Prescribed Fire: Liability, Regulation, and Endogenous Risk

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1 Introduction

For many decisions, timing is crucial. For decisions with potential environmental impacts, the timing of an action will be affected by the extent to which the decision maker bears all the potential costs or benefits of a decision, and legal liability rules provide incentives that may alter the timing of decisions. This paper extends the economic literature on liability rules by focusing on their effects on the timing of decisions that impose potential negative externalities on others, and draws on the existing economic theory of optimal timing of investment, forest rotation decisions under uncertainty. The model is developed around the issues of prescribed fire use and wildfire risk mitigation, two related issues that are regularly in the news but have not received much attention in the economics literature.

The use of prescribed fire faced strong resistance from policy makers and natural resource managers through much of the 20th century (Pyne 1982, Biswell 1989), but is increasingly recognized as a useful tool to increase rangeland and forest productivity, biodiversity, and to reduce wildfire risk and severity (Bernardo et al. 1988, Svejcar 1989, Briggs and Knapp 1995, Zimmerman 1997, Babbitt 1995, Pattison 1998). The Federal government now formally recognizes the use of prescribed fire as an integral element of wildfire management (U.S. Department of the Interior, U.S. Department of Agriculture 1995), and the use of prescribed fire on federal land is increasing. Haines et al. (1998) report that the number of national forests using prescribed fire increased by 76 percent between 1985 and 1994 (Shaver 2000). About 900,000 acres of Federal land was treated with prescribed fire in 1995, and the acreage had increased to 2.2 million acres by 1999 (National Interagency Fire Center 2001).

Nonetheless, prescribed burning is an inherently risky resource management tool. A prescribed fire set by the US National Park Service near Los Alamos, New Mexico in May 2000 resulted in a 48,000-acre wildfire, destroying about 220 homes and affecting about 400 families (Claims Magazine Staff Writer 2000). Litigation resulting from an escaped wildfire can be costly and time-consuming as well. For example, the plaintiff in a case (Lowe vs Jones et al., Case No. CJ 95-345) tried in Osage County, Oklahoma argued for $9.3 million in damages in a 200-acre wildfire that the plaintiff claimed resulted from a prescribed burn on adjacent property. No structures were burned, only grassland. Although no judgement was found for the plaintiff, legal and other fees for the defense approached $0.5 million.

In the absence of statutory law, the Common Law relating to prescribed fire is generally based upon negligence: to be found liable for damage to a neighbor's property, the burner must be found to not have taken a reasonable level of precaution to reduce the likelihood of damage to the neighbor's property (25 ALR5th 391). Today, virtually all states have codified civil or criminal statutory law for prescribed burning, but the structure of these laws varies substantially across states. Only four states impose strict liability on prescribed burners such that they are liable for the damage caused by an escaped prescribed fire regardless of the precautions they take to control the fire. Most states with prescribed fire statutes impose negligence rules of some form on the prescribed burner, but again, these negligence rules vary substantially across states. In some states, losing control of a prescribed fire is *prima facie* evidence of negligence. In others, the burden of proof is on the plaintiff to show the negligence of the individual who performed the prescribed fire. Not only do prescribed burning laws vary substantially across states, but these laws currently are in flux. The laws in most states have been revised since 1990, and a number of statutes are currently under review.

A model of the incentive effects of basic liability alternatives on prescribed fire use, precaution, and timing is developed. The model builds on a previous paper by Yoder et al. (2003) that examines the comparative advantages of various liability rules and regulatory regimes for addressing prescribed fire risk. Because prescribed fire is often used to mitigate wildfire risk (Prestemon et al. 2001, Loomis et al. 2000), the analysis is extended to compare the efficacy of different liability rules when prescribed fire can be used to reduce the risk of a landholding contributing to the spread of naturally occurring wildfire. The model is then applied to an empirical examination of prescribed fire use and risk in the United States. Data for all prescribed fires are not currently available, but annual, state-level estimates of the number and average size of *escaped* prescribed fires are available. These data are used here to show the effect of variation in the stringency of liability and related statutory law on the incidence of escaped prescribed fires.

The next section begins with a model of efficient prescribed fire use, and then proceeds to examine the incentives and implications associated with strict liability and negligence rules. Wildfire risk is then introduced to show how it changes the efficient use of prescribed fire in relation to each liability rule.

2 A model of prescribed fire use and timing

Prescribed fire use is modelled as a modified Faustmann rotation problem in which the landowner maximizes the net present value of all future fire rotations by choosing the length of time between prescribed burns. In addition to timing, two other precautionary inputs are available: mitigation of potential damage, and precautionary effort to reduce the probability of unintentional damage occurring (the importance of the distinction between these two inputs will become apparent in the discussion of liability). Given the burner's private optimal input use and timing, the burner pursues a prescribed fire rotation if his private expected net present value of doing so is positive, but does not if the expected net present value is nonpositive.

A number of specifications for the time-path of prescribed fire benefits, and probabilities of prescribed fire escapes, and damage specifications are possible. It is assumed here that benefits from land productivity, $R(t)$, are received in the period of production rather than at the end of a rotation as in a standard timber rotation model. This specification more closely resembles the benefit stream from prairie upon which forage benefits or wildlife benefits accrue.[1] The value of one rotation of prescribed fire of a given size, viewed from the perspective of the end of a rotation, is modelled in the following way:

$$Y(T, B, V) = e^{rT}\left(\int_0^T R(t)e^{-rt}\mathrm{d}t - W^v V\right) - D(V)P(B, T) - W^b B, \tag{1}$$

where

- t is a time index starting at the completion of the last fire, and T is denotes the time at which the prescribed fire is performed.
- $R(t)$ is the value of production for the t^{th} year after the last burn. $\int_0^T R(t)e^{-rt}\mathrm{d}t$ is therefore the stream of benefits between fires.
- V represents investment in mitigation of potential damage. W^v is the marginal cost of investment. The investment is assumed to be made at the beginning of each rotation.
- $D(V)$ is potential damage, or the level of damage in the event that damage occurs. This damage may include the additional costs incurred for extinguishing a wildfire that would not have been incurred otherwise, but for the purposes of this paper these costs are assumed exogenous and implicit in $D(V)$.

[1] In a timber production setting, the decision could be modelled as a nested rotation problem with two state variables: one representing the time from the last harvest, and one representing the time from the last prescribed fire.

- B is the level of precautionary effort exerted to control a prescribed fire when one is performed, and W^b is the marginal cost of prescribed fire precautionary effort.

- $P(B,t)$ is the probability of damage given a fire in period t and precaution B. If a fire in period t starts by natural causes (unintentional), then $B = 0$, which is to say that no prescribed burn preparation is performed. $P(0,t)$ is the probability of a fire in period t causing damage to neighboring property given no precaution by the landowner ($B = 0$).

- r is the discount rate.

The term "timing" and its index t are used for clarity, but it can be considered to represent a vector of characteristics that changes over time related to both the value and the volatility of the vegetation.

The present value of all future rotations is then:[2]

$$\begin{aligned} PV(T,B,V) &= \sum_{i=1}^{\infty} Y(T,B,V)e^{-irT} \\ &= \frac{Y(T,B,V)}{e^{rT}-1}. \end{aligned} \tag{2}$$

The first-order necessary conditions for a maximum of this expected present value func-

[2]The second representation of $PV(T,B,V)$ follows from the first because of the infinite sum:

$$\sum_{i=1}^{\infty} e^{-irT} = e^{-rT}\sum_{i=0}^{\infty} e^{-irT} = \frac{e^{-rT}}{1-e^{-rT}} = \frac{1}{e^{rT}-1}.$$

tion are

$$R(T) - D(V)P_T \leq rPV(\cdot) - r\left[D(V)P(B,T) + W^b B\right] \tag{3a}$$

$$-e^{-rT}D_V(V)P(B,T) \leq W^v \tag{3b}$$

$$-D(V)P_B(B,T) \leq W^b \tag{3c}$$

where subscripts denote partial derivatives. Condition 3a is the first-order condition for the optimal timing to perform a prescribed burn, and is essentially a Faustmann-type result. The left-hand side is the expected benefit of waiting to perform a prescribed burn in period T (or the opportunity cost of burning), net the change in expected damage at time T. The right hand side represents the opportunity cost of waiting (or the benefits of not waiting). This includes the usual Faustmann rent term $[rPV(\cdot)]$ minus the value of expected damage and precaution costs in period T. Condition 3b shows that damage mitigation effort V is performed such that the marginal cost of mitigation $[W^v]$ is equated to the present value of the marginal expected benefit of mitigation given the the possibility of prescribed fire. Condition 3c shows that during the prescribed burning, the expected marginal reduction in damage from prescribed burning precaution is equated with the marginal cost of precaution during a prescribed burn.

One important characteristic of prescribed fire risk is seasonality. Over the course of a number of years, there are likely to be a number of local optima, and functions corresponding to the "marginal benefit of waiting" and the "marginal cost of waiting" could conceivably cross numerous times as well. The first-order condition for T can be interpreted as a switching condition applicable to a dynamic programming framework (Thomson 1992).[3]

[3]the problem of asset replacement under uncertainty has a similar structure. Recent papers by (Dixit et al., Willassen 1998, Sødal 2002) on optimal investment focus on problems in which the change in the value of investment over time follows a Markov Process. The structure of uncertainty is different here in that a

Figure 1: Present value stream of benefits and expected damage over time. Top: levels. Bottom: marginals.

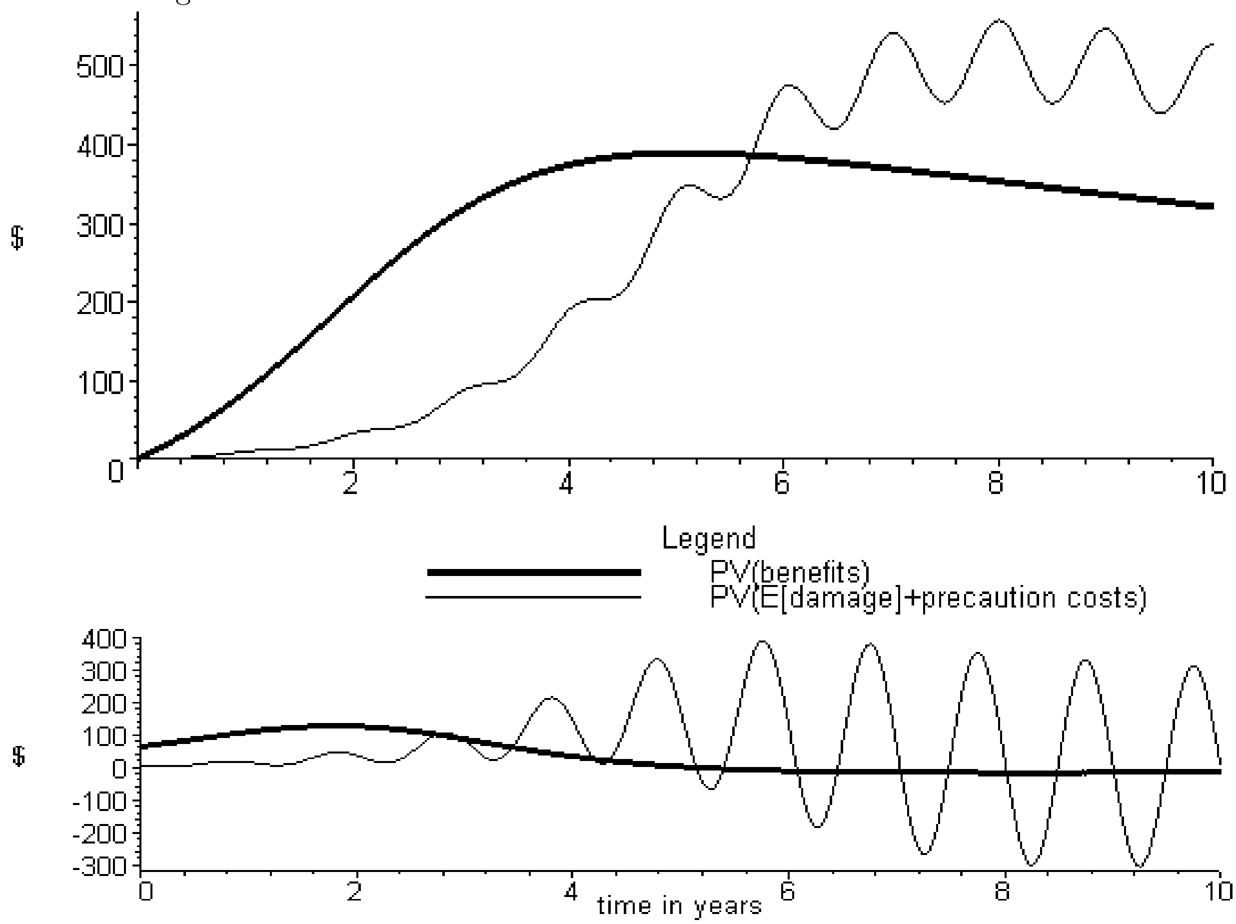


Figure 1 shows one plausible stream of the present value of benefits and costs from a prescribed fire in which timing across years and within years matters. The cyclical nature of fire risk is very important for prescribed burning and is represented by the annual cycle of the expected damage functions. Vegetation growth is usually cyclic as well, but this cycle is omitted for clarity. Also in the figure, both the benefits and the risk of fire use grows as vegetation matures, but that the vegetation growth temporally leads fire damage risk

deterministic evolution of the expected value function is assumed, but the agent faces the possibility that a catastrophic event will end a rotation and reduce the value of the resource.

in terms of the long term trend. This lag in fire damage risk thus provides a window for maximizing the net value of prescribed burning that disappears after a number of years ("Burn early and burn often" is a common motto among prescribed fire professionals). The marginal benefit and marginal cost curves cross virtually every year, but it is in the third year (t=3.24) that the benefits of a prescribed burn are maximized. If a burn is not performed at that time, then in any given year there is local optimum for performing a prescribed burn.[4]

3 Timing and care under strict liability and negligence

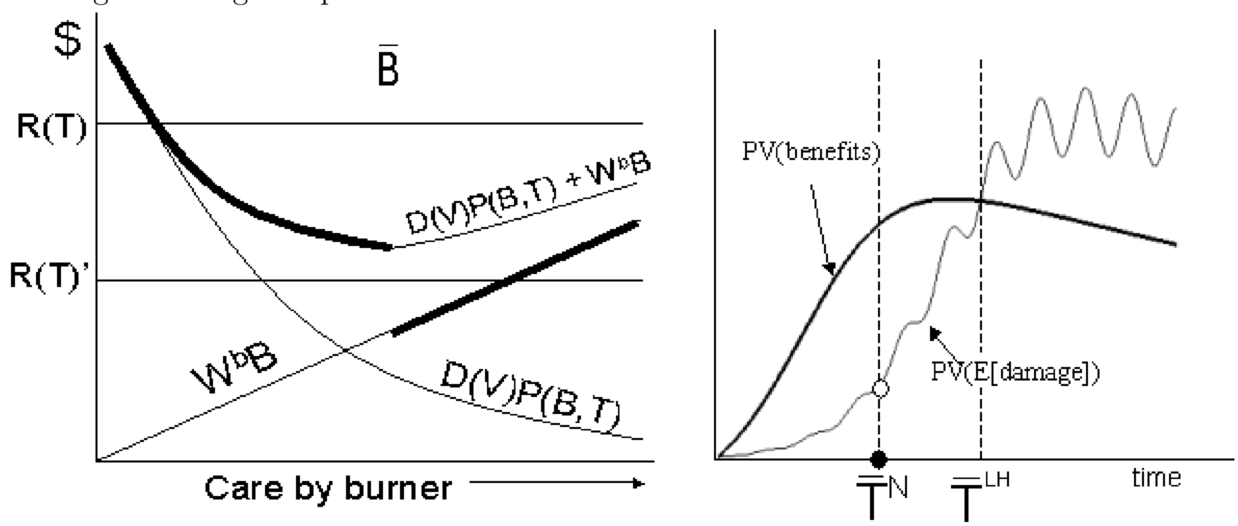
The previous section presents the foundation of the model of prescribed fire timing and precautionary incentives, and provides the necessary conditions for efficient timing and damage mitigation and precaution by participants. The focus of this section is a comparison of timing and precautionary incentives under strict liability versus a negligence standard.

In the previous section, the incidence of benefits, damage costs, and mitigation costs between participants is ignored. In this section, the benefits and costs are distributed as follows. The burner bears all benefits $[\int_0^T R(t)\mathrm{d}t]$ from fires. To maintain a focus on the externality effects associated with cross-boundary spread of fire, define $P(B,t)$ as the probability of a fire (prescribed or otherwise) spreading to a neighbor's land and inflicting damage on the neighbor's property. Investment in mitigation of potential damage, V, is performed by the victim, and precautionary effort, B, is performed by the prescribed burner when a prescribed fire is performed.

To begin, assume that a two-dimensional negligence standard is set at the efficient level

[4] Given multiple optima and a cyclical fire risk, the assumptions $P_{Bt} > 0$ and $P_{tt} < 0$ no longer strictly hold for all t. However, it is reasonable to assume that at the chosen T under each liability rule, $P_T > 0$, which implies that expected damage is increasing at the margin. Then $P_{BT} > 0$, assuming that precaution and burning early are technical complements for risk reduction.

Figure 2: Precaution and timing under a negligence rule. Left: precaution given a prescribed fire. Right: timing of a prescribed fire.



according to first-order conditions 3a and 3c for timing ($\bar{T} = T^*$) and precaution, ($\bar{B} = B^*$). If the burner satisfies these standards, he does not bear the damage costs if a fire escapes. In order to maximize his own private net benefits, the burner will choose exactly precaution level $\bar{B}$ and timing $\bar{T}$ in order to satisfy the standard at minimum cost. This result is shown in figure 2 (left panel), in which discontinuities in the expected damage functions for both B and T induce efficient precaution.[5] Notice, however, that unlike the standard on $\bar{B}$, $\bar{T}$ is a two sided standard — the burner must not burn too early, nor too late, or he will be forced by the court to bear the costs of an escaped fire (This result is shown in figure 2, right panel, $\bar{T}$). Under the assumption of full information, the victim knows that the burner has the incentive to satisfy the negligence standard and expects to incur any damage sustained. The victim therefore has an incentive to perform efficient damage mitigation V^*.

This exact form of negligence rule $\bar{T}$ at V^*, is generally not implemented, arguably due to high information costs. Instead, aspects of prescribed fire law appear more similar to a

[5]This argument follows Brown (1973) and others since.

"Learned Hand" negligence rule in which a burner is found negligent if the net social benefit is nonpositive, e.g. to the right of $\bar{T}^{LH}$ in figure 2. A negligence rule set at $\bar{T}^{LH}$ will tend to induce excessively long rotation lengths, leading to higher than optimal expected damage.

In contrast to negligence rules, strict liability rule requires the burner fully reimburses the neighbor for damage. Under this rule, the neighbor has no incentive to exert damage mitigation effort; his private benefits of doing so are zero because he is fully reimbursed for any damage incurred. Therefore, potential damage under a strict liability rule is at it's maximum: $D(0) = D^{\max}$. If the efficient level of V is larger than zero, potential damage under a strict liability rule will be higher than under a negligent rule.

4 Implications for the incidence of escaped prescribed fires

Landowners respond differently to strict liability and negligence rules. The number of landowners choosing to perform prescribed fires will differ, and their timing and precaution levels will differ. Under a strict liability rule, potential damage will be higher than the efficient level. Under a negligence rule, burners do not bear the damage from an escaped prescribed fire at all given that they satisfy the negligence standard, so expected damage costs to the burner are zero. According to the Envelope Theorem, the effect of an increase in $D(V)$ on the expected net present value of prescribed fire rotations is

$$\frac{\partial PV(\cdot)}{\partial D(V)} = -\frac{P(B^s, T^s)}{e^{rT} - 1} < 0. \tag{4}$$

This may affect whether a landowner finds it in his interest to perform prescribed fire rotations in exactly the same way that zero profits induces a firm to shut down in a simple model of the firm. If the benefits from prescribed burning vary from landholding to landholding and expected net present value of prescribed fire rotations can be nonpositive, fewer landowners will choose to pursue prescribed fire practices at all under a strict liability rule than when neighbors have a stronger incentive to mitigate potential damage. This leads to the first of several implications from the model that are tested empirically in the following section:

Proposition 1. *Fewer landowners will use prescribed fire under strict liability than an efficient negligence rule.*

Consider now the effects of the difference in expected damage costs under strict liability and negligence rules. The change in T and B with respect to a change in $D(V)$ are:

$$\frac{\mathrm{d}T}{\mathrm{d}D(V)} = \frac{D(V)}{|\mathbf{H}|}[(rP - P_T)P_{BB} + P_B P_{BT}] \lesseqgtr 0 \tag{5}$$

$$\frac{\mathrm{d}B}{\mathrm{d}D(V)} = \frac{D(V)}{|\mathbf{H}|}[(P_T - rP)P_{BT} + P_B(\mathbf{H}_{11}/D(V))] \lesseqgtr 0 \tag{6}$$

where $|\mathbf{H}| > 0$ is the determinant of the Hessian matrix for the problem and $\mathbf{H}_{11} < 0$ is the upper left element of **H**Both of these results are indeterminate. However, if the risk of escape is increasing rapidly (P_T large) and/or the probability of escape is low ($P(B, T)$ low, then rotation lengths will be shorter and precaution usage will be higher where D is large; burners will burn early before the risk gets too high. By doing so, the marginal product of precaution tends to be lower, and precautionary effort may be lower than it would be later. On the other hand, if a potential burner already is in a situation with mature, hard-to-control fuel loads, large potential damage induces a longer wait and, when a prescribed fire is used, more precautionary effort. In these situations, however, it is also more likely that the net expected benefits of prescribed fire will be negative and a prescribed fire rotation will not be utilized at all.[6]

In summary, strict liability leads to less (zero) risk mitigation by neighbors than an efficient negligence rule, so $D(V)$ is larger, leading in turn to shorter rotation lengths in young, rapidly growing fuel loads, or longer rotation lengths if landowners find themselves with more mature, coarse vegetation.

These differences in rotation length and precaution affect the probability of an escape given that a fire is started. Based on the comparative statics results 5, the change in $P(B, T)$ with respect to a change in $D(T)$ is

$$\begin{aligned}\frac{\partial P(B^s, T^s)}{\partial D(V)} &= \frac{\partial P}{\partial B}\frac{\partial B}{\partial D(V)} + \frac{\partial P}{\partial T}\frac{\partial T}{\partial D(V)} \\ &= \frac{D(V)}{|\mathbf{H}|}\Big[(rP - P_T)(P_T P_{BB} - P_B P_{BT}) + P_T P_B P_{BT} + P_B^2(\mathbf{H}_{11}/D)\Big] \lesseqgtr 0.\end{aligned}$$

The second and third terms in the sum are negative. The first term will be negative unless $rP > P_T$. Because potential damage will be larger under strict liability, the endogenous probability of escape under strict liability will tend to be smaller than under an efficient negligence rule unless the probability of escape is very high relative to the change in the probability of escape over time.

Proposition 2. *A strict liability rule will tend to induce a smaller endogenous probability of escape than a negligence rule.*

[6] In the simple case where T is the only choice variable, then the comparative static results turns entirely on $rP - P_T$. If P is increasing at a rate smaller than r, then the rotation lengths will be longer for large D. If P is increasing at a rate larger than r, then an increase in D leads to a decrease in rotation length T. According to equation 5 the use of the input B makes it more likely that rotation lengths will be shorter as D increases. Similarly, in the single input case with B, $\frac{\mathrm{d}B}{\mathrm{d}D(V)} > 0$. With rotation length T as an additional choice variable, only a large probability of damage will induce decreasing T to the point where the marginal product of B is smaller than before the increase in D.

5 Wildfire risk and prescribed fire timing

An important element of wildfire risk mitigation is fuel load management, and a crucial factor in wildfire risk is the volume and characteristics of the vegetation as a fuel load. Because plants grow over time and in doing so change in terms of fire ignition and fire intensity potentials, a dynamic approach is called for that accounts for these changes over time. The decision whether or not to perform a prescribed fire then becomes a decision about *when*, if ever, to burn. The Faustmann-type model is extended here to account for wildlife risk. This section draws on Englin et al. (2000) and Reed (1984), who develop similar models of optimal timber harvest in the face of wildfire risk.

The timing of prescribed burning matters to the neighbor for two reasons: first, performing a prescribed burn reduces the fuel load on the burner's land, and thereby may change the probability of a wildfire occurring on the burners land, thus reducing the probability of a fire spreading onto the neighbor's land. Therefore prescribed burning provides positive expected benefits to the neighbor in terms of a reduction in wildfire risk. Of course, prescribed burning is risky as well, and the probability of a prescribed fire escaping onto the neighbors land depends in part on the intensity of the prescribed fire. Fire intensity is in turn dependent on the coarseness and volume of the fuel load, both which tend in many vegetative systems to increase over time. Thus, generally speaking, the longer a prescribed burn is postponed, the higher the probability of escape for any given level of precautionary effort by the burner.

Consider two scenarios: One in which a prescribed fire is performed that consumes vegetative fuel before a wildfire occurs, and one in which a wildfire occurs by natural causes before a prescribed fire is performed. Using notation similar to Englin et al. (2000), let $Y(X, T, V, B)$ be the value of one rotation (fire to fire). X is a variable representing the duration between either a prescribed fire or a wildfire; it is a random variable because the occurrence of a wildfire is a random event. T, V, and B are defined as before. If a wildfire precedes the date chosen for a prescribed fire then the rotation is cut short by a wildfire and $X < T$. If the rotation is completed with a prescribed fire, then $X = T$. The two possible outcomes for $Y(X,T,V,B)$ as viewed from the end of the rotation are

$$Y(X,T,V,B) = \begin{cases} e^{rX}\left(\int_0^X R(t)e^{-rt}dt - W^v V\right) - D(V)P(0,X) & \text{if } X < T \\ e^{rT}\left(\int_0^T R(t)e^{-rt}dt - W^v V\right) - D(V)P(B,T) - W^b B & \text{if } X = T. \end{cases} \tag{7}$$

Given the two possible outcomes, the expected net present value of the property is the sum of the two values times their respective probability of occurrence. Following Reed (1984, p. 189), allow wildfire risk to vary as a function of the age of the vegetation by assuming a non-homogeneous Poisson distribution for the time between wildfires. To define this distribution, let

$$m(t) = \int_0^X \lambda(t)\mathrm{d}t,$$

where $\lambda(t)$ is the mean of the Poisson distribution at time t. It follows that the time between successive wildfires (given no intervening prescribed burn) is $F(t) = 1 - e^{-m(t)}$, and the probability density function is $m'(t)e^{-m(t)}$ (Thomasian 1969, p.584-587). Notice also that $m'(z) = \lambda(z)$ which is the probability of a wildfire at any instant z, and that if $\lambda(t) = \lambda$, then the Poisson distribution is unchanging (homogeneous) over time.

If a prescribed burn is performed at time T, this wildfire distribution is censored at time T. Specifically, the probability density function for t is

$$f(t) = \begin{cases} \lambda(t)e^{-m(t)} & \text{for } 0 < t < T \\ e^{-m(T)} & \text{for } t = T \end{cases} \tag{8}$$

for any chosen prescribed fire rotation length T, the probability of wildfire occurrence before the prescribed fire is performed is $\text{Prob}(X < T)$=$1 - e^{-m(T)}$.

Following Englin et al. (2000), the expected net present value of of the land for a chosen is

$$\text{PV}(X, T, B, V) = \frac{\text{E}\left[e^{-rX}Y(X, T, B, V)\right]}{1 - \text{E}[e^{-rX}]}. \tag{9}$$

The numerator of $\text{PV}(T, B, V)$ is the expected net present value of a single rotation given the probability of a wildfire occurring prior to T:

$$\begin{aligned}
&\text{E}\left[e^{-rt}Y(X, T, B, V)\right] = \\
&\qquad \int_0^T e^{-rt}\left[e^{rt}\left(\int_0^t R(z)e^{-rz}dz - W^v V\right) - D(V)P(0, t)\right]\lambda(t)e^{-m(t)}\text{d}t \\
&\qquad\quad + e^{-rT}\left[e^{rT}\left(\int_0^T R(t)e^{-rt}dt - W^v V\right) - D(V)P(B, T) - W^b B\right]e^{-m(T)}
\end{aligned} \tag{10}$$

The denominator of $\text{PV}(T, B, V)$ is the expected discount factor, where

$$\begin{aligned}
\text{E}\left[e^{-rX}\right] &= \int_0^X e^{-rt}\lambda(t)e^{-m(t)}\text{d}t \\
&= \int_0^T e^{-rt}\lambda(t)e^{-m(t)}\text{d}t + e^{-rT}e^{-m(T)}.
\end{aligned}$$

Efficient timing T and effort levels V and B are those values that satisfy the first-order conditions $\partial PV(\cdot)/\partial T = 0$, $\partial PV(\cdot)/\partial B = 0$, and $\partial PV(\cdot)/\partial V = 0$. After rearrangement and simplification, these conditions can be represented as

$$R(T) - D(V)[P_T(B,T) + \lambda(T)P(0,T)] \geq rPV(T) - (r+\lambda(T))\left[D(V)P(B,T) + W^b B\right] \quad (11a)$$

$$-D_V(V)\left[\int_0^T P(0,t)e^{-(rt+m(t))}\lambda(t)\mathrm{d}t + p(B,T)e^{-(rT+m(T))}\right] \geq W^v \quad (11b)$$

$$-D(V)p_B(B,T) \geq W^b. \quad (11c)$$

These first-order conditions are not of direct concern for this paper and will not be discussed in detail, but are provided for comparison to first-order-conditions 3a–3c.

What is of direct interest for this paper is the impact of the liability on the timing of prescribed burning in the presence of wildfire risk. A growing literature supports the hypothesis that prescribed fire can be used to reduce wildfire risk (Prestemon et al. 2001). Under a strict liability rule, prescribed burners are held liable for any damage spreading as a result of a fire they start. However, such a liability rule does not impose liability for unintentional wildfires spreading to neighboring land.[7] This fact leads to a further difference between efficient incentive for prescribed fire timing. To show this, assume in this section only that victims cannot mitigate potential damage (this assumption simplifies the formal analysis substantially). Given this assumption, it can be shown that as change in timing with respect to a change in the instantaneous risk of wildfire at the time of the prescribed fire is

$$\frac{\partial T}{\partial \lambda(T)} = -\frac{D^2 P_{BB}(P(0,T) - P(B,T))}{|\mathbf{H}|} < 0,$$

where $|\mathbf{H}| > 0$ to ensure a maximum. This result suggests that if the burner ignores the probability of wildfire (effectively assuming it as zero rather than positive), the burner will wait too long before performing a prescribed fire. Given that a negligence standard is set

[7] A handful of states have negligence rules relating to the spread of wildfires, but this is a different matter.

according to first-order conditions 11c and 11a, prescribed fire rotations will be performed (and therefore more prescribed fires in any given time period).[8]

Proposition 3. *More prescribed fire, and more escaped prescribed fires, will tend to occur under an efficient negligence rule relative to a strict liability rule when the risk of natural wildfires is high.*

6 Additional implications and extensions

Based on the same logic as proposition 4 and the hypothesis that victim mitigation will be lower under a strict liability rule, the following proposition holds:

Proposition 4. *As the value of potential damage increases, the number of escaped prescribed fires decreases.*

This is perhaps the most intuitively obvious result, but it has implications about where prescribed fires will be set and the extent of precaution in various settings. For example, vegetation management may be crucial on the rural-urban fringe, but the risks associated with prescribed fire will induce both fewer prescribed fires and more precaution given that one is performed.

Precaution costs also affect the use of prescribed fires as a land management tool. Generally speaking, as the size of a prescribed fire increases, the per-acre cost of precaution decreases (Cleaves et al. 2000). Furthermore, for any given planned fire size, it is more likely that a fire will be kept within the borders of larger landholdings of a fire temporarily escapes. Therefore, more reported escapes are expected where landholdings are small.

Proposition 5. *As landholding size increases, the number of escapes decreases.*

[8]The implications of endogenous potential damage have not yet been formally derived.

Finally, holding precaution and timing constant, it is likely that the probability of escaped prescribed fires will be highly correlated with the incidence of wildfires, simply because fuel and weather conditions that make wildfires more likely will also make prescribed fires more difficult to control.

Proposition 6. *The probability of escaped prescribed fire will be correlated with the probability of a wildfire from other causes.*

Liability imposed through the courts is rarely used in isolation. In the terms of the present topic, Kolstad et al. (1990) show that when a burner is uncertain about how the court will interpret a negligence rule, *ex ante* regulation can, under certain reasonable circumstances, improve the economic efficiency of prescribed fire use and precaution. Furthermore, in such circumstances, *ex ante* regulation should be set below the efficient level of precaution.

Yoder et al. (2003) review in relative detail the characteristics of negligence rules, and find that they are usually quite vague, leaving a lot of room open for interpretation of the specifics of a case. Furthermore, it is difficult to argue that any negligence standards are so clear as to suggest that if a landowner misses the optimal timing of a fire that he would be found negligent if a prescribed fire were to be performed later in the vegetation cycle.

In a manner consistent with Kolstad et al. (1990), *ex post* liability rules are often bolstered in state statutes by an array of *ex ante* regulations. Burning permits are often required, burn bans for certain weather conditions and times of year, and criminal penalties for negligent burning are often imposed. The use of burn bans is illustrated in figure 2. They generally apply only to the time of year in which the risk of escape is highest (often over one summer month), or imposed intermittently as weather calls for it.

7 Conclusion

This paper develops a model of liability that incorporates the issue of timing and waiting, and examines the issue of prescribed fire in which there is a risk of escape and damage to neighboring property. The model is used to develop implications about the incentive effects of strict liability versus a negligence rule on burner precaution and timing, and victim incentives. The model is extended to examine the importance of prescribed fire as a wildfire mitigation tool.

A number of implications follow from the model. In general, although a strictly defined negligence rule that pinpoints the appropriate timing of risky action can induce efficient timing behavior, a Learned Hand negligence rule, which is arguably more feasibly implemented by the courts, leads to excessively long prescribed fire rotations. When prescribed fire can be used to mitigate the risk of wildfires, strict liability on prescribed fire use tends to lead to shorter prescribed fire rotations unless the vegetation has already reached a mature stage, in which case strict liability leads to excessive waiting or no prescribed fire use at all even if efficiency dictates it should be used. Negligence rules, on the other hand, tends to induce too much prescribed fire use, and excessively long rotation lengths.

A great deal of research and data are needed to better understand the tradeoffs associated with prescribed fire use. Little information is available about the extent of damage associated with prescribed fire in the aggregate, or even the fraction of prescribed fires that do become out of control. Nowhere in this analysis is the number of prescribed fires actually relied upon. These data may soon be available for a few recent years, but again they will be in aggregate form and not directly related to the data on wildfires originating as prescribed fires. Just as importantly, the benefits of prescribed fire are only now beginning to be understood, and to some extent rediscovered.

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