.)}{\partial d} \leq 0$ and $k(0,d)=0$. An individual landowner cannot affect the market price of timber through their salvage behavior.[5]

The key assumption in our study, and also in the Amacher et al. model, is that fuel reduction affects severity of a fire once one arrives, but it does not affect the probability of fire arrival in any period. This has some support in the literature, and in fact a recent survey of burning (an important fuel reduction activity) concluded that burning of fuels is most likely only to affect fire severity (Fernandes and Botelho, 2004). The authors also state that their reading of previous work implies there is not enough evidence to suggest, at this point, that burning has any significant effect on the probability of fire arriving in a given stand or a given acre. This effect of fuel reduction also appears to have support in insurance underwriting, according to a recent US Forest Service report (United States Department of Agriculture [USDA] Forest Service, 2003). In practice, our assumption about fuel reduction makes sense if one considers a lightning strike on a specific tree, or a fire arriving on an acre through flying embers or root systems from a burning adjacent area (the most common form of arrival for any single landowner). One additional advantage of this assumption is that the value of information we establish later amounts to a lower bound. The value of making better decisions would be even greater if fuel reduction affected both fire losses and the probability of fire arrival.

The landowner needs to have information about the magnitude of the fire arrival rate. This is defined as the probability that fire arrives during an interval of 1 year within each rotation. The landowner is unlikely to be aware of the precise magnitude of this fire arrival rate at each point in time.[6] The consequences of underestimating or overestimating the fire arrival rate are examined in this paper. The value of information is then defined as the difference in the maximum present value of expected rents obtained with and without accurate information (see Appendix A).

The simulation was conducted for loblolly pine. All functional forms used in the simulation are presented in Table 1.[7] These were based on available published evidence. Marginal costs for establishing trees on burned and unburned land were taken from Dubois et al. (2001). Stumpage prices net of harvesting costs per thousand board feet of pine sawtimber were obtained from TimberMart South (TMS, 2002). The marginal cost of replanting burned land was less than the marginal cost of replanting unburned land, because the soil requires less preparation (Dubois et al., 2001; Smith, 1986). The loblolly pine forest volume function was taken from Chang (1984) and Amacher et al. (1991). Referring to Table 1, a base age 25 site index of 80 ft ($E=80$) was used for the harvest volume function. For lack of conclusive evidence (see Waldrop et al., 1987; Waldrop, 1997), fuel reduction was not assumed to affect forest yield.

The possibility that a landowner values nontimber benefits was accommodated by assuming a nontimber

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[4] These assumptions make the simulation tractable. Previous studies that have used similar assumptions for both the probability of fire arrival (or risk) and independence of this risk over time include Stainback and Alavalapati (2004), Englin et al. (2000), Amacher et al. (in press), Fina et al. (2001), and Reed (1984, 1987).

[5] For a regional study that considers how salvage affects timber markets, see Prestemon and Holmes (2000).

[6] It is reasonable to expect that a nonindustrial private landowner will never know the precise probability of fire arrival in each future period, so that learning here is not assumed to occur. Learning is certainly an important future research topic.

[7] The program used for the simulation is MATLAB version 6.1, with optimal values determined using search algorithms applied to the appropriately defined objective functions. As mentioned earlier, the first-order conditions for the problem considered are very unwieldy. Rather than deriving the first-order conditions and numerically solving them, we used gradient-free, global search algorithms for finding the solution to each problem. Two algorithms were used: Matlab's built in *fminsearch* routine, which employs a simplex search routine, and the public domain plug-in for Matlab, *gblsolve*, which is a global optimization routine that relies on Lipschitzian optimization (see Jones et al., 1993).

Table 1
Functional forms and base values of parameters used in simulation

Type	Function	Assumed form
Timber volume	$V(X,d)$	$e^{\alpha-\frac{\beta_1}{X^2}-\frac{\beta_3}{dX}-\frac{\beta_3}{XE}-\frac{\beta_4}{E^2}}(\beta_1=3418.11,\beta_2=740.82,\beta_3=34.01,\beta_4=1527.67,\alpha=9.75)$
Average fire arrival rate function	Constant average arrival rate λ	$\frac{t_0}{t_b-t_a}\quad(t_a=0,\ t_b=50)$
Nontimber benefits	$B(t)$	$b_0 t e^{-(b_1 t)}$ $(b_1=1/60;\ b_0=8/60)$
Cost of fuel reduction	$C_3(d)$	$c_0+c_3 z$ $(c_0=5;\ c_3=0.04)$
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	$k(z,d)$	$k_0\left(1-e^{\left(-\frac{k_1(k_2+z)}{d}\right)}\right)(k_0=0.9936;k_1=2/3;k_2=1)$

benefit function that has the conventional form (for these types of models) following Hartman (1976) and Englin et al. (2000), and was similar to the ones used in Swallow et al. (1993), Swallow et al. (1997), and Vincent and Boscolo (2000). This value function peaks at age 60, which for loblolly pine is consistent with old growth values attached to pine forests, such as habitat values for woodpeckers.[8]

Fire arrival probability in each period (i.e., the average arrival rate) was simulated using a uniform distribution. That is, we assumed that the fire arrival rate, denoted by λ, was constant over time. A scale parameter for this distribution, t_0, was used to simulate under- and overestimation of this rate by the landowner (see Table 1). The timber salvage function $k(.)$ was concave in its arguments and bounded by zero and one.

Finally, total costs of fuel reduction were assumed to have variable and fixed components, with total costs of z ranging between \$20 and \$40 per acre (Table 1). This is consistent with per acre costs of activities such as burning of surface fuels in the southeastern U.S. (Dubois et al., 2001).[9] The interest rate was assumed to be 5% in the simulations.

3. Simulation results

Baseline simulation results are presented in Table 2.[10] The magnitude of the average fire arrival rate was varied using the scaling parameter of the distribution of fire arrival, t_0 (see Table 1). Changes in this scaling parameter are directly and linearly related to changes in the average arrival rate, and therefore fire risk, in all periods during each rotation. A

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[8] Whenever nontimber benefits were included, the concavity of the objective function was checked. The value of nontimber benefits per year in our simulation was calibrated according to assumptions used elsewhere in the South (Wear and Greis, 2002). We examined several alternative peak ages and paths for nontimber benefits in the simulation, motivated by Swallow et al., 1993; Englin and Klan, 1990, but we found that these different paths did not make significant differences in our value of information estimates.

[9] It is possible that the costs of fuel reduction undertaken in an existing mature stand could be significantly higher than our total cost of z, however, our use of a repeating rotations model assumes the landowner begins with bare land, so that fuel reduction is done when the stand is relatively young. Allowing a landowner to start with an existing mature stand for the first rotation, which would have a high cost of fuel reduction, would not be difficult but would unnecessarily complicate notation without adding new insights.

[10] The *fminsearch* routine in MATLAB was efficient at finding solutions given an appropriate set of starting values. The latter were typically derived using the *gblsolve* routine, which we found to be adept at getting very close to the solution given very wide intervals over which to search. For each basic scenario that we considered, we verified that the solutions identified did in fact yield global maxima by conducting sensitivity analyses and by plotting the objective function in each choice variable. Despite the complexity of our model, we found that the objective function had only minor non-concavities.

Table 2
Changes in fire arrival rates (t_0) and landowner decisions

Model	t_0	T^*	d^*	s^*	z^*	$k(d^*,z^*)$	Expected rents
Without nontimber benefits	1	24.7	300	9.9	498	0.67	173
	2	27.6	244	9.6	680	0.84	103
	3	30.5	200	9.9	673	0.89	44
With nontimber benefits	1	25.8	295	10.7	533	0.70	210
	2	29.1	239	10.6	707	0.86	140
	3	32.7	192	11.4	690	0.90	81

doubling of t_0 results in a doubling of the average fire arrival rate at each point in time. In the first row of Table 1 ($t_0=1$), the average arrival rate of fire is assumed to take on a value of 1/50 (i.e., $t_0/50$), i.e., a fire arrives on average once every 50 years. The next two rows show the effects of increases in fire risk. With $t_0=2$, λ takes on a value of 2/50 ($t_0/50$), and with $t_0=3$ it takes on a value of 3/50. Given this, the results in the table can be used to show the landowner's choices and maximum rents when the landowner under and over estimates the true value of t_0, assumed to equal 2, by plus or minus 50%.

In Table 2, planting density (d) is measured in number of trees per acre, fuel reduction is measured in units of effort (z) applied per acre, and the timing of fuel reduction (s) and rotation age (T) are measured in years. The 'Expected Rents' column measures the present value of maximum expected rents evaluated at the optimal choices conditional on information the landowner has at his disposal at the time decisions are made (beginning of rotation). Also shown are salvage proportions when decisions are made optimally should fire arrive before the end of the rotation.

Referring to the results, maximum rents are decreasing in fire risk. Increased fire risk tends to also decrease planting density significantly. This is because the marginal expected benefits of increased planting are decreased, as higher fire risk implies greater cumulative probability that a fire will arrive before the end of the rotation, i.e., before the time that planting density contributes to rents through increased yield (see Table 1). Therefore, at higher risk levels, the effect of planting density on the salvage function $k(.)$ dominates the effects of planting density on the volume function $V(.)$ in the landowner's objective function. We can show that the cumulative probability at rotation age, which accounts for changes in rotation age with changes in fire risk, equals 0.43 when $t_0=1$, but it increases to 0.84 when $t_0=3$ for the fire arrival distribution.

Another interesting result is the inclusion of nontimber benefits. Nontimber benefits afford the landowner with additional rents from holding timber. These additional rents reduce the marginal contribution of planting density to increased yield, and rents, at harvest time. Accordingly, comparing the landowner who does and does not value nontimber benefits, it appears that the relative decrease in planting density is larger for the landowner who values nontimber benefits, especially at $t_0=2$ and $t_0=1$. In the face of increasing fire risk, the landowner who values nontimber benefits will also plant less, given that nontimber benefits provide an alternative form of rents (i.e., besides timber income). At very high levels of risk ($t_0=3$), there is less benefit from planting because fire is more likely to arrive before the contribution of planting to harvest is realized.

Our results show that introducing fuel reduction as a landowner choice allows the landowner some defense against high fire risk, and models without fuel reduction will miss this important interaction. Notice in the table that fuel reduction increases dramatically as fire risk increases. Increases in z are over 50% at $t_0=2$ as they are at $t_0=1$; there is a small decrease in fuel reduction from $t_0=2$ to $t_0=3$, mainly because the risk of fire is so high at $t_0=3$ that the landowner plants less, requiring less fuel reduction at the margin for salvage purposes (see the salvage function in Table 1). The increase in fuel reduction as fire risk increases is not as dramatic for landowners who value nontimber benefits. This is true for the same reason that planting density decreases were not as large for this landowner.

The optimal timing of fuel reduction ranges from 9 to 11 years in the table. For loblolly pine, these solutions are consistent with treatment ages recommended in practice for activities such as burning of fuels and brush removal (Wade and Lundsford, 1990). It is also worth noting that the level of fuel reduction appears to be considerably more sensitive to fire risk than the timing of this reduction. As fire risk increases, the landowner without nontimber benefits does not change their timing of fuel reduction (even though this landowner increases fuel reduction as we saw above). However, when the landowner values nontimber benefits, it appears that fuel reduction is done slightly later in the rotation, although the increase may not be statistically significant if one were to look at a large sample of landowners.

Perhaps the most striking observation from the table, and one that abstracts considerably from previous research, concerns how the landowner's rotation age choice responds to increases in fire risk. Reed (1984) and Englin et al. (2000) showed that increasing fire risk, measured like we do with an increasing fire arrival rate, shortens the rotation. They suggest that this occurs as the expected marginal cost of delaying harvest increases with fire risk. We do not find such a result here when fuel reduction is included as a decision for the landowner. Rather, referring to the table and the salvage function $k(.)$ evaluated at optimal choices, we see that fuel reduction increases salvage (see also Table 1). This additional protection for the landowner, should fire arrive, implies that the marginal expected cost of delaying harvesting decreases. This leads to increased rotation ages as fuel reduction increases in response to increases in fire risk.

We also again find an interesting dichotomy here with nontimber benefits. When the landowner values nontimber benefits, the increase in rotation age with increases in fire risk is greater. These landowners employ greater fuel reduction and longer rotation ages (more than 2 years at the highest level of t_0) compared to the landowner who does not value nontimber benefits. Again, nontimber benefits, modeled in the spirit of Hartman, provide the landowner with an additional benefit for extending any rotation. Thus, as fuel reduction decreases the marginal exposure of fire risk faced by the landowner, the landowner increases rotation age to enjoy additional nontimber benefits. The landowner who does not value nontimber benefits extends the rotation only because of increased salvage possibilities from increased fuel reduction. The landowner who values nontimber benefits enjoys these increased salvage possibilities plus additional nontimber benefits.

The responsiveness of fuel reduction and the increase in salvageable timber (i.e., decreases in fire losses) that occur as fire arrival rates increase suggest that improved information could encourage landowners to undertake fuel reduction at higher levels. We would therefore expect fire losses to be lower in cases where landowners on a landscape have this information. The results from Table 2 are consistent with this argument. Referring to the table, suppose landowners learned that the arrival rate was consistent with $t_0=3$ when they currently thought that the arrival rate was $t_0=1$. This landowner would increase fuel reduction for the next and subsequent rotations, thereby reducing fire losses by about 20% regardless of whether they valued nontimber benefits or not. Expected rents would also increase. Clearly there is a value of information concerning fire risk to the nonindustrial private landowner.

In Table 3, we compute the value of information using the results in Table 2. The elements of Table 3 were constructed by estimating the value of information as the difference in maximum expected rents of the landowner either over- or underestimating the

Table 3
Value of information about fire arrival rate[a]

Model	t_0	Expected rents if rate underestimated by 50%	Expected rents if rate overestimated by 50%	Expected rents if rate known accurately	Increase in rents	% Increase in rents
Without nontimber benefits	2.00		99	103	5	4.8
	2.00	***93***		***103***	***11***	***11.7***
With nontimber benefits	2.00		135	140	5	3.6
	2.00	***130***		***140***	***10***	***8.0***

[a] Results for underestimating rate by 50% in bold italics; results for overestimating rate by 50% in regular font.

average arrival rate. Formally, this value of information can be constructed in the following way. Suppose we denote the maximum expected rents as a function of all landowner decisions when these decisions are made optimally, conditional on information available to the landowner when the decisions are made. Let the true information set be ψ^*. Referring to Appendix A, let $M(d^*,z^*,s^*,T^*;\ \psi^*)$ denote maximum Faustmann rents when decisions are made optimally given perfect information, and let $M(d_0,z_0,s_0,T_0;\ \psi^0)$ denote maximum rents when decisions are made with inaccurate information, ψ_0. The value of information is given by $M(d^*,z^*,s^*,T^*;\ \psi^*)-M(d_0,z_0,s_0,T_0;\ \psi^*)$. The differences we observed in Table 2 are directly related to this value.

Referring to Table 3, we have computed the value of information for the case where a landowner either over- or underestimates risk of fire for each rotation. Using the computation above, from Table 2 we arrive at the value of information as the increased maximum expected rents from the landowner knowing the correct value of t_0. The bolded italicized numbers in Table 3 represent cases where a landowner underestimates fire risk, while non-bolded numbers represent cases where the landowner over–estimates fire risk.

As the table shows, except for a few scenarios, the value of this type of information is positive, ranging from nearly 4% to nearly 12% of rents depending on whether the landowner values nontimber benefits or not. Recall we saw in Table 2 that landowners who valued nontimber benefits enjoyed an additional form of rents throughout the rotation, and this meant that they were not affected as much on the margin by fire risk as those landowners who do not value nontimber benefits. This follows through to the value of information computation. Landowners who value nontimber benefits do not obtain as much benefit from information, because information does not cause them to make better decisions that affect nontimber benefits much (only rotation age affects nontimber benefits owing to their Hartman form). The maximum benefit of information regarding the fire arrival rate to this type of landowner is 8%, or roughly 10 dollars per acre, when the landowner underestimates the true magnitude of the fire arrival rate.

The story is somewhat different for a landowner who does not value nontimber benefits. Here, the only rents captured by the landowner are those from harvesting at rotation age. Thus, the benefit of having better information to this landowner, in terms of decreasing fire losses, is higher. Referring to Table 3, maximum rent increases by about 11 dollars per acre, or about 12%, when the landowner underestimates fire risk and receives information about the true rate.

Perhaps the most important result to take from the table concerns over- versus underestimation of fire arrival rates. It is probably the case that most landowners underestimate the probability that fire will arrive during a rotation. Our results show that this landowner's rents are reduced the most from not having correct information, regardless of whether the landowner values nontimber benefits or not. Referring to the table, the difference in maximum expected rent increases for a landowner who underestimates risk relative to one that overestimates the true value of fire arrival rates is 6.9% and 4.4% for the landowner who does not and does value nontimber benefits respectively. Clearly, the landowner who overestimates fire arrival rates will take greater steps to reduce risk through increased fuel reduction and lower planting densities (see Table 2). In terms of fire losses, the misinformed landowner is always better overestimating fire risks when making decisions.

4. Conclusions

Fires are happening frequently along the wildland–urban fringe. Two features of forest fire risk will become increasingly important in this area. First, this fringe will be populated by nonindustrial private landowners with multiple reasons for owning forest land. As land continues to fragment, it is expected that there will be large numbers of these landowners in close proximity. Second, landowners will, as always with long-term assets such as forests, be forced to make decisions with imperfect knowledge of fire arrival probabilities. Not knowing fire arrival probabilities will result in poorly informed decisions being made regarding forest management. These mistakes will then reduce the rents a landowner can earn from forest management. However, these mistakes will also increase fire losses should fire arrive, because landowners who have better information will undertake costly fuel reduction to protect their forests. Reduced severity of fire because of fuel reduction can also benefit the government through decreased fire suppression expenditures once fire arrives on a given acre.

We study these issues in this paper, using a simulation based on a Faustmann model under uncertainty suggested first by Reed (1984) and Englin et al. (2000), who studied rotation age decisions, and modified recently by Amacher et al. (in press) to include fuel reduction, planting density, rotation age, and, most importantly, the level and timing of fuel reduction. The underlying probability structure of this model is to assume that fires arrive via a Poisson distribution. Fuel reduction reduces severity of fire when it arrives. Both landowners who do and do not value nontimber benefits, in the Hartman sense (Hartman, 1976) are considered.

We examine, using a simulation based on published information, both how decisions are made under various levels of fire risk, and how information regarding fire arrival rates affects these decisions. We then compute a value of information as the increase in expected maximum rents when the landowner has perfect information about fire arrival rates compared to the case where the landowner either under- or overestimates the fire arrival rate.

We find that increases in fire risk do not necessarily decrease rotation age, as others have repeatedly shown. Rather, increased risk prompts landowners to increase fuel reduction efforts and plant less in response to additional costs of continuing any rotation. This in turn leads to increased rotation ages. Landowners who value nontimber benefits do not respond as much to the increased fire risk, as these landowners enjoy an additional contribution to rents that does not depend on fire arrival as much as forest yields. These landowners are not likely to change behavior as much when new information is available.

The value of information computations is consistent with these observations. Misinformed landowners stand to gain upwards of 10–12% of rents when information becomes available, with information being less important for the landowner who values nontimber benefits. Most importantly, the value of information is higher for those landowners who underestimate the fire arrival rate than for those who overestimate fire arrival rates, irrespective of whether the landowner values nontimber benefits or not. This is because the latter will take steps to defend themselves against high fire risk through their fuel reduction choices.

There are some worthwhile extensions that could be considered. First, anything the government can do to encourage fuel reduction, such as disseminating information about fire risks, will lead to the type of behavior that reduces fire suppression and related social costs. Landowners with imperfect information themselves stand to benefit upwards of 10–11 dollars per acre from correct information about the magnitude of the fire arrival probability, and this can be significant on a large scale. The policy implications of fuel reduction have yet to be studied. Second, the importance of fuel reduction to nontimber benefits or to forest volume could be considered, but we suspect that inclusion of these effects would only increase the value of information. Other salvage assumptions might also be examined, as this is also important in the absolute value that information affords the forest landowner.

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Appendix A. Landowner fire risk model

Fires arrive randomly over time via a Poisson process with parameter λ, which captures the average fire arrival rate. The probability of fire arrival is assumed here to follow a uniform distribution, so that λ is constant—this amounts to assuming a random walk consistent with inherently unpredictable weather and demographic-related effects on fire occurrence. The time between fire arrivals during any rotation is an exponential random variable, X, with a cumulative distribution function $(1-\mathrm{e}^{-m(X)})$, where $m(X)\equiv\int_0^X \lambda(u)\mathrm{d}u$ and the probability density function for X is $\lambda(X)\mathrm{e}^{-m(X)}$.

Given a rotation age of T, the probability that a fire arrives before the end of a rotation is $Pr(X<T)=(1-e^{-m(T)})$. The probability the stand reaches the rotation age and is "destroyed" through harvesting is then $Pr(X=T)=e^{-m(T)}$.

To construct expected rents for the landowner, we need to specify a salvage function, a volume function, and nontimber benefits as functions of important landowner decisions. The salvage function is discussed in the text. Forest volume at harvest is assumed to be a concave function of rotation age and planting density, $V(X,d)$, where $\frac{\partial V(.)}{\partial X}>0$ and $\frac{\partial V(.)}{\partial d}>0$. Little is known about whether fuel reduction affects forest volume. Given that these treatments cover strategies such as brush removal and burning of surface fuels, it is safe to assume that z does not affect harvest volume. Indeed, the effects of burning of surface fuel and other fire protection activities on volume have been deemed inconclusive at best (Waldrop et al., 1987; Waldrop, 1997). We therefore assume that $V(.)$ does not depend on z. Nontimber benefits are introduced in a conventional manner, following Hartman (1976) and Englin et al. (2000), according to the following felicity function for periods with no harvesting, $\delta\int_0^t B(t)e^{-rt}dt$, where r is the interest rate, and δ is the weight attached to nontimber benefits by the landowner ($0\le\delta\le1$). Nontimber benefits are assumed not to depend on z, mainly because previous research does not provide any quantitative evidence regarding this relationship.

Let Y denote the landowner's current value of cash flow, or net rent. This is a random variable in our model because it depends on the arrival of fire. There are three possible realizations for Y. If a fire occurs at $X<s$, i.e., before fuel reduction is applied, then the landowner salvages nothing and incurs a cost of reestablishing a new forest,

$$Y_1 = e^{rX}\delta\int_0^X B(t)e^{-rt}dt - C_2(d) \quad \text{if } X<s, \tag{A1}$$

where $C_2(d)$ is the cost of planting per acre on burned land.

If fire occurs during the time interval $s\le X<T$, that is, after fuel reduction has been applied but before the rotation age is reached, then the landowner salvages a portion of stock, incurs the cost of reestablishment, and incurs a compounded cost of z previously incurred at time s,

$$Y_2 = pk(z,d)V(X,d) + e^{rX}\delta\int_0^X B(t)e^{-rt}dt - C_2(z)e^{r(X-s)} \quad \text{if } s\le X<T, \tag{A2}$$

where p is timber harvest price, taken exogenously by the landowner, $C_3(z)$ is the compounded cost of fuel reduction paid at time s, and $k(z,d)$ is the salvage function (discussed in the text).

Finally, if the rotation period T is reached without a fire, then the landowner harvests all of the timber stock, incurs the cost of establishing a new forest, and incurs the compounded cost of z paid at time s,

$$Y_3 = pV(T,d) + e^{rX}\delta\int_0^T B(t)e^{-rt}dt - C_1(d) - C_3(z)e^{r(T-s)} \quad \text{if } X=T. \tag{A3}$$

where $C_1(d)$ is the cost of planting per acre on unburned land.

Using (2)–(4), the landowner maximizes expected net discounted rents for an infinite series of rotations,

$$M(d^*,z^*,s^*,T^*)\equiv\text{Max}_{d,z,s,T}\frac{E(e^{-rX}Y)}{(1-E(e^{-rX}))} - c_1, \tag{A4}$$

where c_1 is initial planting cost in the first period (subsequent planting costs are included in Eqs. (A1) (A2) (A3). The value of information is developed in Amacher et al. (in press) as the difference in the maximum present value of rents with and without accurate information. Suppose the true information set is ψ^*. Then $M(d^*,z^*,s^*,T^*;\ \psi^*)$ is the maximum expected rent when decisions are made optimally given accurate information. Let $M(d_0,z_0,s_0,T_0;\ \psi^0)$ denote maximum expected rents when decisions are made with an "inaccurate" information set ψ^0. The value of information is then $M(d^*,z^*,s^*,T^*;\ \psi^*)-M(d_0,z_0,s_0,T_0;\ \psi^*)$.

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