Adjacency Externalities and Forest Fire Prevention

Christian S. L. Crowley, Arun S. Malik, Gregory S. Amacher, and Robert G. Haight

ABSTRACT. This paper models landowner behavior on timberland subject to damage by fire. We examine how management decisions by adjacent landowners yield outcomes that diverge from the social optimum, and consider how this divergence depends on landowner preferences and information. We conduct a numerical simulation in which landowners interact through the effects of their fire prevention activities on a common risk of fire. The results reveal significant social inefficiencies related to externalities associated with private fuel treatment decisions. We consider a policy for aligning social and private decisions by requiring landowners to share the government's cost of fire suppression. (JEL Q23, Q28)

I. INTRODUCTION

Policymakers dealing with forest fires in the United States must account for the actions of non-industrial private landowners, the group that holds the majority of U.S. forestland. Decisions made by these private landowners can have widespread effects on the extent and severity of fires. Two important decisions are the planting density of timber stands, and the level and timing of fuel treatment. Fuel treatment can take various forms, such as pruning, thinning, clearing of brush, or burning of surface fuels.\(^1\)

A forest landscape may contain neighboring stands managed by several independent landowners, which raises the importance of adjacency externalities: a fire burning in one stand can easily spread to a neighboring stand. Thus, a landowner ignoring the risk of fire on his stand potentially endangers a neighbor's property as well. Given this relationship, fuel treatment activity exhibits positive externalities: when one landowner undertakes fuel treatment, nearby landowners enjoy the benefits of lower fire risk. Given this externality, it is expected that private landowners will not undertake fuel treatment at socially optimal levels. This inefficiency is aggravated by a second externality, namely that landowners do not bear the direct cost of government-funded fire suppression on their lands. The presence of this second externality further reduces the likelihood that a landowner will choose the socially optimal level of fuel treatment.

The economics of fire risk for a single stand have been studied by Amacher, Malik, and Haight (2005, 2006), Lankoande and Yoder (2005), Yoder (2004), Reed (1984), and Englin, Boxall, and Hauer (2000). Amacher, Malik, and Haight develop a single-stand model to examine fire risk, fuel treatment, and the externality associated with the landowner not bearing fire suppression costs. We build on the work of Amacher, Malik, and Haight and develop a new model of two adjacent stands managed by landowners who can differ in terms of their information sets and their preferences. Adjacent stands are linked by a common risk of fire that depends on the level of fuel

\(^{1}\) Fuel treatment can also take the form of fire breaks installed at initial planting. As in other studies, we only model measures undertaken during the growth of a timber rotation, such as those mentioned above.
treatment on each stand. Each of the adjacent landowners seeks to maximize the private site value of his land, in both standing timber and non-timber amenities. As in Amacher, Malik, and Haight, fuel treatment also affects the salvage possibilities for a fire-damaged stand.

We use our model to examine how management decisions by adjacent landowners yield outcomes that diverge from the social optimum, and to understand how this divergence depends on landowner preferences and information. The results reveal significant social inefficiencies related to the externalities associated with private fuel treatment decisions. We further consider the possibility of aligning social and private decisions by means of a policy that requires landowners to share the government's cost of fire suppression.

To our knowledge, no previous work considers the interaction of adjacent landowners in the presence of the aforementioned externalities. Some studies have considered problems arising from multiple adjoining forest stands or landowners, mostly in non-fire contexts. Bowes and Krutilla (1985) first examined stand interdependence, proposing that a government could use linear programming to maximize rents from multiple stands. Swallow and Wear (1993) modeled stands linked through non-timber benefits. Yoder (2004) considered the effects of prescribed burning in one stand on the fire risk for an exogenous downwind stand, finding that the upwind landowner fails to undertake prescribed burning at the socially optimal point in a rotation. Finally, Amacher, Koskela, and Ollikainen (2004) developed a model of stand interdependency to consider optimal rotation-age decisions when non-timber benefits production is linked across stands, though without considering choices related to fuel treatment and fire risk.

The remainder of this paper is organized as follows. In Section 2, a model is developed with adjacent landowners making forest management decisions, including the level and timing of fuel treatment. Section 3 develops a numerical simulation, the results of which are discussed in Section 4. The simulation approach allows comparisons of optimal decision-making by landowners having various information sets and preferences. Section 4 also includes a discussion of the fire suppression cost-sharing policy. Section 5 contains concluding remarks.

II. MODEL

Overview

The model is based on two adjacent landowners and the stand that each manages. Landowners and stands are indexed by \( i = (A, B) \). Landowners make the following choices independently to maximize their private site values: \(^2\) planting density in trees per acre \((D')\), rotation age in years \((T')\), level of fuel treatment effort \((Z')\), and stand age at which fuel treatment is applied \((S')\). Fuel treatment effort \((Z')\) is an index of landowner effort in undertaking fuel treatment measures (e.g., pruning, thinning, clearing, or burning of surface fuels); in the remainder of this paper, \( Z' \) is referred to as simply “fuel treatment.” A landowner’s choices depend on his information set, possibly including the management decisions of the neighboring landowner. As a benchmark, we also consider a Government Agency managing a single stand, and managing both stands jointly. The Government Agency’s problem serves as a baseline, allowing us to compute the social cost of the externalities inherent in private land ownership. The Government Agency is assumed to be tasked with managing public lands, that is, forest stands held in the public trust, as opposed to privately held and managed stands. Apart from differences in management decisions, the two stands are identical, and all landowners face the same values for their timber and non-timber benefits.

\(^2\) “Private” site values are the timber and non-timber amenities accruing to the landowner directly, and do not include the government’s cost of fire suppression; only the Government Agency accounts for fire suppression costs.
Government fire suppression is undertaken when a stand ignites. The level of government fire suppression provided for Stand $i$ is denoted by $G^i$; it is chosen to maximize the social site value of Stand $i$, taken to be the total value of a stand's timber and non-timber benefits, net of fire suppression costs paid by the government. The government's choice of $G^i$ is determined by the government's reaction function in a Stackelberg game, in which Landowner $i$ acts as a leader, and the government acts as a follower (a single-stand version of this game is found in Amacher, Malik, and Haight 2006). The resulting government reaction function for each stand depends on choices made by Landowner $i$ prior to the fire. This reaction function is given by $G = G(x, Z', D')$, where $x$ is a random variable that represents the time at which the stand is destroyed by fire. This reaction function is formally developed in Section 3.

We examine the effects of landowner interactions in a conventional Faustmann framework. Consistent with previous literature (Reed 1984; Englin, Boxall, and Hauer 2000; Amacher, Malik, and Haight 2005) we assume that landowners make management choices at the outset. We further assume that if one stand ignites, the adjacent stand ignites as well. A similar assumption is made by Insley and Lei (2007), among others. However, the fire arrival function used by these authors is fixed at an exogenously determined level.4

We also follow the existing literature in assuming that stands are replanted immediately after a fire (Reed, 1984; Amacher, Malik, and Haight 2005).

The assumption that both stands burn in the event of a fire is plausible for small, adjacent stands. In addition, the assumption avoids possible time inconsistency of the landowners' decisions. If instead we assume that a stand could burn in isolation, management decisions made at the outset need not remain optimal at all points in the future. This possibility is a result of linking fire risk across stands in our model—each landowner's choice of fuel treatment influences fire risk on both stands.4 If we allowed just one stand, say Stand A, to burn and subsequently be replanted, the choices made by the owner of the adjacent unburned Stand B may no longer be optimal, as these choices were made without knowing the time of destruction of Stand A. Because the fire risk faced by Landowner B is determined in part by fuel treatment on Stand A, Stand B's fire risk may change after the unexpected replanting of Stand A.5

Another important feature of our model is the interaction between fuel treatment, fire arrival rates (i.e., the average number of fires over a fixed time period), and stand damage resulting from a fire (or equivalent-
ly, the amount of marketable timber available for salvage after a fire). In previous studies addressing forest fire management, there has been some disagreement concerning these interactions. Yoder (2004) assumes that fuel treatment (prescribed burning in his model) reduces the fire arrival rate but does not affect damage to the stand once fire arrives (see also Reed 1987). On the other hand, Amacher, Malik, and Haight (2005) assume that fuel treatment affects salvage possibilities but not the fire arrival rate. To a large extent, this variation in assumptions reflects inconclusive evidence in the biological literature. For example, Wade and Lundsford (1990) present biometric evidence that fuel treatment affects the severity of fire damage. Graham, McCaffrey, and Jain (2004) also find some evidence that fuel treatment affects the likelihood of relatively harmless ground fires becoming damaging crown fires, implying that fuel treatment can enhance a stand’s “immunity” to fire. However, in a recent broad-scale survey of the literature, Fernandes and Botelho (2004) were unable to draw any conclusions as to the effect of fuel treatment on fire probabilities for a single stand. Many of the studies they survey reflect the fact that, in addition to locally generated fires started from a lightning strike, fires also frequently arrive from neighboring stands and off-site events.

We take a more general approach by combining the assumptions in Yoder (2004) and Amacher, Malik, and Haight (2005, 2006). Because fire from one stand is assumed to always spread to the adjoining stand, we allow fuel treatment on either stand to affect the fire arrival rate for both stands. Without this assumption, fire arrival rates could differ for the two stands, which would be inconsistent with the assumption that both stands always burn together. On the other hand, a stand’s salvage possibilities depend on fuel treatment undertaken in that stand alone. These assumptions seem appropriate when moving from the single-stand models of the literature to our adjacent-stand model.

Given the above discussion, two externalities are expected to affect private landowner decisions. First, a landowner may not account for government costs of fire suppression when making decisions (as in Amacher, Malik, and Haight 2006). Second, a landowner may not account for his fuel treatment’s beneficial effect for a neighboring landowner, and vice versa.

**Fire Arrival Rate and Timber Salvage**

As noted above, the fire arrival rate, or probability of stand ignition, is given by a function common to both stands. We follow earlier work (Reed 1984; Insley and Lei 2007) and model fire arrival as a Poisson process. Different from earlier work, we allow the mean of this process to vary with fuel treatment effort: \( \lambda = \lambda(\phi, Z^A, Z^B) \). The parameter \( \phi \) captures the rate of incendiary events, such as lightning strikes. The likelihood of such events leading to stand ignition depends on the levels of fuel treatment undertaken on both stands, with the probability of stand ignition decreasing as a decreasing rate with fuel treatment levels:

\[
\frac{\partial \lambda(.)}{\partial \phi} > 0, \quad \text{and} \quad \frac{\partial \lambda(.)}{\partial Z^i} < 0,
\]

\[
\frac{\partial^2 \lambda(.)}{\partial (Z^i)^2} > 0, \quad i = (A, B).
\]

Thus, a higher level of fuel treatment on either stand reduces the likelihood of an incendiary event causing a fire that consumes some, or all, of both stands.

Following a fire, the fraction of a stand’s timber that can be salvaged for sale is given by \( k^i = k(G^i, Z^i, D^i) \). Following our earlier discussion, the salvage fraction for Stand \( i \) is increasing in government-provided fire suppression for Stand \( i \), \( \frac{\partial k(.)}{\partial G^i} > 0 \), and in

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6 Examples of fire-spread mechanisms include “lofting,” in which embers from a fire are blown aloft, then land and ignite a near-by stand, and fire spreading through root systems to the trees of an adjacent stand.

7 For our purposes, “incendiary events” is a catch-all term for any source of fire, including arson and accidents.
fire prevention effort undertaken by Landowner $i$, $\partial k(.) / \partial Z^i > 0$. The salvage function is decreasing in planting density, $\partial k(.) / \partial D^i < 0$, as more densely planted stands can fuel more intense fires. Consistent with the usual assumption of decreasing returns, $k(.)$ is concave in $G^i$ and $Z^i$, and convex in $D^i$.

Thus, fuel treatment on either stand influences whether a fire breaks out; once started, a fire burns both stands, with salvage levels determined entirely by "local" variables. For instance, once a fire front crosses the border from Stand A to Stand B, salvage on Stand B is determined by fuel treatment undertaken on Stand B, along with the planting density and government fire suppression for this stand.

Timber and Non-Timber Benefits, and Costs

Timber harvesting benefits are given by a value function, $V(P, x^i, D^i, E)$, which measures harvest revenue as a function of timber price ($P$), time of stand "destruction" ($x^i$) by routine harvesting or fire, planting density ($D^i$), and the site index ($E$), which gives a measure of site quality. As in Lankoande and Yoder (2005), fuel treatment does not affect timber values. Landowners are assumed to be price takers, so harvests and salvage do not affect the market price of timber.

In addition to harvesting, landowners capture rent in the form of non-timber benefits. The current value of Stand $i$ non-timber benefits accrued by stand age $x$ is given by $e^{\delta x} \int_0^x e^{-\delta t} B'(t) \, dt$, where $\delta$ is the discount rate and $B'(t)$ captures instantaneous non-timber benefits. This formulation follows earlier studies that consider non-timber benefits (Hartman 1976; England, Boxall, and Hauer 2000; and Amacher, Malik, and Haight 2005).

The per-acre cost of planting the initial stand and of replanting after each harvest is denoted $c^H(D^i)$. The cost of replanting after a fire is denoted $c^F(D^i)$. These costs are assumed to be linear in planting density, but the two costs are not equal, as planting on burned land requires less site preparation than planting after a harvest (Dubois et al. 2001; Waldrop 1997). The per-acre cost of fuel treatment is given by $c^F(Z^i)$. The cost of government-provided fire fighting assistance is denoted by $c^G(G^i)$.

Social Site Value

The expected social site value of a stand is the expected value of a stand’s timber and non-timber benefits, net of fire suppression costs paid by the government. The site value of a stand at time of "destruction" ($x$) depends in part on whether the stand is destroyed by harvesting or by fire, and on whether a fire arrives before or after fuel treatment has been undertaken. In our two-stand model, the relative timing of fuel treatment on the two stands also affects site value. The two adjacent landowners need not undertake fuel treatment at the same point in a rotation, so in general $S^A \neq S^B$. For example, suppose Landowner A undertake fuel treatment first, so that $S^A < S^B$. Given the interlinked nature of the fire risk facing the two stands, Landowner B would then see the fire arrival rate drop before he has undertaken any fuel treatment of his own.

As shown by Reed (1984), in the presence of fire risk, the expected social site value for an infinite number of rotations is given by $J = \sum_{n=1}^{\infty} E[e^{-\delta(nx)} Y]$, where $Y$ represents the social site value of the stand at harvest, and $x$ is the time of stand destruction (by harvest or fire). Note that Reed assumes that there is no cost associated with the first planting, that is, the first harvest is made from trees already growing on the site. Following Reed’s approach, and including the cost of planting the first rotation, the expected social site value for Stand $i (i = A, B)$ can be rewritten using the cost of planting to be tax-deductible if a fire occurs (as is true in practice) requires only a simple modification: the cost of replanting after a fire would include a discount equal to the percentage tax bracket of the landowner.

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8 The site index is taken to be the average height of the dominant and co-dominant trees in a stand at a given base age, e.g., 80 feet tall for a 25-year-old tree.
closed form of an infinite sum:
\[ J^I = -e^H + \frac{E[e^{-\delta_x}Y^I]}{1 - E[e^{-\delta_x}]} \]  

[1]

The denominator in [1] can be evaluated by taking the expected value given the risk of fire \((\lambda = \lambda(\phi, Z^A, Z^B))\), and discounting using the discount rate \(\delta\):

\[
1 - E[e^{-\delta_x}] = 1 - \int_0^T e^{-\delta_x} \cdot e^{-\lambda x} \, dx - (e^{-\lambda T} - 1)
\]

\[
= \frac{\delta}{\lambda + \delta} \left( 1 - e^{-(\lambda + \delta)T} \right)
\]

\[
= \frac{\delta}{\lambda + \delta} \int_0^T e^{-\lambda x} \, dx
\]

The numerator in [1] includes the social site value, which, as noted above, varies over time. We identify four possible cases for the social site value that depend on the relative timing of fuel treatment and fire arrival. Some of these cases vanish when one or both landowners choose to perform no treatment. Assuming that both landowners choose to apply some treatment, the four cases are:

- **Y1**: a fire occurs before either landowner has undertaken treatment;
- **Y2**: a fire occurs after only one landowner has undertaken treatment;
- **Y3**: a fire occurs after both landowners have undertaken treatment;
- **Y4**: no fire occurs, and the stand is harvested.

Using these four cases, and the new expression for the denominator, equation [1] can be rewritten

\[
J^I = -e^H + \frac{E[e^{-\delta_x} \cdot \{Y_1^I + Y_2^I + Y_3^I + Y_4^I\}]}{\delta \int_0^T e^{-\delta x} \cdot dx}
\]

[2]

The first term in [2] is the cost incurred by the landowner for the first planting. As this cost is incurred at the outset, there is no discounting applied, nor is there any uncertainty from the risk of fire. Inside the expectation operator are the four possible cases for social site value. The first of these, \(Y_1^I\), represents the value of the stand, net of fire suppression costs, if a fire occurs before either Landowner A or B has applied fuel treatment, so \(x < \min(S^A, S^B)\). Furthermore \(Z' = 0\) and \(c^Z(Z') = 0\) for \(i = (A, B)\). Written out in full, the expected (discounted) site value for \(Y_1^I\) is

\[
E[e^{-\delta_x}Y_1^I] = \int_{\min(S^A, S^B)}^\infty e^{-\lambda x} \cdot e^{-\delta x} \left\{ e^{\delta x} \left[ \int_0^x e^{-\lambda t} B(t) \, dt \right] \right\} dx
\]

Note there is no superscript for the stand age \(x\) as stands are always the same age, given the assumption that both stands burn, and are replanted, simultaneously.

The second possibility for the social site value, \(Y_2^I\), represents the value of the stand if a fire occurs after only one landowner has undertaken fuel treatment. Note that for this term only, if Landowner \(i\) moves first in undertaking fuel treatment, then for Landowner \(j\) (i.e., the other landowner) \(Z' = 0\), as the stands burn before he planned to undertake treatment. In this and subsequent terms, fuel treatment costs are compounded forward from the time of application (\(S^i\)) to age \(x\). Written out in full, the expected (discounted) site value for \(Y_2^I\) is

\[
E[e^{-\delta_x}Y_2^I] = \int_{\min(S^A, S^B)}^\infty e^{-\lambda x} \cdot e^{-\delta x} \left\{ e^{\delta x} \left[ \int_0^x e^{-\lambda t} B(t) \, dt \right] \right\} dx
\]

The third possibility for the social site value, \(Y_3^I\), represents the value of the stand if a fire occurs after both landowners have applied
fuel treatment, but before the rotation age is reached: max \((S^A, S^B) \leq x < T^i, \ Z^i \geq 0, \ i = (A, B)\). Written out in full, the expected (discounted) site value for \(Y^i_A\) is

\[
E[e^{-\delta x} Y^i_A] = \int_0^T \lambda e^{-\lambda x} e^{-\delta x} \left\{ e^{\delta x} \int_0^x e^{-\delta t} B(t) \, dt \right\} \, dx + k \left( \dot{G}, Z^i, D^i \right) \cdot V(P, x, D^i, E) - c^F(D^i) - c^Z(Z^i) e^{\gamma x - S^i} - c^G(\dot{G}) \, dx.
\]

The superscript on the rotation age \(T^i\) is needed because the rotation ages for the two stands can differ, given different landowner types.\(^{10}\)

The fourth possibility for the social site value, \(Y^i_A\), represents the value of the stand if no fire occurs and the stand is harvested at its rotation age. Written out in full, the expected (discounted) site value for \(Y^i_A\) is

\[
E[e^{-\delta x} Y^i_A] = e^{-\delta T^i} e^{-\delta T^i} \left\{ e^{\delta T^i} \int_0^{T^i} e^{-\delta t} B(t) \, dt \right\} + V(P, T^i, D^i, E) - c^H(D^i) - c^Z(Z^i) e^{\gamma (T^i - S^i)}.
\]

Again, the superscript on the rotation age \(T^i\) allows the rotation ages for the two stands to differ between landowner types.

**Landowner Types**

We consider four types of landowners, shown in Table 1. Landowners are differentiated by their preferences and information sets. As noted earlier, one of the four is a Government Agency tasked with managing land held in the public trust. This landowner type maximizes the objective function in \([2]\). The Government Agency is the only landowner type that internalizes government fire suppression costs. Including this landowner provides an analytical benchmark for computing costs related to the externalities we consider. Though the Government Agency is fully aware of the cross-stand effects of fuel treatment on fire risk, in our analysis, a Government Agency managing a single stand does not consider the effect of its choices on an adjacent stand’s site value (this is true for all the private landowner types). Only a single Government Agency (with perfect information) jointly managing both stands achieves the first-best outcome, in which all externalities are internalized.\(^{11}\)

\footnote{\(^{10}\) As noted in footnote 5, with one exception, the rotation ages for the two stands were within a few months of each other. Therefore we ignored the unlikely possibility of fire arriving after only one landowner had harvested his stand at his rotation age.}

\footnote{\(^{11}\) The first-best outcome is not achieved when the two adjacent stands are independently managed by two distinct Government Agencies acting independently. This sort of situation might arise if two adjacent public stands are managed by different authorities (e.g., a national forest and a state forest). Simulation results (available upon request) confirm that in this situation, the combined social site value for the two sites is lower due to a suboptimal level of fuel treatment on each stand.}
In addition to the Government Agency, there are three types of private landowners, all of which ignore government fire suppression costs as well as the effects of their decisions on their neighbor’s welfare. The Informed Landowner is most similar to the Government Agency, in that he recognizes the reduction in fire risk resulting from fuel treatment undertaken by his neighbor. The Informed Landowner differs from the Government Agency in that he ignores the cost of government fire suppression for any fires occurring on his stand.

The Uninformed Landowner, like the Informed Landowner, recognizes the benefits of undertaking fuel treatment on his stand to reduce fire risk and improve salvage. But unlike the Informed Landowner, the Uninformed Landowner is unaware that treatment on one stand affects fire risk on adjacent stands. In other words, the Uninformed Landowner is ignorant of the cross-stand benefits of fuel treatment. In terms of our simulations, this landowner acts as if his neighbor undertakes no fuel treatment. We consider this landowner type for two reasons: (1) this landowner type duplicates the behavior of a traditional Faustmann landowner operating in isolation, providing a useful reference point, and (2) this landowner type aids in understanding how differences in information drive differences in landowner behavior. In particular, comparing outcomes for the Informed and Uninformed Landowners (see Table 1), these landowners do not engage in strategic behavior with their neighbors, hence the Nash equilibrium for simulations involving them is trivial.

The fourth landowner type is the Harvest-only Landowner. The Harvest-only Landowner is assumed to apply no fuel treatment whatsoever. In our simulation, the Harvest-only Landowner comes closest to the single landowner modeled in Reed (1984) and Englin, Boxall, and Hauer (2000), and is included for the sake of comparison. As shown in Table 1, the Uninformed and Harvest-only Landowners typically overestimate fire risk, because they ignore the reduction in fire risk stemming from their neighbor’s fuel treatment.

**Landowner Interactions**

The interactions among the landowners and the government fire suppression agency are modeled as an infinitely repeated, non-cooperative game. The infinitely repeated game consists of three sub-games. The first sub-game is a non-cooperative, simultaneous-move game played by the two landowners, in which each landowner uses his objective function and information set to choose rotation age, planting density, and level and timing of fuel treatment (if any). The potential for strategic interaction between these landowners stems from the presence of both landowners’ fuel treatment choices in the common fire arrival rate function: \( \lambda(\phi, Z^A, Z^B) \). A Nash equilibrium characterizes the interaction between landowners in this sub-game. A detailed explanation of the procedure used to find the Nash equilibrium in our simulations is provided in Appendix 1. Given the characteristics of the Uninformed and Harvest-only Landowners (see Table 1), these landowners do not engage in strategic behavior with their neighbors, hence the Nash equilibrium for simulations involving them is trivial.

Each landowner makes his choices knowing how the government chooses the level of fire suppression. As described below, this choice is made by the government when a stand is struck by fire. Accordingly, each landowner acts as a leader in a Stackelberg sub-game with the government. These interactions constitute the other two sub-games of the stage game, and are modeled by incorporating the government’s reaction function in each landowner’s decision problem.

Each stage-game ends when the two stands reach their rotation ages untouched by fire, and the stands are harvested, or when both stands burn. In the latter case, as described above, timber is salvaged and the stands are replanted. A landowner’s choices are identical from one stage game to the next. However, the government’s suppression choices may vary, because the government’s choice of suppression depends, in part, on when during a rotation a fire
TABLE 2
SIMULATION FUNCTIONAL FORMS AND PARAMETER VALUES

<table>
<thead>
<tr>
<th>Function</th>
<th>Definition</th>
<th>Specification</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta )</td>
<td>Discount rate</td>
<td>( B(x) = b_0 x e^{-b_1} )</td>
<td>( \delta = 0.03 )</td>
</tr>
<tr>
<td>( B(x) )</td>
<td>Non-timber benefits</td>
<td>( c^\delta(\tilde{G}) = c_0^\delta + c_1^\delta \tilde{G} )</td>
<td>( b_0 = b_1; b_1 = \frac{1}{a_0} )</td>
</tr>
<tr>
<td>( c )</td>
<td>Cost of government firefighting assistance</td>
<td>( \tilde{c}^\delta(\tilde{Z}) = c_2^\delta + c^\delta Z )</td>
<td>( c_2^\delta = 4; c_\delta = 0.04 )</td>
</tr>
<tr>
<td>( \tilde{c} )</td>
<td>Cost of fuel treatment</td>
<td>( \tilde{c}^\delta(D) = c^\delta D )</td>
<td>( c^\delta = 0.30 )</td>
</tr>
<tr>
<td>( c )</td>
<td>Cost of planting after a harvest</td>
<td>( \tilde{c}(D) = c^\delta D )</td>
<td>( c^\delta = 0.30 )</td>
</tr>
<tr>
<td>( V )</td>
<td>Timber value (price times the growth function)</td>
<td>( V(T, x, D, E) )</td>
<td>( E = 80; a = 9.75; )</td>
</tr>
<tr>
<td>( \tilde{G} )</td>
<td>Level of government firefighting assistance</td>
<td>( \tilde{G}(x, Z, D) = \frac{k_0(x + k_1 Z + k_2 Z^4)}{D} )</td>
<td>( k_0 = 0.1; k_1 = 2.5; k_2 = 10; k_3 = 0.2 )</td>
</tr>
<tr>
<td>( k )</td>
<td>Salvageable fraction of timber after a fire</td>
<td>( k(\tilde{G}, Z, D) = 1 - \hat{e}^{\tilde{G}(k_1 Z + k_2 \tilde{G} + k_3 Z^4)} )</td>
<td>( k_0 = 0.1; k_1 = 2.5; k_2 = 10; k_3 = 0.2 )</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Fire arrival rate</td>
<td>( \lambda(\phi, Z^4, Z^6) = \phi \left[ 1 - \frac{\sqrt{Z^4 M}}{M} \right] \left[ 1 - \frac{\sqrt{Z^6}}{M} \right] )</td>
<td>( \phi = 0.02; M = 500 )</td>
</tr>
</tbody>
</table>

Notes: \( D \) = Planting Density; \( E \) = Site Index; \( \tilde{G} \) = Level of Fire Suppression; \( T \) = Rotation Age; \( Z \) = Level of Fuel Treatment; \( x \) = Stand Age; \( \phi \) = Incendiary Events.

occurs, if at all. If no fire occurs before the rotation ages of the two stands, then no fire suppression is undertaken. If a fire occurs before either rotation age is reached, the government chooses the fire suppression effort for each stand, to maximize the sum of the current-period site values, net of fire suppression costs, given the landowners’ prior choices of \( D' \), \( T' \), \( S' \), and \( Z' \):

\[
\max_{G_0, \tilde{G}_0} \left\{ [k(x, Z^4, G^4) \cdot V(x, D^4) - \tilde{c}^\delta(G^4)] + [k(x, Z^6, G^6) \cdot V(x, D^6) - \tilde{c}^\delta(G^6)] \right\} \]  

The government’s reaction functions, \( \tilde{G}^\delta = \tilde{G}(x, Z^4, D^4) \), are derived from the first-order conditions for the above problem. Lankoande and Yoder (2005) follow a similar approach in modeling government fire suppression, assuming that suppression is provided at a level that equates the marginal cost and benefits of suppression. These reaction functions are discussed more fully in the next section.

III. SIMULATION

The simulations are based on the objective function in [2], modified for private landowners following Table 1, and using the functional forms and parameters reported in Table 2. Parameter values were chosen to avoid degenerate or nonsensical solutions, such as a landowner applying fuel
treatment for a rotation after the harvest date. The robustness of the simulation results to parameter assumptions is shown in the sensitivity analysis of Appendix 3.

The species of tree chosen for the simulation is loblolly pine, *Pinus taeda*, a species commonly modeled in the literature, and planted by private landowners in the Southeast. Functional forms and parameters for growth functions, non-timber benefit functions, and cost functions were adapted from those used in the single stand analyses of Amacher, Malik, and Haight (2005, 2006). The value function \( V(.) \) is based on a forest growth function first proposed by Chang (1984). The site index \( (E) \) was assumed to allow a 25-year-old tree to reach 80 feet in height, which is reasonable for loblolly pine. Little is known about the impact of fuel treatment on timber yields, and timber-growth effect studies of prescribed burns have been inconclusive (Waldrop et al. 1987; Waldrop 1997). We follow studies of thinning by Betters, Steinkamp, and Turner (1991) and Cawrse, Betters, and Kent (1984) in assuming that fuel treatment has no effect on harvest yield.

Stumpage prices for pine sawtimber are from TimberMart South (TMS 2001). Costs for replanting a stand after a fire and after a harvest are taken from Dubois et al. (2001). The non-timber benefit function is similar to forms used by Swallow and Wear (1993), Swallow, Takludar, and Wear (1997), and Vincent and Boscolo (2000); as in Amacher, Malik, and Haight (2006), this non-timber benefits function peaks at a stand age of 60 years with a maximum annual value of $2.94 per acre.

No precedents could be found in the literature for a salvage function, beyond Reed's random specification. Following Amacher, Malik, and Haight (2005, 2006), a functional form was chosen that exhibited the following desired characteristics: values ranging between zero and one, strict concavity in government fire suppression and fuel treatment, and strict convexity in planting density (over the range of values used in the simulation).

There is also no published work we are aware of that analytically characterizes the effects of fuel treatment on fire risk, especially in the case of adjacent stands. We posit, consistent with what was assumed earlier, that fuel treatment on any one stand yields a reduction or "discount" in the fire risk facing both stands. Accordingly, we choose a simple functional form for the fire arrival rate that is decreasing in fuel treatment for either stand, at a decreasing rate:

\[
\lambda(\phi, Z^A, Z^B) = \phi \left[ 1 - \frac{\sqrt{Z^A}}{M} \right] \left[ 1 - \frac{\sqrt{Z^B}}{M} \right].
\]

The parameter \( \phi \) captures the number of incendiary events over a 100-year period. The first bracketed term captures the discount effect of fuel treatment undertaken on Stand A stand, while the final term captures the discount effect of fuel treatment on Stand B. \( M \) is a scaling factor that can be used to control the effectiveness of fuel treatment in lowering the fire arrival rate.

Figure 1 shows the fire arrival rate function graphed over fuel treatment for Stands A and B, with \( M \) set to 250, a relatively low value that allows the graph to display a clearer curvature. The fuel treatment axes range from \( Z = 0 \) to \( Z = 1,000 \), covering the range of values observed in the simulations. To facilitate viewing the graph contours, the scale on the \( Z \) axes has been reversed, so that the values range from \( Z = 1,000 \) at the origin, to \( Z = 0 \) at the outer edges. The fire arrival rate function in the baseline simulation takes on values in the range of 1.9 to 2.0 fires every hundred years.

---

13 Simply imposing a constraint of the form \( S \leq T \) to avoid such nonsensical outcomes would not yield plausible results. If the solution to the landowner's problem without this constraint yields \( S > T \), adding the constraint would result in the corner solution \( S = T \), given the concavity of the landowner's decision problem. This corner solution is also implausible: there is no reason for landowners to engage in fuel treatment at the rotation age. The underlying parameters and functional forms of the landowner's decision problem must be such that \( S < T \) is optimal.

14 Kline (2004) reports that the literature lacks economic analyses of the benefits and costs of fuel treatment; the debate over the precise stand-based effects of these measures continues.
Two fires per century is considered moderate fire risk in the literature. In our sensitivity analysis (see Appendix 3), we examine arrival rates covering a broader range from 1.0 to 4.0 fires every hundred years, and find that the basic results do not change. The fire arrival rates used in our simulation are similar to those in Reed (1984) and Englin, Boxall, and Hauer (2000).

The cost of fuel treatment can vary widely depending on geographic region, local conditions, and the method of fire prevention chosen by the landowner. Schaaf et al. (2004) report that per-acre fuel treatment costs vary by treatment activity and vegetative class, with average prescribed-fire treatment costs equaling $225 per acre. Dubois et al. (2001) report numbers nearly an order of magnitude lower for the southeastern United States, where loblolly pine is common. In our study, fuel treatment cost is assumed to be a linear function of effort ($Z'$), with fixed and variable cost components. This function was calibrated to fall within the range of costs reported in the literature (see Table 2).

Government fire suppression costs require some discussion. Cameron (1987) finds a sizable fixed-cost element due to use of equipment such as helicopters and flying tankers. In our study, fire suppression cost is assumed to be a linear function of effort ($G$), with fixed and variable cost components. This function has been calibrated to fall in the lower end of the range found in the literature (see Table 2): between $28 and $243 per acre, depending in part on when a fire occurs during a rotation. Higher per-acre fire suppression costs in the literature are driven in part by protection of
Table 3

SOCIAL SITE VALUE OF STAND A FOR DIFFERENT LANDOWNER PAIRS

<table>
<thead>
<tr>
<th>Stand B</th>
<th>G ($)</th>
<th>ILO ($)</th>
<th>ULO ($)</th>
<th>HLO ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>116.56</td>
<td>116.26</td>
<td>116.26</td>
<td>115.17</td>
</tr>
<tr>
<td>ILO</td>
<td>114.21</td>
<td>113.81</td>
<td>113.82</td>
<td>112.63</td>
</tr>
<tr>
<td>ULO</td>
<td>114.22</td>
<td>113.89</td>
<td>113.90</td>
<td>112.63</td>
</tr>
<tr>
<td>HLO</td>
<td>99.64</td>
<td>99.16</td>
<td>99.16</td>
<td>97.40</td>
</tr>
</tbody>
</table>

Notes: GA = Government Agency; ILO = Informed Landowner; ULO = Uninformed Landowner; HLO = Harvest-only Landowner.

Table 4

COMBINED SOCIAL SITE VALUES FOR BOTH STANDS FOR DIFFERENT LANDOWNER PAIRS

<table>
<thead>
<tr>
<th>Stand B</th>
<th>GA ($)</th>
<th>ILO ($)</th>
<th>ULO ($)</th>
<th>HLO ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>233.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILO</td>
<td>230.47</td>
<td>227.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULO</td>
<td>230.48</td>
<td>227.71</td>
<td>227.80</td>
<td></td>
</tr>
<tr>
<td>HLO</td>
<td>214.81</td>
<td>211.80</td>
<td>211.80</td>
<td>194.80</td>
</tr>
</tbody>
</table>

Notes: GA = Government Agency; ILO = Informed Landowner; ULO = Uninformed Landowner; HLO = Harvest-only Landowner.

structures and communities within the urban-forest interface (USDA FS 2000; Arno and Brown 1989). We assume for simplicity that there are no permanent structures on either stand.

Using the functional forms in Table 2, the government’s reaction functions can be derived from the first-order conditions of the government’s problem in [3]:

\[
\dot{G}(x, Z^i, D^i) = \frac{D^i}{k_0(k_2 + k_3Z^i)} \ln \left( \frac{k_0 V(x, D^i)(k_2 + k_3Z^i)}{D^i e^G} \right) - \frac{k_1Z^i}{k_2 + k_3Z^i}, \quad i = (A, B). \]  

If a fire occurs before stand age \( S^i \), Landowner \( i \) will not have applied fuel treatment, and \( Z^i \) is set to zero in the above expression.

In the early years of a rotation, timber and non-timber values may be too low to warrant any government fire suppression. For the parameter values used in this study, the government provides a positive level of fire suppression beginning around the eighth year of a rotation. This roughly coincides with the typical age at which loblolly pine progresses from the seedling stage to the merchantable pole timber stage. For stand ages with positive levels of fire suppression, our simulations imply that fire suppression and fuel treatment are strategic substitutes for most stand ages, that is, the government tends to provide less fire suppression for stands with higher levels of fuel treatment.\(^{15}\)

IV. RESULTS

Social Site Values

Table 3 shows simulated social site values for Stand A given different combinations of landowner-types on the two stands. With four different possible landowner-types for each of the two stands, there are sixteen landowner-pair scenarios. Social site values are found by substituting each landowner’s (privately) optimal choices into the objective function in [2]; thus, the social site values include the fire suppression costs that private landowners ignore. The combined (or joint) social site values for Stand A and Stand B are presented in Table 4. Optimal values for the landowner’s decision variables under all sixteen scenarios are reported for reference in Appendix 2.

A baseline entry in the upper left corner of Table 3 (and subsequent tables) shows the social site value when the two stands are jointly managed by a Government Agency (GA), yielding the first-best outcome. For this scenario only, both stands are optimized simultaneously using a single maximand.

\(^{15}\) For some simulation cases with stands aged roughly between eight and eleven years, there is a complementary relationship between fire suppression and fuel treatment. This appears to be an artifact of the functional forms chosen for the model, and does not significantly affect the analysis.
containing the choice variables for both stands. As both stands are identical, and managed identically, the choice variables take on identical values for the two stands.

When examining the tables, it should be kept in mind that small differences in per-acre social site values represent considerable sums of money, given that non-industrial private landowners hold nearly 300 million acres of forest land in the United States (Alig et al. 2003). Moreover, as is true for any simulation based in part on hypothetical data, the qualitative patterns revealed by the simulation are likely to be more robust than the exact numerical differences obtained.

Examining the top row of Table 3, we see that a Government Agency managing both stands jointly achieves a social site value for Stand A of $116.56 per acre. This is the first-best outcome. If, instead of joint management of the two stands by the Government Agency, there is a Government Agency on Stand A and an Informed Landowner on Stand B, the social site value for Stand A falls to $116.26 per acre. Similarly, when Stand B is managed by an Uninformed Landowner, the best the Government Agency on Stand A can achieve is a site value of $116.26 per acre (the two site values are equal after rounding to the nearest cent). When Stand B is managed by a Harvest-only Landowner, the Government Agency’s site value for Stand A falls to $115.17 per acre.

The second row of Table 3 gives the Informed Landowner’s performance on Stand A, when facing different types of neighbors on Stand B. As before, social site values fall as the neighboring landowner type is switched from a Government Agency to a Harvest-only Landowner. Interestingly, the decline is not monotonic across landowner types: site value actually rises slightly if an Informed Landowner on Stand B is replaced with an Uninformed Landowner. This finding is examined further below. The third and fourth rows of Table 3 report Stand A site values under an Uninformed Landowner and a Harvest-only Landowner.

The small differences observed in the results for the Informed and Uninformed landowners stem at least, in part, from our choices of functional form and parameter values for the fire arrival rate function. Under this function, changes in fuel treatment by a landowner, over the range observed in the simulations, result in only modest changes (on the order of a few percent) in fire arrival rates. Lacking empirical information on the precise relationship between fuel treatment and fire arrival rates, we chose to conservatively employ a simple functional form that was robust to variations in fuel treatment levels, while exhibiting decreasing returns to fuel treatment.\footnote{This robustness is important given that we examine a range of landowner-types, with fuel treatment levels varying from zero to over 250 in the sensitivity analyses.}

Table 3 can also be read vertically. Reading down a column is equivalent to assuming a fixed landowner-type for Stand B, and comparing how the management of Stand A affects the site value for Stand A. Here we see that even with a Government Agency managing the adjacent Stand B, as Stand A moves from the first-best case to Harvest-only Landowner management, its site value decreases significantly. A similar result is shown in the other columns as well. In the fourth column, the neighbor is a Harvest-only Landowner. Recall that this landowner type undertakes no fuel treatment: therefore, the site values in the fourth column could be interpreted as the optimum for a single stand in isolation (i.e., with no adjacent stand).

Although these results indicate a clear preference for management by a Government Agency rather than a Harvest-only Landowner, the results are less decisive when comparing Informed and Uninformed Landowners. Comparing the second and third rows of Table 3, we see that for any given neighbor on Stand B, an Uninformed Landowner on Stand A achieves a social site value no lower than that achieved by the Informed Landowner. In fact, for any neighbor on Stand B other than a Harvest-only Landowner, Stand A has a higher site value under an Uninformed Landowner than
under an Informed Landowner. In addition, examining the second and third columns, we see that given any manager on Stand A, society is no worse off if the neighbor on Stand B is changed from an Informed Landowner to an Uninformed Landowner. Again, for any landowner other than a Harvest-only Landowner or a Government Agency, society would prefer to have the neighbor be an Uninformed Landowner, rather than an Informed Landowner.

These seemingly counterintuitive results reflect free-riding by the Informed Landowner. Fuel treatment functions as a public good since fuel treatment undertaken by one landowner yields benefits to adjacent landowners. The Informed Landowner is aware of the cross-stand benefits of fuel treatment, so he will reduce the level of fuel treatment he undertakes when fuel treatment is undertaken by his neighbor. Free-riding reduces the social site value by imposing higher fire suppression costs on the government. There is no scope for such free riding by the other private landowner types: the Uninformed and Harvest-only Landowners are unaware of the cross-stand effects of fuel treatment, effectively assuming, in terms of their simulated behavior, that their neighbor applies no fuel treatment.

This outcome is an example of Lipsey and Lancaster’s “theory of second best.” In the fire problem considered, there are two market failures present. First, the cost of fire suppression is not borne by the landowner, and second, management decisions on one stand, specifically fuel treatment levels, affect the risk of fire on a neighboring stand. Switching from an Uninformed Landowner to an Informed Landowner partially corrects the second market failure but does not address the first one. The result is an outcome that is (socially) less desirable than when neither market failure is corrected. The cross-stand market failure is only partially corrected here because the Informed Landowner still ignores the effect of his fuel treatment choice on his neighbor’s site value; he only takes into account the effect of his neighbor’s fuel treatment choice on his own welfare.

This argument is borne out by the results in Appendix 2, which reports all management choices by all landowner types. With a Harvest-only Landowner (who undertakes no fuel treatment) on Stand B, an Informed Landowner on Stand A chooses a fuel treatment level of 135.07. When Stand B is managed instead by an Uninformed Landowner, the level of fuel treatment on Stand B rises from zero to 135.07. Now the Informed Landowner on Stand A free-rides off Stand B’s positive level of fuel treatment, so he reduces his level of treatment from 135.07 to 133.06. In contrast, an Uninformed Landowner on Stand A is unaware of the effects of his neighbor’s fuel treatment on his stand, and does not reduce his level of treatment when his neighbor is changed from a Harvest-only Landowner to one who undertakes some fuel treatment. The Uninformed Landowner’s level of fuel treatment effort remains at 135.07. Though this level of fuel treatment is higher than that undertaken by the Informed Landowner, it is still below the socially desirable level of fuel treatment. Appendix 2 reports that the Government Agency, which internalizes fire suppression costs, applies a level of fuel treatment effort of 227.02 or higher, depending on the landowner type on the adjacent stand.

As Table 4 shows, the highest combined social site value for the two stands is achieved under joint management by a Government Agency, while the lowest social site value is seen with Harvest-only Landowners managing both stands. The upper off-diagonal entries of Table 4 are omitted, as entries for identical pairs are

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17 If the neighbor on Stand B is a Harvest-only Landowner, then Stand A has a social site value of $112.63 under either an Informed or an Uninformed Landowner. The reason for this equality of Stand A site values when the neighbor is a Harvest-only Landowner is that in this case the Uninformed Landowner’s ignorance of the cross-stand effects of fuel treatment is irrelevant since his neighbor applies no fuel treatment.

18 The tendency of the Informed Landowner to reduce his fuel treatment is offset to some degree by the fact that reductions in fuel treatment lead to a smaller fraction of timber salvaged in the event of fire.
TABLE 5
COMBINED FIRE SUPPRESSION COSTS FOR BOTH STANDS FOR DIFFERENT LANDOWNER PAIRS

<table>
<thead>
<tr>
<th>Stand A</th>
<th>GA</th>
<th>ILO</th>
<th>ULO</th>
<th>HLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand B</td>
<td>($)</td>
<td>($)</td>
<td>($)</td>
<td>($)</td>
</tr>
<tr>
<td>GA</td>
<td>122.88</td>
<td>146.22</td>
<td>146.18</td>
<td>209.16</td>
</tr>
<tr>
<td>ILO</td>
<td>122.22</td>
<td>140.73</td>
<td>167.93</td>
<td>231.37</td>
</tr>
<tr>
<td>ULO</td>
<td>122.18</td>
<td>167.38</td>
<td>166.82</td>
<td>293.91</td>
</tr>
<tr>
<td>HLO</td>
<td>136.74</td>
<td>126.92</td>
<td>126.65</td>
<td>124.79</td>
</tr>
</tbody>
</table>

Notes: GA = Government Agency; ILO = Informed Landowner; ULO = Uninformed Landowner; HLO = Harvest-only Landowner.

Fire Suppression Costs

The above results imply that a change in the distribution of landowner types across a landscape will invariably lead to changes in expected fire suppression costs borne by the government. Variations in fire suppression costs for both stands combined are shown in Table 5. The first-best outcome, with the Government Agency managing both stands jointly, is the least-cost option for the government, with fire suppression expenditures totaling $122.88 for the two stands. Costs more than double in the worst case, rising to $293.91, when both stands are managed by Harvest-only landowners. The theory of second best is also manifest in this table: replacing an Informed Landowner with an Uninformed Landowner lowers fire suppression costs (except for the cases also involving a Harvest-only Landowner). Again, this is due to the reduced fire suppression effort required, given the Uninformed Landowner’s (naïvely) higher level of fuel treatment.

Private Site Values

The results presented thus far compare outcomes for different landowner pairs in terms of social site values. We now compare actual and anticipated private site values to the social site values. The site values that private landowners actually receive are presented in Table 6. These are calculated by substituting each private landowner’s choices into the site value function for the Informed Landowner (see Table 1), since this function correctly includes the cross-stand effects of fuel treatment (but excludes fire suppression costs). Examining the table, we see that the landowner on Stand A always does best with a Government Agency as a neighbor, and worst with a Harvest-only Landowner. But as the owner of Stand B is varied, the changes in Stand A’s site value are small. This is due to the limited reactivity of private landowners to their neighbor’s decisions: the Informed Landowner makes relatively small adjustments in his management choices when his neighbor’s type changes (see Appendix 2), while the Uninformed and Harvest-only Landowners make no adjustments at

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TABLE 6
PRIVATE SITE VALUE OF STAND A FOR DIFFERENT LANDOWNER PAIRS

<table>
<thead>
<tr>
<th>Stand B</th>
<th>GA</th>
<th>ILO</th>
<th>ULO</th>
<th>HLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand A</td>
<td>($)</td>
<td>($)</td>
<td>($)</td>
<td>($)</td>
</tr>
<tr>
<td>GA</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>ILO</td>
<td>136.74</td>
<td>126.92</td>
<td>126.65</td>
<td>124.79</td>
</tr>
<tr>
<td>ULO</td>
<td>136.74</td>
<td>126.92</td>
<td>126.65</td>
<td>124.79</td>
</tr>
<tr>
<td>HLO</td>
<td>126.43</td>
<td>126.09</td>
<td>126.09</td>
<td>124.79</td>
</tr>
</tbody>
</table>

Notes: GA = Government Agency; ILO = Informed Landowner; ULO = Uninformed Landowner; HLO = Harvest-only Landowner.

---

Suppression costs are found using the government’s reaction function, equation [5], evaluated at the landowners’ choices for planting density and fuel treatment. The government’s reaction function takes on values from zero (at the beginning of a rotation) up to some maximum just before the stand is harvested at its rotation age. This maximum value is multiplied by the cost of government effort to give the values reported in Table 5. The entries in Table 5 do not give the present value of the stream of fire suppression costs incurred over the life of a stand, which is more difficult to interpret and compare to real-world data.
Table 7 presents "anticipated" private site values. These are the site values that private landowners anticipate receiving, given their management choices. Anticipated private site value is computed by substituting a landowner's choices into his (perceived) site value function. Note that this site value function is mis-specified for the Uninformed and Harvest-only Landowners, given their limited information sets. This mis-specification means that the anticipated site values for these two landowner-types differ from the actual private site values. Nevertheless, the anticipated site values for these landowners are of interest, because they are the motivation behind the landowners' choices, given their information sets.

The values in Table 7 are for Stand A, assuming a Government Agency manages the adjacent Stand B (although this assumption is unimportant to the results). Two types of anticipated site values are presented: "unregulated" site values are obtained when the landowner is free to manage his stand as he wishes (as we have assumed thus far), while "regulated" site values reflect a hypothetical situation in which the landowner is required to adopt the Government Agency's choices (which are less preferred from the perspective of the private landowner).

As can be seen by comparing the first and second columns in Table 7, anticipated (unregulated) private site values are higher than social site values. This primarily reflects the failure of private landowners to internalize fire suppression costs. The third column shows the anticipated private site value for the regulated stand. This figure is the anticipated private site value for a landowner who is forced to adopt socially optimal choices. The question of how much worse off a private landowner thinks he would be under regulation is answered in percentage terms in the fourth column of the table. For landowners whose behavior is relatively close to that of the Government Agency, regulation would be less of an imposition. Recall that the Informed Landowner is closest to the Government Agency in terms of their information sets, and the only difference between Informed and Uninformed Landowners is in recognition of cross-stand fuel treatment effects on fire arrival rates. Referring to the table, both Informed and Uninformed Landowners would expect a reduction of less than 2% in their private returns if they were forced to adopt socially optimal choices. In contrast, the Harvest-only Landowner would expect a 14.2% reduction in his site value under regulation. Thus, the Harvest-only Landowner would be the most resistant, by far.
to policies requiring fire prevention on forest lands.

Fire Suppression Cost-Sharing

The differences between social and private site values across the landowner pairs suggest some scope for policies aimed at reducing these differences. The results in Table 4 and Table 5 indicate that for these simulations, the externality associated with fire suppression costs is larger than the cross-stand fire risk externality. Switching from a Government Agency to any other landowner-type results in larger changes in social site values and fire suppression costs than switching from an Informed Landowner to an Uninformed Landowner or vice versa. We therefore examine a policy that addresses the fire suppression cost externality directly, by having each landowner pay 50% of the government's fire suppression costs. To model this cost-sharing policy, we modify the simulations by subtracting the term $\frac{1}{2}[c^G (.)]$ from the objective function of the private landowner whenever there is a fire. The cost-sharing policy results in a change in the level of fuel treatment on Stand A as shown in Table 8. The changes are substantial in many cases. The Informed and Uninformed Landowners increase fuel treatment by nearly 25% relative to no-cost sharing levels. Furthermore, the Government Agency can actually reduce his level of fuel treatment slightly when paired with any landowner except the Harvest-only Landowner.

Table 9 shows the change in combined social site value under the cost-sharing policy. The greatest improvements are realized when Informed and Uninformed Landowners are paired together. Site values are relatively unresponsive to the cost-sharing policy when the landscape is populated by Harvest-only Landowners, as this type fails to make use of fuel treatment,

\[^{22}\text{The revenues generated by this policy are treated as pure transfers to the general treasury and, therefore, do not alter the government's objective function in equation [3].}\]
which is the most effective means of increasing social site value.

Table 10 reports changes in total fire suppression expenditures relative to the no-cost-sharing case. Suppression costs fall by anywhere from 2.6% to 14.0%, depending on the landowner pair considered. The greatest reductions are for Uninformed and Informed Landowners paired together. As noted above, these landowners have a significant response to the cost sharing policy, and this markedly reduces suppression costs, given the substitutability between fire prevention and suppression.

V. CONCLUDING REMARKS

We developed a model of adjacent landowners, whose fuel treatment levels affect a common fire risk, to examine two externalities present in forest land management: the failure of landowners to bear the costs of suppressing fires that occur on their lands, and the influence of one landowner’s fuel treatment choice on the fire risk facing his neighbor. We considered four landowner types that differ in terms of preferences and information sets.

The most surprising result, and the novelty of our work, follows from the potential in our model for free riding between adjacent landowners. The presence of this behavior means that improving landowners’ information about the relationship between management decisions and fire risk could actually lower social welfare. Specifically, we find that social site values can be lower with a landowner who is aware of the cross-stand effects of fuel treatment than with a landowner who is unaware of these effects. The Informed Landowner is aware of the effects of his neighbor’s fuel treatment level, and is able to free-ride off his neighbor’s efforts, reducing his own fuel treatment effort. We find this behavior can lead to higher expected fire suppression costs and lower social site values. The Informed Landowner is the only private landowner type displaying this free-riding behavior; the other private landowners do not recognize the cross-stand effects of fuel treatment.

The simulation results indicate modest consequences from free-riding in terms of social site values and fire suppression costs. This is due in part to our choice of functional forms and parameter values. It could also be related to the presence of a single adjacent landowner in our model. With multiple adjacent landowners, the scope for free-riding would be greater, and its consequences could well be magnified.

It is difficult to identify policies that would specifically target this free-riding, and the underlying externality generated by interlinked fire risk. However, a Coasian solution suggests itself: landowners could buy out their neighbors and increase their (contiguous) landholdings. In addition to lowering fire risk for the original stand, the higher returns that accrue to more “active” managers, specifically those who engage in fuel treatment, would provide a further incentive for (say) Informed Landowners to buy neighboring lands managed by Harvest-only Landowners (who do not engage in fuel treatment).

Compared to the modest impact of the cross-stand fire risk externality, our simulations show substantial effects for the fire suppression cost externality, both in terms of reducing social site values and increasing fire suppression costs. We find that a policy requiring landowners to pay half the fire suppression costs incurred by the government is fairly effective, reducing total fire suppression costs by up to 14%, and increasing social site values by up to 4%. Increasing the share of suppression costs borne by private landowners results in larger reductions in total fire suppression costs, and larger increases in social site values.23 The landowners that are most responsive to the cost-sharing policy are those that willingly engage in some fuel treatment (the Informed and Uninformed Landowners). Landowners who do not engage in fuel treatment (Harvest-only Landowners) are severely limited in their ability to mitigate fire risk.

23 Requiring landowners to bear all the costs of fire suppression makes the Informed Landowner’s objective function identical to that of a Government Agency managing a single stand (see Table 1).
An examination of the results in Table 4 and Table 5 reveals that the largest reductions in social site values, and the largest increases in fire suppression costs, occur when any of the “active” landowners is switched to a Harvest-only Landowner. This echoes the findings in Amacher, Malik, and Haight (2005). Recall that the Harvest-only Landowner is wholly ignorant of the benefits of fuel treatment, both in terms of the reduction in fire risk, and the increase in salvage in the event of fire. Thus, our findings suggest that a policy of educating landowners about the own-stand benefits of fuel treatment, in particular increased salvage in the event of fire, would increase total social site values.

Our results comparing unregulated and regulated private site values yield an additional motivation for educating landowners about the private benefits of fuel treatment. We find that the difference between regulated and unregulated outcomes is much smaller for the active (Informed and Uninformed) landowners than for the Harvest-only Landowner. Thus, emphasizing the benefits of fuel treatment would lower landowner resistance to government policies aimed at harmonizing private and socially optimal management choices.

APPENDIX I

PROCEDURE FOR SIMULATING NASH EQUILIBRIUM

The procedure begins with Simulation A (i.e., for Stand A) using arbitrary values for the level and timing of fuel treatment on the adjacent Stand B. These starting values are referred to as $Z^B$ and $S^B$, denoting the level and timing of treatment undertaken on Stand B. Stand A decisions are then optimized using a coarse grid search to establish a starting vector for a more targeted simplex search. The targeted search provides the vector of optimal choices for Stand A, given the arbitrary $Z^B$ and $S^B$. This vector of optimal choices for Stand A is given by $v^A = (D^*A, S^*A, Z^*A, T^*A | Z^B, S^B)$, indicating that the optimal choices of Landowner A are conditional on the level and timing of fuel treatment undertaken by Landowner B. These Landowner B variables may not have yet reached their optimal values, so they are written without a star superscript.

At this point the procedure switches to Simulation B, which considers the choices of Landowner B, given Landowner A as the neighbor. This procedure makes use of $Z^A$ and $S^A$, taken from Landowner A’s optimal choice in Simulation B: $Z^A = Z^*A$, $S^A = S^*A$. The coarse and targeted optimizations then return Landowner B’s vector of (conditional) optimal choices: $v^B = (D^B, S^B, Z^B, T^B | Z^A, S^A)$. As in $v^A$, no stars are used for the conditioning elements $Z^A$ and $S^A$. This indicates that Landowner B’s choices are optimal given the values that were assigned to Landowner A’s choices.

The process is then repeated, finding both landowners’ optimum choices until $v^A$ and $v^B$ converge to stable values. These optimal values constitute the Nash equilibrium for the simulation. The equilibrium values are used to determine landowner behavior over the infinite series of rotations, and are also used in the government’s reaction function to determine the level of fire suppression services delivered to each stand (in the event of a fire).
## APPENDIX 2

### OPTIMAL STAND A CHOICES, AND ACTUAL PRIVATE AND SOCIAL SITE VALUES FOR DIFFERENT LANDOWNER PAIRS

*T* = Rotation Age  
*D* = Planting Density  
*S* = Timing of Fuel Treatment  
*Z* = Level of Fuel Treatment  

GA = Government Agency, ILO = Informed Landowner,  
ULO = Uninformed Landowner, HLO = Harvest-only Landowner

<table>
<thead>
<tr>
<th></th>
<th>T (Years)</th>
<th>D (Trees per Acre)</th>
<th>S (Years)</th>
<th>Z</th>
<th>Pvt. Site Value ($)</th>
<th>Soc. Site Value ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Government Agency (GA) on Stand B</strong></td>
<td></td>
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<tr>
<td>GA</td>
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<td>204.80</td>
<td>10.56</td>
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<td>ILO</td>
<td>28.42</td>
<td>214.54</td>
<td>9.47</td>
<td>134.92</td>
<td>136.74</td>
<td>114.21</td>
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<tr>
<td>ULO</td>
<td>28.42</td>
<td>214.53</td>
<td>9.47</td>
<td>135.07</td>
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<td>114.22</td>
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<td>194.65</td>
<td>0.00</td>
<td>0.00</td>
<td>124.79</td>
<td>99.64</td>
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<td><strong>Informed Landowner (ILO) on Stand B</strong></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>GA</td>
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<td>204.29</td>
<td>10.67</td>
<td>223.51</td>
<td>116.26</td>
<td>116.26</td>
</tr>
<tr>
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<td>133.07</td>
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<td>113.81</td>
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<td>135.07</td>
<td>135.65</td>
<td>113.89</td>
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<td>0.00</td>
<td>0.00</td>
<td>124.79</td>
<td>99.16</td>
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<td></td>
</tr>
<tr>
<td>GA</td>
<td>28.34</td>
<td>204.29</td>
<td>10.67</td>
<td>223.51</td>
<td>116.26</td>
<td>116.26</td>
</tr>
<tr>
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<td>214.65</td>
<td>9.49</td>
<td>133.06</td>
<td>136.51</td>
<td>113.90</td>
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<tr>
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<td>9.47</td>
<td>135.07</td>
<td>135.65</td>
<td>113.90</td>
</tr>
<tr>
<td>HLO</td>
<td>28.02</td>
<td>194.65</td>
<td>0.00</td>
<td>0.00</td>
<td>124.79</td>
<td>99.16</td>
</tr>
<tr>
<td><strong>Harvest-only Landowner (HLO) on Stand B</strong></td>
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<tr>
<td>GA</td>
<td>28.38</td>
<td>204.00</td>
<td>10.64</td>
<td>227.02</td>
<td>115.17</td>
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<td>214.53</td>
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<td>135.07</td>
<td>135.65</td>
<td>112.63</td>
</tr>
<tr>
<td>ULO</td>
<td>28.42</td>
<td>214.53</td>
<td>9.47</td>
<td>135.07</td>
<td>135.65</td>
<td>112.63</td>
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<tr>
<td>HLO</td>
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<td>0.00</td>
<td>0.00</td>
<td>124.79</td>
<td>97.40</td>
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APPENDIX 3
SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to explore the effects of changes in several simulation parameters. Some care was necessary in choosing parameter values, as certain combinations result in degenerate solutions, like applying fuel treatment for a rotation only after the harvest ($S > 7$).

The sensitivity analysis examined the robustness of the simulation results to changes in certain parameter values. The parameters considered are: (1) the risk of incendiary events ($\phi$), (2) the cost of government fire suppression ($c$), (3) the cost of fuel treatment ($c'$), and (4) the effectiveness of fuel treatment ($M$). Each of these parameters was considered in turn, via a pair of simulations. For the first simulation in each pair, the baseline parameter setting was halved. For the second simulation in each pair, the baseline parameter setting was doubled. The results of this analysis are presented in Table 11 through Table 14.

In the table headings, the extreme upper left cell shows the halved or doubled values for the parameter under consideration. In the table itself, the combined site value for the two stands under the first-best outcome is reported in the upper left cell, while other cells report percent deviations from that first-best outcome. This differs somewhat from the typical approach for a sensitivity analysis, which might consider a parameter’s effect on the site value under a constant landowner pair. As the focus of this study is on private management’s effect on site value, the objective is to quantify deviations from the first-best outcome, rather than deviations from some private-value, “nth best” outcome. Thus, this analysis reports parameter effects on deviations from the best possible outcome under each landowner pair, given the various parameter settings.

The tables indicate that deviations from the first-best site value depend most heavily on the risk of fire. As shown in Table 11, when the risk of ignition is low ($\phi = 0.01$, or one fire every hundred years), the worst outcome has a site value only 2.9% below that of the first-best outcome. In contrast, when ignition risk is high ($\phi = 0.04$, or four fires every hundred years), the worst outcome has a site value 70% below that of first-best outcome. Ignition risk is also the strongest determinant of how high the site value can go under the first-best scenario: a low risk allows the site value to reach $304.93 for the two acres taken together, while a high risk limits site value to $107.43 for the two acres.

Changes in other parameters result in more moderate effects on deviations from the first-best site value, as well as on variations in the maximum possible first-best site value. Changes in the variable cost of fire suppression have a small effect on the first-best site value. The range of site values for the two stands under the first-best case is from $247.54 with inexpensive fire suppression ($0.25 per unit, in Table 12's upper half) to $216.92 with expensive suppression ($1.00 per unit, in Table 12's lower half). Also, there is little effect on deviations from the first-best outcome. The only noteworthy differences are in the site values involving a Harvest-only Landowner: when fire suppression

TABLE 11
<table>
<thead>
<tr>
<th>Stand A</th>
<th>GA</th>
<th>ILO</th>
<th>ULO</th>
<th>HLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi = 0.01$</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GA</td>
<td>304.93</td>
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</tr>
<tr>
<td>ILO</td>
<td>-0.4%</td>
<td>-0.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULO</td>
<td>-0.4%</td>
<td>-0.8%</td>
<td>-0.8%</td>
<td></td>
</tr>
<tr>
<td>HLO</td>
<td>-1.4%</td>
<td>-1.8%</td>
<td>-1.8%</td>
<td>-2.9%</td>
</tr>
<tr>
<td>$\phi = 0.04$</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GA</td>
<td>107.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILO</td>
<td>-4.7%</td>
<td>-9.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULO</td>
<td>-4.7%</td>
<td>-9.6%</td>
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<td></td>
</tr>
<tr>
<td>HLO</td>
<td>-34.1%</td>
<td>-39.2%</td>
<td>-39.2%</td>
<td>-70.0%</td>
</tr>
</tbody>
</table>

Notes: GA = Government Agency; ILO = Informed Landowner; ULO = Uninformed Landowner; HLO = Harvest-only Landowner.

TABLE 12
<table>
<thead>
<tr>
<th>Stand A</th>
<th>GA</th>
<th>ILO</th>
<th>ULO</th>
<th>HLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c = 0.25$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GA</td>
<td>247.54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILO</td>
<td>-1.1%</td>
<td>-2.3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULO</td>
<td>-1.1%</td>
<td>-2.3%</td>
<td>-2.2%</td>
<td></td>
</tr>
<tr>
<td>HLO</td>
<td>-4.9%</td>
<td>-6.1%</td>
<td>-6.1%</td>
<td>-10.3%</td>
</tr>
<tr>
<td>$c = 1.00$</td>
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</tr>
<tr>
<td>GA</td>
<td>216.92</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILO</td>
<td>-1.1%</td>
<td>-2.2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULO</td>
<td>-1.1%</td>
<td>-2.2%</td>
<td>-2.1%</td>
<td></td>
</tr>
<tr>
<td>HLO</td>
<td>-9.1%</td>
<td>-10.3%</td>
<td>-10.3%</td>
<td>-19.0%</td>
</tr>
</tbody>
</table>

Notes: GA = Government Agency; ILO = Informed Landowner; ULO = Uninformed Landowner; HLO = Harvest-only Landowner.
TABLE 13
Sensitivity Analysis: Cost of Fuel Treatment
(First-Best Site Value and Percentage Deviation, for Both Stands Combined)

<table>
<thead>
<tr>
<th>Stand A</th>
<th>GA</th>
<th>ILO</th>
<th>ULO</th>
<th>HLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε^2 = 0.02</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>GA</td>
<td>249.08</td>
<td>-1.1%</td>
<td>-2.3%</td>
<td></td>
</tr>
<tr>
<td>ILO</td>
<td>-1.1%</td>
<td>-2.2%</td>
<td>-2.2%</td>
<td></td>
</tr>
<tr>
<td>ULO</td>
<td>-10.4%</td>
<td>-11.7%</td>
<td>-11.7%</td>
<td>-21.8%</td>
</tr>
<tr>
<td>HLO</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ε^2 = 0.08</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GA</td>
<td>216.06</td>
<td>-1.1%</td>
<td>-2.3%</td>
<td></td>
</tr>
<tr>
<td>ILO</td>
<td>-1.1%</td>
<td>-2.3%</td>
<td>-2.3%</td>
<td></td>
</tr>
<tr>
<td>ULO</td>
<td>-4.7%</td>
<td>-5.9%</td>
<td>-5.9%</td>
<td>-9.8%</td>
</tr>
</tbody>
</table>

Notes: GA = Government Agency; ILO = Informed Landowner; ULO = Uninformed Landowner.
is inexpensive, site values under these landowner pairs are anywhere from 4.9% to 10.3% below the Government Agency’s site value. The deviations nearly double under expensive fire suppression, when landowner pairs including a Harvest-only Landowner at best achieve site values from 9.1% to 19.0% below the first-best outcome. These results indicate that when fire suppression is expensive, the government’s limited fire-suppression budget is less able to counteract the management effects of the Harvest-only Landowner’s mis-specified problem.

Changes in the variable cost of fuel treatment likewise have a small effect on the first-best site value. The range of site values for the two stands under the first-best case is from $249.08 with inexpensive treatment ($0.02 per unit, in Table 13’s upper half) to $216.06 with expensive treatment ($0.08 per unit, in Table 13’s lower half). Also there is little effect on deviations from the first-best outcome. Again, the only noteworthy differences are in the site values involving a Harvest-only Landowner: when fuel treatment is inexpensive, site values under these landowner pairs are anywhere from 10.4% to 21.8% below the Government Agency’s site value. These deviations are more than double those under expensive fuel treatment, when landowner pairs including a Harvest-only Landowner achieve site values from 4.7% to 9.8% below the first-best outcome. These results indicate that when fuel treatment is inexpensive, the government’s fire suppression is a poor substitute for private fuel treatment. That is, the greatest improvement in site value is to be had from applying cheap fuel treatment before a fire arrives, rather than relatively expensive fire suppression after a fire has started.

Changes in the effectiveness of fuel treatment have a very small effect on the first-best site value. Note that a change in the effectiveness of treatment impacts the site value via the fire arrival rate function. The range of site values for the two stands under the first-best case is from $238.72 with effective treatment ($M = 250$, in Table 14’s upper half) to $230.29 with ineffective treatment ($M = 1,000$, in Table 14’s lower half). This small range for the two cases is driven by the functional form of the fire arrival rate function, which remains within the rather narrow range of 1.76 to 1.94 over this wide range of $M$ values.

With the effectiveness of fuel treatment there is again little effect on deviations from the first-best outcome. Again this is mainly seen in scenarios involving a Harvest-only Landowner. Even here, the differences are small: when fuel treatment is effective ($M = 250$), site values under these landowner pairs are anywhere from 7.5% to 15.4% below the Government Agency’s site value. Deviations are slightly greater with ineffective fire treatment ($M = 1,000$); landowner pairs including a Harvest-only Landowner at best achieve site values from 8.4% to 18.4% below the first-best outcome.

Comparing the results from Table 11 through Table 14, it seems that site value is most sensitive by far to ignition risk, which has substantial effects on both the maximum combined site value attainable in the first-best case, and on the
deviations from this site value once private landowners get involved. The site value is less sensitive to changes in variable costs of fire suppression or fuel treatment. These variables have a modest impact on the maximum combined site value attainable in the first-best case, and deviations from the first-best case are most evident when a Harvest-only Landowner is involved. Lastly, the effectiveness of fuel treatment has a small effect (via the fire arrival rate function) on both the maximum combined site value under the first-best case, and on deviations from that first-best outcome. Again, the most noticeable differences involve a Harvest-only Landowner.

References


