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The social costs of homeowner decisions in fire-prone communities: Information, insurance, and amenities

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ABSTRACT

In this article, we consider wildfire risk management decisions using a dynamic stochastic model of homeowner interaction in a setting where spatial externalities arise. Our central objective is to apply observations from the social science literature about homeowner preferences to this economic externality problem and determine how assumptions about insurance, information and starting fuel loads affect outcomes and the effectiveness of policy. Three new features of our approach are, first, to assess fuel treatment behavior under potential misinformation scenarios, second, to allow for heterogeneous starting fuel loads across ownerships, and, finally, to evaluate the effectiveness of insurance and direct regulation at improving outcomes. Among other results, we find that risk-adjusted insurance may not create incentives for fuel treatment when government suppression exists, and in games with heterogeneous starting fuel loads, the social costs from misinformation can persist over a greater range of fire probability and damage function parameter values. These results suggest that, even as information about wildfire improves, the social costs inherent in private decisions will be more persistent than previously thought on landscapes where fuel stock differs across ownerships.

1. Introduction

In recent years, the extent and severity of wildfires in the western U.S. have become an important policy issue (Dombeck et al., 2004; National Interagency Fire Center, 2011). Annual wildfire suppression often exceeds $1 billion, and this suppression has left large amounts of hazardous forest fuels on U.S. landscapes putting communities at risk. Given budget-constrained governments, the fuel reduction decisions individual landowners make in the wildland–urban interface (WUI) are critical, yet these measures are costly and as a result many landowners fail to mitigate risk.

Because wildfire moves across landscapes and ownership boundaries, forest fuel conditions on an individual property affect wildfire damage on both the individual property and neighboring properties. Positive spatial externalities (i.e., benefits to adjacent landowners) created by removing hazardous forest fuels have been documented (Hann and Strohm, 2003) and found significant for large wildfires (Finney, 2001; Gill and Bradstock, 1998). Fuel reduction undertaken on an individual property limits the accumulation of forest fuels and decreases the risk of fire damage on neighboring properties. Recognizing these spatial links, many landowners living in the WUI consider the state of neighboring forests when making decisions about investment in fuel treatment (Brenkert-Smith et al., 2005; Monroe and Nelson, 2004). The pattern of fuel treatment on the landscape, therefore, depends on the pattern of landowner risk mitigating decisions across the landscape and how these decisions interact.

The relatively few economic studies of risk-mitigating decisions in the context of spatial externalities with multiple landowners include Butry and Donovan (2008), Shafran (2008) and Busby et al. (2012).[3] Butry and Donovan (2008) develop a simulation model to evaluate several landscape-level fuel treatment strategies and illustrate the benefits from collective action, but do not examine landowner interaction. Busby et al. (2012) and Shafran (2008) develop game theoretic models that allow for strategic interaction between landowners.

Through the use of written survey and interview data, social science research has recently explored a variety of reasons landowners fail to undertake fuel reduction. These include misinformation about wildfire risk (Talberth et al., 2006), a reliance on and an overly optimistic belief in the ability of government suppression to protect private property (Fried et al., 1999; Gardner et al., 1987; McCaffrey, 2006), or that insurance will always be available to compensate landowners for wildfire damages (Brenkert-Smith et al., 2005). Brenkert-Smith et al. (2005) also note that availability of insurance is an important factor in that landowners view losses as less costly when they are insured, which

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[3] Crowley et al. (2009) use a Faustmann model to examine similar spatial externalities among adjacent forest landowners, but insurance and home structures are not considered.

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begs the question of how the possibility of insurance drops (loss of access to landowner insurance) might affect behavior. Reluctance to remove hazardous fuel may also be due to positive amenity values that vegetation provides to landowners (Brenkert-Smith et al., 2005; Talberth et al., 2006). Collectively, these studies show that landowner incentives for fuel treatment depend in complex ways on the information landowners have, the presence of public agency fire suppression, amenity values and the availability of insurance.

The focus on wildfire education programs in many fire-prone communities also reflects the need, highlighted in the social science research, to improve landowner information about wildfire and the benefits of risk-mitigating fuel treatments. State, federal and community education programs focus primarily on fire behavior, vegetation management, and raising awareness about fire danger (e.g., Bitterroot Community Wildfire Protection Plan, 2010; Colorado Springs Fire Department, 2011; Sunriver Owners Association, 2010). In addition, numerous studies have pointed to the need to improve information about wildfire and risk management (e.g., Bowman et al., 2008; Jarrett et al., 2009). To better understand the impact of misinformation on the fuel treatment decision and social costs, we examine cases where landowners have misinformation about the probability of fire, fire damage and the spatial externalities associated with fuel management decisions. Identifying the sources of misinformation with the greatest social costs will improve the ability of land management agencies and communities to design effective education programs.

Similar to Busby et al. (2012) and Shafran (2008), our purpose is to examine the fuel treatment decision between adjacent landowners where spatial externalities are present, but our work goes beyond existing literature to include investigating the role of insurance and the possibility that landowners are misinformed about wildfire risk. We also build upon the recent insights from social science research and specify a dynamic economic model of the fuel treatment decision that incorporates key spatial features of the wildfire risk management problem and allows an exploration of the social inefficiencies associated with misinformation, government suppression, and insurance programs. We use our model to, first, assess fuel treatment behavior and associated social costs for landowners with misinformation about wildfire, and, second, to examine outcomes when landowners make fuel treatment decisions over time on a landscape that begins initially with unequal fuel loads across ownerships. This is a departure from related Faustmann-based studies that assume that starting fuels are equal or zero (e.g., Crowley et al., 2009). Relaxing this assumption permits study of the strategic interaction between landowners in a more realistic setting, given that individual ownerships are managed independently. Finally, we evaluate the effectiveness of insurance, where the cost of coverage depends on landowners' fuel management decisions, and we consider fuel treatment cost-sharing and fuel stock regulation as a means for reducing social costs. A better understanding of the fuel treatment decision in the cases we examine will improve the ability of policy-makers and public land managers to craft more effective public policies, leading to better protected and informed WUI communities.

The remainder of this paper is organized as follows. First, we outline a stochastic dynamic game theoretic model that captures features of spatial externalities, strategic behavior, misinformation, and insurance for two adjacent properties in a fire-prone area. In Section 2, we describe the simulation approach used to solve this model for various types of imperfect information and spatial externalities inherent in the problem. Sections 3 and 4 describe the results from the fuel treatment game and policy applications, respectively. Finally, in Section 5, we offer a discussion of the results, concluding remarks, and policy recommendations.

2. Model of a Fire-Prone Community

We begin by examining the strategic incentives for two adjacent landowners (labeled by subscripts k and j) living in the fire-prone WUI. Initially, we assume that each landowner values amenities generated by forest vegetation, is aware of the positive relationship between forest fuels and wildfire damage, and knows the probability of fire in each time period. Both landowners begin with insurance, but if fire damage is costly it can reduce landowner access to insurance in future time periods.

In what follows, we describe the model using landowner k as the primary landowner and j as the adjacent landowner, although the same general specification holds also for landowner j. The spatial features of the model are driven by the landscape pattern of forest fuel. When a fire occurs, it may damage homes, reduce landscape amenities by consuming vegetation, and lead to insurance drops. The severity of wildfire impacts increases when there is more fuel on the landscape. The presence of fire suppression can reduce wildfire damage but is costly. The sequence of events described by the model is outlined in Table 1.

2.1. Fuels, Fire, and Suppression

In every time period, each landowner's choice is whether to undertake fuel treatment on their property or to let forest vegetation grow. By removing flammable vegetation, fuel treatment reduces damage to the landowner's property structure if a wildfire occurs. For example, the state of fuel loading for landowner k at time t is given by Z_t^k, and this fuel load changes over time according to:

$$Z_t^k = \gamma\left(Z_{t-1}^k - M_{t-1}^k\right) \tag{1}$$

where M_{t-1}^k is the amount of fuel removed by landowner k at time $t-1$ and γ is a community fuel growth rate that does not vary over landowners k and j. Later in the simulation, we discuss a simplified index for M_t^k that represents Eq. (1) and is more tractable in the dynamic programming solution process. With this in mind, the convex cost of fuel treatment paid by landowner k is a function of fuel removed on property k at time t:$C_M(M_t^k)$, such that $C'_M\left(M_t^k\right) > 0$ and $C''_M\left(M_t^k\right) < 0$. For the simulation, we separate $C_M(M_t^k)$ into fixed and variable components.

Both landowners take the probability of a fire occurring on their property as independent of the fuel stock on the landscape, as in Amacher et al. (2005) and Amacher et al. (2006). Fire can arrive each year in the community with a probability at time t equal to:

$$p(t) = pf_t, \forall t. \tag{2}$$

When a fire occurs, both landowner parcels are assumed to burn, but fire damage and fuel consumption on each individual property depend on the fuel present on each landowner's property and the adjacent property, and as in Amacher et al. (2005, 2006), and Busby et al. (2012).

We assume a government agency (noted as 'Government' in what follows) expends effort to suppress fires in the time period that fire arrives. As in Crowley et al. (2009) and Busby et al. (2012), Government acts as a follower by observing a fire at time t, and then choosing

Table 1
Sequence of events in each time period.

1. Landowners k, j choose fuel treatment.
2. Insurance premium for current period is calculated, according to post-treatment fuel stock.
3. Fire occurs or does not occur.
4. Government chooses level of fire suppression.
5. Landowners k, j realize payoffs (losses from fire).
6. Insurance drops, if any, are made.
7. Fuel stock grows.

suppression effort (g) at time t. Government is not forward-looking, but chooses suppression effort in response to a fire event and the current fuel landscape at the time of fire.[4] The choice of g is solved to maximize property value net of fire damage and suppression cost.[5] Each landowner's fuel reduction reduces total suppression costs, but individual landowners do not consider Government suppression costs in their fuel treatment decision.

2.2. Landowner Values at Risk

Landowners k and j make a fuel reduction choice each time period t to maximize the value of their structure plus the value of amenities they enjoy on their property over time. The value of the structure for landowner k is: $H^k_{t+1} = H^k_t \cdot (1+\delta)$, where δ is an exogenous rate of market appreciation. Amenity value is related directly to fuel load, comprised of natural vegetation or landscaping (Donovan and Butry, 2010), on the individual and adjacent property. The amenity value at time t for landowner k is concave and increasing in fuel present across the landscape, $A^k_t = A(Z^k_t, Z^j_t)$, where, $A'(Z^k_t, Z^j_t) > 0$, and concave, $A''(Z^k_t, Z^j_t) < 0$. We assume that landowners' properties are spatial complements so that up to a certain point fuel accumulating on adjacent property j will increase amenity value of landowner k and vice versa (Amacher et al., 2004; Donovan and Butry, 2010; Swallow and Wear, 1993). In the model, amenities have both private and public goods characteristics; they are private in the sense that a landowner captures amenities as part of total property value, $H^k_t + A^k_t$, but are public in that a landowner's decisions concerning fuels impact the amenities of other property owners through spatial neighborhood effects.

2.3. Damage Function

When fire arrives its impact is represented by a damage function that gives the proportion of fuel stock (Z), structure value (H), and amenity value (A) lost on parcel k as a function of the configuration of the post-treatment fuel stock on the landscape, $D^{k,q} = D^{k,q}(Z^k_{t-1} - M^k_{t-1}; g)$, where $q = Z,H,A$. Following Busby et al. (2012), we assume that fire acts similarly on all three variables. After a fire, post-fire fuel load, structure value, and amenity value are:

$$Z^k_t = \left(Z^k_{t-1} - M^k_{t-1}\right) \cdot \left(1 - D^{k,q=Z}\right) \tag{3a}$$

$$H^k_t = H^k_{t-1} \cdot \left(1 - D^{k,q=H}\right) \tag{3b}$$

$$A^k_t = A^k_{t-1} \cdot \left(1 - D^{k,q=A}\right). \tag{3c}$$

Fire damage for parcel k is a linear function of the post-treatment fuel stock on the individual parcel and the neighboring parcel, so that:

$$D^{k,q} = \sum_{j=1}^{2} w^{k,j} \cdot \left(Z^j_{t-1} - M^j_{t-1}\right). \tag{4}$$

The weight, $w^{k,j}$, represents the contribution of parcel k's post-treatment fuel stock to damage on the adjacent parcel j. The bigger the weight assigned to parcel j, the more important that parcel's fuel stock in determining fire damage on parcel k. The damage function is deterministic, linearly increasing in post-treatment (pre-fire) fuel stock, bounded by 0 and 1 by a scaling factor, and continuous. Wildfire damage is a function of the amount of fuel on the landscape and, hence, of the previous fuel reduction decisions made by each landowner.[6]

2.4. Insurance

From the start both landowners are fully insured for wildfire damage by private insurance. The cost of insurance, or the homeowner premium, depends on fire probability, the value of the house insured, and indirectly on the fuel stock on parcels k and j because fuel determines likely damages from fire. For example, landowner k's cost of insurance at time t is: $I^k_t = I(pf_t, H^k_t, Z^j_t, Z^k_t)$. Insurance is risk-adjusted so that cost decreases with fuel stock.[7] After a fire that arrives in time t, insurance compensates insured landowners for lost structure value so that for landowners k and j we have $H^k_t = H^k_{t+1}$ and $H^j_t = H^{kj}_{t+1}$, and reconstruction costs to the landowners are zero. Uninsured landowners, however, must pay reconstruction costs following fire.

In some cases, an insurance company will drop property owners if a fire arrives that is severe enough to cause major damage and very high reconstruction costs for the insurer (Shafran, 2008). An insurance drop will occur at the time of fire t_f if the total value of fire damage is greater than an exogenously determined proportion of total pre-fire value, which we denote as I^{drop}.[8] After a drop, the landowner risks paying the full cost of structure replacement if there is another fire. The possibility of an individual landowner being dropped therefore depends on their fuel treatment choices as well as the adjacent landowner's choices through time.

2.5. Dynamic Nash Equilibrium

Links between landowners come through fire damage, amenities, and, upon fire arrival, the availability of insurance. Together, the failure of private landowners to account for spatial externalities by potentially free riding off of the adjacent landowner's fuel reduction and the failure to consider the government's cost of suppression create a wedge between the private fuel treatment decisions and the socially optimal outcome a social planner would choose. To examine this, we solve for the Nash equilibrium by constructing a best response of each landowner to the fuel treatment decision of the other landowner at each time t. The solution from this problem, called a policy function, is then a dynamic reaction function, solved at each point in time, that explains a given landowner's behavior as a function of the current state of fuel on the adjacent landowner's property as well as their own. Simultaneously solving the reaction functions for both landowners at each point in time yields a subgame perfect Nash equilibrium (SPNE) path of fuel treatment decisions.

Adopting the convention that all parameters are known at time t but are unknown from time $t+1$ on, and assuming a time horizon of N periods, the reaction function for the two landowners is given by the solution to:

$$M^k\left(Z^k_t, Z^j_t\right) = \max_{\{M^k_t | M^j_t\}} \sum_{t=0}^{N} \beta^t EV\left(Z^k_t, Z^j_t\right) \tag{5a}$$

[4] It is difficult to imagine a strategic or forward-looking fire suppression agency. For example, a forward-looking Government might reduce suppression in early periods in order to create incentives for landowners to undertake greater fuel reduction in later periods. Politically, this type of behavior would be extremely unpopular.

[5] Even though the post-fire reconstruction cost to a fully insured landowner is zero, the Government still considers this cost when choosing fire suppression. Without this assumption, we would have to make the alternative, unrealistic assumption that the Government only suppresses fires when landowners are uninsured.

[6] Recent wildfire risk-mitigation literature involving forest fires and timberland management (Amacher et al., 2006; Crowley et al., 2009, for example), makes the simplifying assumption that fires set the fuel loading to zero in the year of the fire. In reality, however, all forest vegetation is rarely consumed in a wildfire.

[7] While it may not be typical for insurance companies to assess fuel loads on insured landowners' parcels, assuming that this is the case that provides landowners with incentive to undertake fuel treatment and an indication of how effective insurance might be at inducing landowner action to mitigate wildfire risk.

[8] In cases where drops occur, often landowners can enroll in high cost private insurance with consolidators. We do not include such a possibility because it is not important to our results.

$$M^j\left(Z_t^j, Z_t^k\right) = \max_{\{M_t^j|M_t^k\}} \sum_{t=0}^{N} \beta^t EV\left(Z_t^j, Z_t^k\right) \quad (5b)$$

where β is the discount factor.

The next step in the solution method is to construct a value function, or Bellman equation, that depends on the current value of the structure less all costs, plus an expected value of the landowner's property in terms of future decisions that the landowner begins making in the next period. This time-dependent expected value depends on all of the arguments in $V(\cdot)$ from time $t+1$ onward, given known parameters at time t since $EV(\cdot)$ is evaluated one time period ahead and all time t parameters are known with certainty at the end of time t. Because landowners take the solution to Government's suppression effort in any time period of fire as given, the Bellman equation is given by Eqs. (6a) and (6b) for the two landowners for all periods $t = 1,\ldots,T$:

$$V\left(Z_t^k, Z_t^j\right) = \max_{\{M_t^k\}} \left(H_t^k + A_t^k - I_t^k - C_M\left(M_t^k\right) + \beta EV\left(Z_{t+1}^k, Z_{t+1}^j\right)\right) \quad (6a)$$

$$V\left(Z_t^j, Z_t^k\right) = \max_{\{M_t^j\}} \left(H_t^j + A_t^j - I_t^j - C_M\left(M_t^j\right) + \beta EV\left(Z_{t+1}^j, Z_{t+1}^k\right)\right) \quad (6b)$$

where Eqs. (6a) and (6b) represent landowners k and j respectively, E is an expectation operator taken over the fire probability distribution. This problem is a standard stochastic dynamic programming formulation, albeit with new features from our problem, and as such the policy function solution to Eqs. (6a) and (6b) gives the fuel reduction choices for each landowner at each point in time.

2.6. Misinformation and Policy Instruments

We explore three sources of misinformation that affect landowners' fuel decisions and are targeted in wildfire education programs, assuming for simplicity that landowners do not revise beliefs over time. The first source of misinformation is for landowners to underestimate the probability of fire over time, so that from Eq. (2), landowners use $\widetilde{pf}_t < pf_t, \forall t$ in Eqs. (6a) and (6b). This situation could arise if landowners had no prior experience with fire and limited knowledge of current or historical fire occurrence. In fact, even individuals with hazard experience tend to underestimate the risks associated with low probability catastrophic events (Kahneman and Tversky, 1979).

The second source of misinformation we examine is the case where landowners underestimate fire damage. This type of misinformation might exist among landowners who are over-confident in the effectiveness of Government suppression or who overestimate the availability of suppression resources. Limited suppression resource availability may be particularly severe in extreme fire years and constrains the ability of government agencies to suppress fires (Canton-Thompson et al., 2008). This mistake would lead landowners to underestimate the damage function, $\tilde{}D^{k,q} < D^{k,q}$, and undervalue fuel treatment.

Finally, the third source of misinformation we explore is the case where landowners fail to recognize the spillover effects of their fuel treatment actions on the adjacent landowner, as well as fail to recognize how the adjacent landowner's decisions affect their own welfare. Here each landowner assumes that only the fuel stock on their parcel contributes to wildfire damage, thus wrongly believing that fuel on the adjacent parcel does not affect fire damage on their parcel, and vice versa. This belief might be representative of owners with limited knowledge of fire scale (i.e., that large fires cross ownership boundaries) or limited understanding of fire behavior and the positive spatial externalities from fuel treatment (Hann and Strohm, 2003).

Several policy instruments, designed to align the incentives of a social planner and private landowners, are relevant in our model. A social planner would solve for the path of fuel treatment across the entire landscape to maximize the joint returns to both landowners net of all costs, including Government suppression:

$$V^{SP} = \max_{\{M_t^j, M_t^k\}} \left(\sum_{t=0}^{T} \beta^t \left(EV^k\left(Z_t^k, Z_t^j\right) + EV^j\left(Z_t^j, Z_t^k\right) - C_g(g)\right)\right). \quad (7)$$

The *socially optimal* fuel treatment path maximizes Eq. (7) and is defined as $V^{SP}(M_t^{j*}, M_t^{k*})\ \forall\ t$. Using the solution to the social planner's problem, we can compute the social costs associated with private landowner decisions from Eqs. (6a) and (6b) by calculating the difference between the social planner's value function (Eq. (7)) evaluated at the optimal solution and the value function evaluated at the solution to the Nash game. Social costs are greatest when the wedge between private and socially optimal fuel treatment paths is greatest.

We consider two policy instruments to reduce social costs: a fuel treatment cost-share program and a fuel stock regulation. Under the fuel treatment cost-share program, Government pays a fraction, $\varphi \in [0,1]$, of total fuel treatment cost such that cost faced by landowner k becomes:

$$\tilde{C}_M\left(M_t^k\right) = C_M\left(M_t^k\right)(1-\varphi). \quad (8)$$

The second policy instrument is a fuel stock regulation requiring that fuel stock on the individual parcel does not exceed $\overline{Z}$, an amount specified by a land management agency (or an exogenous homeowner association). For example, the Firewise program specifies fuel standards for 628 participating communities in 40 states within the US (Firewise, 2010). To model the regulation, we introduce a constraint into landowner k's problem such that $Z_t^k \leq \overline{Z}, \forall t$.

3. Numerical Simulation and Parameters

The simulation is structured as a four-period Nash game, with each period comprising ten years, to capture essential features of the model outlined above. To solve for the equilibrium outcome, first we parameterize the decision model. The chosen parameters and functional forms for the base case are described in Table 2. The base case, where structure value and beginning fuel stock on both parcels are equal and landowners' objective functions are symmetric, allows for an exploration of the basic behaviors that arise from the spatial externality between adjacent units. Amenity values and cost parameters were chosen for the given fire probability so that landowners undertake some positive level of fuel treatment.

The parameters we use for the fuel stock growth rate, post-treatment fuel stock, and probability of fire on the landscape are reasonable estimates for eastern Cascade forests in Oregon and Washington States dominated by Ponderosa pine (Agee and Lolley, 2006; Everett et al., 2000). Ponderosa pine dominated forests are also characteristic along the front range of the Rocky Mountains in Colorado, throughout eastern Sierra Nevada Mountain forests in California, and in parts of Arizona, Idaho, Utah, Montana, and New Mexico, making these base case parameter choices relevant across a wide geographical area. However, for completeness, a broad sensitivity analysis of parameter values chosen and their impact on fuel treatment decisions was undertaken and, due to space constraints here, is available from the authors upon request.

The weighting scheme captures how fuel stock on the individual and neighboring unit matters in determining fire damage and amenity value. In the base case, the fuel stocks on parcels k and j matter equally and are, therefore, weighted equally in the treatment decision. The impact of an alternative weighting scheme, where the individual landowner considers only fuel on their own parcel, is explored in the misinformation case where landowners fail to recognize the spillover effects of their fuel treatment actions on the adjacent landowner.

Table 2
Variables, functions, and parameter estimates.

Description		Parameter estimate
Structure value	$H_t^{k,j}$	$H_{t=0}^{k,j} = 200$
Beginning fuel load	$Z_t^{k,j}$	$Z_{t=0}^{k,j} = 3$
Fuel treatment	$M_t^{k,j}$	$M_t^{k,j} = 0,1$
Spatial weights	$w^{k,j}$	$w^{k,j} = 0.5$
Probability of fire	pf_t	$pf_t = 0.05$
Fuel growth function	$\gamma(\cdot) = g_1(Z_t^{k,j} - g_2)^2 + g_3$	$g_1 = -.02$
		$g_2 = 8$
		$g_3 = 2$
Insurance drop threshold (percent of total value damaged)	I^{drop}	$I^{drop} = 0.10$
Reconstruction cost	C_F	$C_F = D^{q=H}$
Fuel treatment cost	$C_M = C_{M_{fixed}} + C_{M_{var}}$	$C_{M_{fixed}} = 0.5$
		$C_{Mvar} = 0.1$
Government suppression cost	$C_t = (w^k(Z_t^j + Z_t^k) + w^j(Z_t^j + Z_t^k))/2 \cdot c_1 + g \cdot c_2$	$c_1 = 0.01$
		$c_2 = 100$
Government suppression effort	g	$g = 1,\ldots,10$
Government suppression effectiveness (maximum percent of total value lost due to fire damage)	g^{effect}	$g^{effect} = 0.10,\ldots,0.28$
Amenity value	$A_t^k = k_1 \cdot (w^k(Z_t^j + Z_t^k) - k_2)^2 + k_3$	$k_1 = -0.008$
		$k_2 = 80$
		$k_3 = 50$
Fire damage to q = Z,H,A	$D^{k,q} = \left(\frac{l_1}{100} \cdot w^k\left(Z_{t-1}^j - M_{t-1}^j + Z_{t-1}^k - M_{t-1}^k\right)\right) - g^{effect}$	$l_1 = 0.95$
Structure value appreciation	δ	$\delta = 0.05$

As described in Section 2, both parcels contain a structure and natural vegetation. Structure value is simply the value of the physical structure on the individual parcel whereas amenity value depends on the forest fuels on the individual and adjacent parcels. Through the suppression decision, Government can reduce the damage to landowners' structures and amenities by ten to twenty-eight percent (g^{effect}) for effort levels (g) one through ten, for the chosen parameters. We assume that the cost of suppression is a linear function of spatially weighted fuel stock.

At the beginning of each of the four ten-year periods, landowners k and j simultaneously decide whether or not to undertake fuel treatment in that period. We specify fuel treatment, defined in Eq. (1), as a binary decision variable so that $M_t^k = 1$ if landowner k undertakes fuel treatment and 0 otherwise. If a landowner undertakes fuel treatment, fuel stock on the individual parcel is reduced to an exogenously determined "safe" level. Greater pre-treatment fuel stocks require a greater amount of fuel to be removed during treatment before the "safe" level is reached.

The uncertainty in each period of the game is completely resolved by the end of the period. There are two states of the world in each period: 'fire' and 'no fire', occurring with frequency pf_t and $(1 - pf_t)$, respectively. If a fire occurs, fuel stock and values on the entire landscape are affected. The extent of damage to structure and amenity values is an increasing function of pre-fire, post-treatment, spatially weighted fuel stock on the individual parcel and the neighboring parcel. The payoff to each player at each stage of the game is determined by the individual landowner's post-fire value net of insurance and fuel treatment costs.

If a fire does not occur, damage to structure and amenity values on all units is zero and the fuel stock continues to grow. After a fire, structures are damaged and amenity values decrease as fuel is consumed. Landowners with insurance are compensated for structure value loss. For example, if there is a fire in $t = 1$, insurance compensation returns structure value to its initial level at the beginning of $t = 2$, but, because fuels are consumed, amenity value is lower at the beginning of $t = 2$ than before the $t = 1$ fire.

To calculate the subgame perfect Nash equilibrium (SPNE) of the multi-period game, we use backward induction and consider, in increasing order of inclusion, each subgame of the game, find a Nash equilibrium of the subgame, and replace the subgame by a new node that has the equilibrium payoffs. This is equivalent to solving Eqs. (6a) and (6b) for the two landowners for all periods $t = 1,\ldots,T$. In the fuel treatment game we have 4 periods and, because in every period each landowner can choose to undertake fuel treatment or not and there is either a fire or not, there are 512 possible subgames at the start of $t = 4$. A general description of the algorithm used to solve for the SPNE of the fuel treatment game is described in Fig. 1.

4. Results

We begin this section with a description of our base case results. Next we relax the assumption that both landowners begin with the same fuel load and solve for the equilibrium outcome when the initial fuel stock is not equal across parcels. Finally, we describe results for the three misinformation scenarios and two policy settings, for the base case parameters and the asymmetric fuel case. For each set of results we compute social cost.

4.1. Base Case

In the base case, for all fire and fuel treatment histories landowners undertake fuel treatment at $t = 2$ only (Fig. 2). For this treatment pattern, government suppression levels are 3, 1, 2 and 4, in periods one through four, respectively. Suppression spending at each observed level is described in Fig. 3. Because government chooses the suppression level to minimize fire damage plus suppression cost, higher levels of suppression effort are observed in periods when landowners do not undertake fuel treatment and allow fuel stock to grow unchecked, increasing the potential for fire damage.

The socially optimal treatment pattern for the base case is to undertake fuel treatment on both parcels in every time period. For this optimal treatment pattern, Government suppression spending is minimized (Fig. 3). There are zero equilibrium outcome insurance drops, but four non-equilibrium treatment-fire histories where landowners begin period 4 without insurance. Social costs—the difference between the socially optimal outcome and the outcome from the game—result from spatial externalities and government suppression. These social costs are quantified as described in Section 2 and illustrated in Fig. 4.

4.2. Heterogeneous Starting Fuel Load

Spatial fire economic models typically assume that both landowners begin with zero fuel loads (Amacher et al., 2006; Crowley

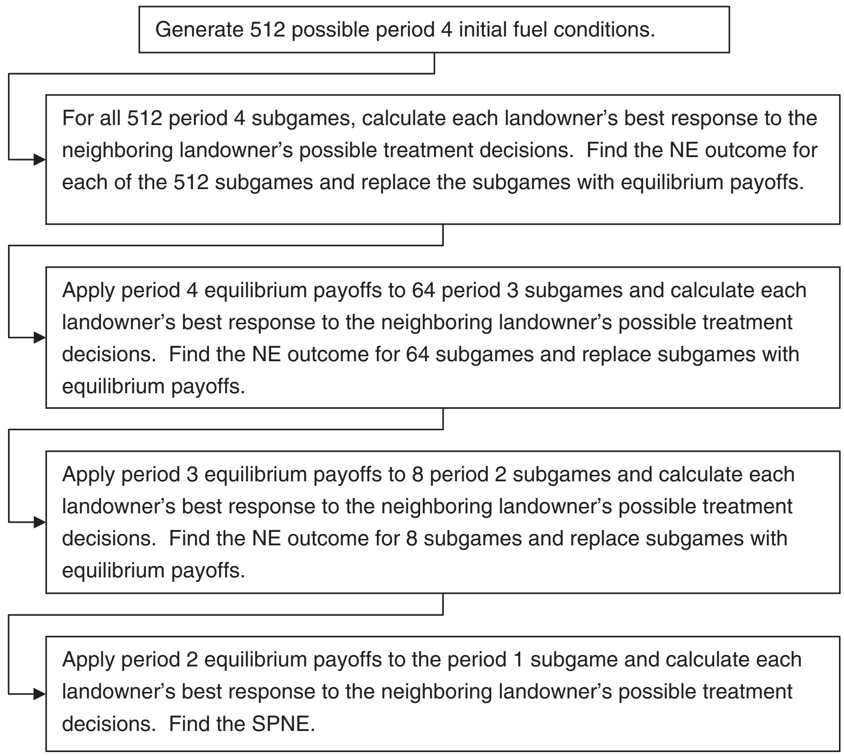

Fig. 1. Algorithm used to solve for the SPNE of the fuel treatment game.

et al., 2009). By relaxing the homogenous fuel assumption so that the initial fuel loads and landowner value functions in Eqs. (6a) and (6b) for landowner *j* and *k*'s properties are not equal, we allow the marginal benefit of fuel treatment on each parcel in the first period to differ across landowners. This more closely approximates actual landscapes, characterized by mixed ownership with landowners making decisions independently, often purchasing parcels at different points in time and with different fuel loads.

When the initial fuel load is greater on one landowner's parcel, ceteris paribus, we observe owners alternating fuel treatments, beginning with treatment on the parcel with the higher fuel load in the case where the landowner with the higher starting fuel loading understands the connection of fuel loading and fire damage. To illustrate, when one landowner begins with a fuel load twice the level as the other landowner (see parameters in Table 2), the owner with the higher fuel load undertakes treatment at $t = 1,3$ while the other owner undertakes fuel treatment at $t = 2$ only. For this level of fuel treatment, Government suppression spending is at level 1 at $t = 1,2,3$ and increases to level 3 at $t = 4$ (Fig. 5). For the heterogeneous

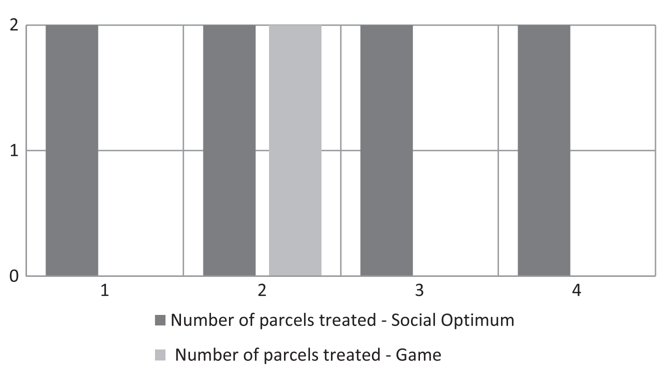

Fig. 2. Number of parcels treated over time.

fuel case, the socially optimal fuel treatment pattern and Government suppression levels are the same as in the base case.

With more fuel on the landscape, there are more treatment-fire histories with severe fire damage than in the base case where initial fuel levels are the same across landowners. While the number of equilibrium outcome insurance drops remains fixed at zero, there are now 32 non-equilibrium treatment-fire histories where landowners begin period 4 without insurance. Insurance drops occur for each treatment history where the landowner with the higher initial fuel load does not treat at $t = 1,2,3$.

4.3. Misinformation

As with many low-probability natural hazards, landowners making fuel treatment decisions often have little experience upon which to base their decisions and may have imperfect information about the hazard itself or how individual actions can reduce damages caused by the hazard. In this section, we model the three cases of misinformation discussed earlier and examine how each case changes the treatment decision pattern, government suppression spending, and social costs. For all three misinformation cases, the base case and the asymmetric fuel case, the socially optimal treatment pattern is to treat both parcels in each of the four time periods. The social costs of misinformation for the base case and the asymmetric fuel case are described in Figs. 4 and 6, respectively (Table 3).

To determine the impact of misinformation about fire probability and damage, we explore landowner decisions over a range of parameter values (Table 4). We find that when landowners believe that the probability of fire is less than or equal to 0.7% or the damage function parameter is 0.16 or less, there is zero fuel treatment. In an effort to limit damages, in both misinformation cases, Government suppression spending increases by 273% above the socially optimal suppression level (Fig. 3). Given the significant increase in suppression spending, there are no equilibrium outcomes with insurance drops and loss of insurance coverage remains limited to 4 non-equilibrium treatment-fire histories.

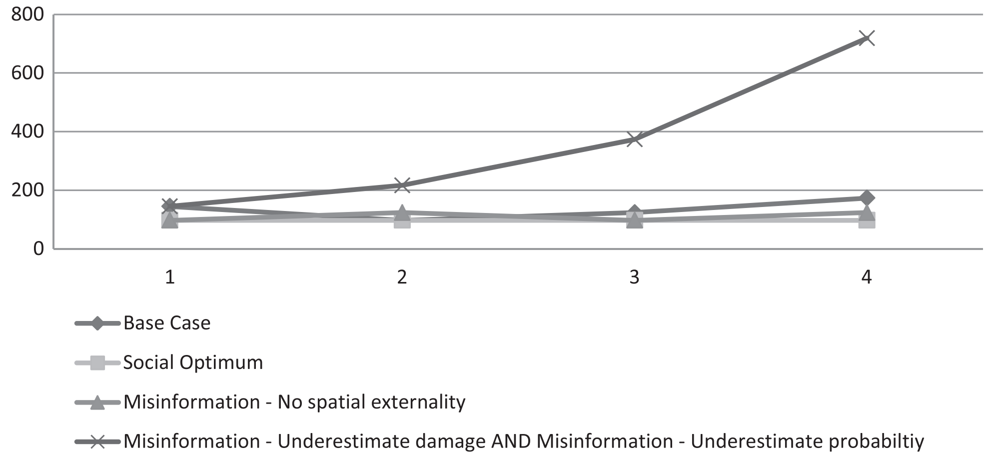

Fig. 3. Suppression spending over time.

When landowners consider only fuel stock on their individual parcel in the calculation of expected fire damage, both landowners undertake fuel treatment at $t = 1,3$ for all fire histories and equilibrium treatment histories. Compared to the base case, there is more fuel treatment on the landscape and, as a result, Government suppression spending decreases (Fig. 3). Landowners increase fuel treatment because the full benefit of treatment accrues directly to the individual landowner and free riding on their neighbor's fuel treatment is, they believe, no longer possible. However, the level of treatment on the landscape remains suboptimal due to the failure of landowners to consider the cost of government suppression. The number of equilibrium and non-equilibrium insurance drops remains unchanged from the base case with perfect information.

4.4. Heterogeneous Fuel and Misinformation

Relaxing the assumption of symmetric starting fuel, we find that when landowners believe that the probability of fire is 0.7% and the damage function parameter is 0.16, the landowner with the higher fuel load undertakes treatment in the first period only and there is no treatment on the neighboring parcel. In this case, total Government suppression spending is 173% above the socially optimal level (Fig. 5) and loss of insurance coverage remains limited to 32 non-equilibrium treatment-fire histories (Table 5).

For the case where landowners fail to recognize the spatial externality, both landowners undertake fuel treatment at $t = 1,3$ for all fire histories and equilibrium treatment histories. Compared to the outcome with asymmetric fuel and perfect information, there is more fuel treatment and less spending on Government suppression (Fig. 5). Without the ability to free ride, the landowner with the lower fuel stock is prompted to increase fuel treatment above the level they would choose with perfect information. However, even with the additional treatment on the landscape, total Government suppression spending remains 136% above the social optimum.

5. Policy Applications

The intent of policy is to improve outcomes and, in the context of the fuel treatment decision, bring the outcome of the strategic game between the two private landowners closer to the social optimum, thereby minimizing social costs. In addition to increasing fuel treatment on the landscape, effective policy will also reduce Government suppression spending. In this section we examine two policies: a fuel stock regulation and a fuel treatment cost-share program.

The fuel stock regulation is a parcel-level standard that requires landowners to maintain their fuel load below a specified level. To comply with the regulation, the individual landowner's fuel stock must meet the standard following the treatment decision in each time period. We examine two regulations: one “strict” and the other “lenient.” For the strict regulation, the standard is set equal to two (the post-treatment fuel stock) and effectively requires fuel treatment in every time period. The lenient standard is set equal to three and gives landowners flexibility in the timing of their fuel treatment.

The second policy we examine is an incentive-based cost-share program where the Government compensates landowners for fifty-percent of fuel treatment costs. By reducing fuel treatment cost to the landowner, this policy seeks to increase fuel treatment on the landscape. However, for the cost-share program to reduce social

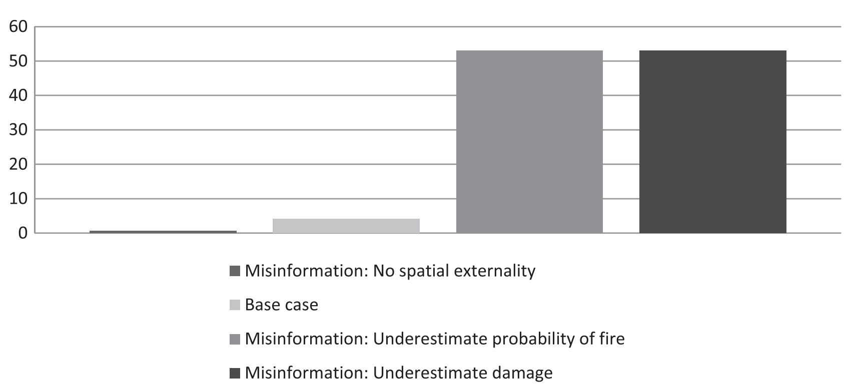

Fig. 4. Social cost for base case and three cases of misinformation.

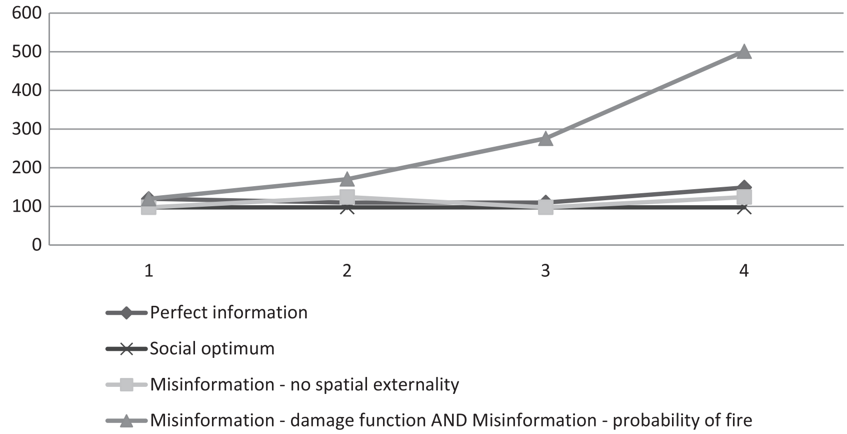

Fig. 5. Suppression spending over time with heterogeneous fuel landscape.

costs, reductions in Government suppression spending must be greater than increases in Government spending on fuel treatment.

5.1. Base Case With Policy

In order to comply with the strict standard, landowners are required to treat their parcel in every period, leading to the socially optimal outcome (Fig. 2). In this case, efficient fuel management and suppression could be easily achieved by policy makers with perfect information. For the lenient standard, both landowners undertake fuel treatment at $t = 1{,}3$. Compared to the base case, the level of fuel treatment on the landscape is closer to the social optimum, but remains suboptimal. Suppression spending for both fuel stock regulations is lower than in the base case (Fig. 7).

When the cost-share program is applied to the base case, landowners undertake fuel treatment at $t = 1{,}3$ only, with suppression costs 14% above the socially optimal suppression level. The present value of Government cost-share expenditures (1.198) is a small fraction of the reduction in suppression spending. However, when the cost-share program is applied to the three cases of misinformation, we find that the effectiveness of the policy depends on the type of misinformation. For cases where landowners have misinformation about the probability of fire and fire damage, the cost-share program has no impact on fuel treatment or suppression decisions. But for the case where landowners are unaware of spatial externalities from fuel treatment, the cost-share program generates fuel treatment at $t = 1{,}2{,}3$ on both parcels and expected suppression spending is only 7% above the social optimum. Again, the present value of Government cost-share expenditures (1.634) is a small fraction of the reduction in suppression spending.

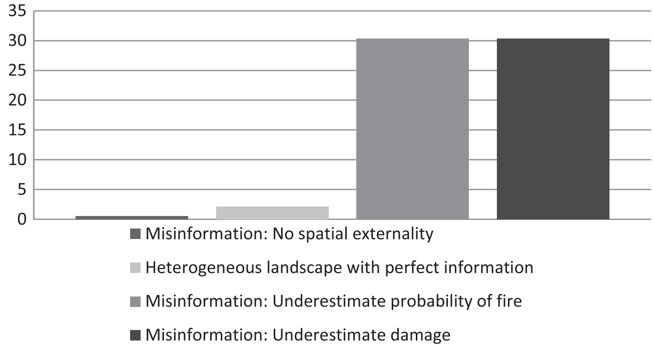

Fig. 6. Social cost for heterogeneous fuel landscape with perfect information and three cases of misinformation.

5.2. Asymmetric Fuel and Policy

When starting fuel stocks differ across landowners, policy results do not always differ from the symmetric starting fuel case; we do not address those cases here. With the cost-share program, landowners undertake fuel treatment at $t = 1{,}3$. Compared to the asymmetric fuel case without the cost-share program, Government suppression spending is 9% below the level observed when landowners have perfect information and 14% above the socially optimal level.

When the cost-share program is applied to the three cases of misinformation, again we find that the effectiveness of the policy depends on the type of misinformation. When landowners have misinformation about the probability of fire and fire damage, we observe an increase in fuel treatment on the parcel with the smaller beginning fuel stock and no change in treatment on the parcel with the larger beginning fuel stock. For these two cases, the landowner with the larger beginning fuel stock undertakes fuel treatment at $t = 1$ only, reducing suppression spending to 6% below the perfect information case. For the case where landowners are unaware of spatial externalities, the cost-share program induces fuel treatment on both parcels and we observe both landowners undertaking fuel treatment at $t = 1{,}2{,}3$ and suppression spending 77% below the perfect information case. In all cases, the present value of Government cost-share expenditures is well below the reduction in suppression spending.

6. Discussion and Concluding Remarks

Examining the wildfire problem in the context of a stochastic repeated Nash game allows us to explore the interaction between landowners in their fuel treatment decisions. Landowner interaction in the fuel treatment game is driven by spatial externalities—that is, fuel treatment on an individual parcel reduces expected damage on the individual and neighboring parcels. In the context of our model, we are able to gain

Table 3
Misinformation and heterogeneous fuel parameters.

Heterogeneous fuel		
Beginning fuel stock on parcel k	$Z^k_{t=0}$	3
Beginning fuel stock on parcel j	$Z^j_{t=0}$	6
Misinformation		
Probability of fire	pf_t	0.007
Insurance premium per dollar of coverage	$I\_premium^k_t$	0.007
Fire damage	$loss^k_t = \frac{l_1}{100} w_Z t^k$	$l_1 = 0.16$
Heterogeneous fuel and misinformation		
Probability of fire	pf_t	0.007
Insurance premium per dollar of coverage	$I\_premium^k_t$	0.007
Fire damage	$loss^k_t = \frac{l_1}{100} w_Z t^k$	$l_1 = 0.16$

Table 4
Misinformation sensitivity analysis.

Probability of fire parameter	
.7% or less	No fuel treatment
.8% up to 5% (base case parameter)	Both landowners undertake fuel treatment in period 2 only (base case treatment level).
Damage function parameter	
0.16 or less	No fuel treatment
0.17 up to 0.95 (base case parameter)	Both landowners undertake fuel treatment in period 2 only (base case treatment level).

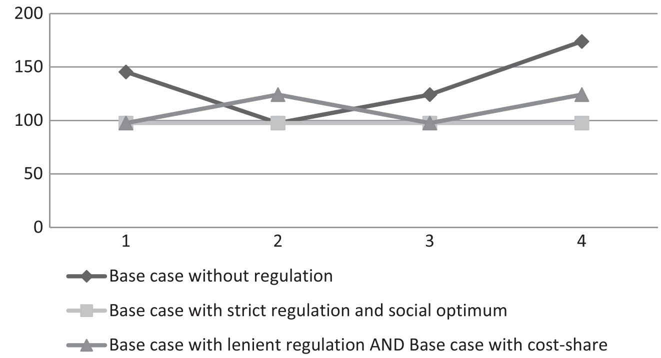

Fig. 7. Suppression spending over time for base case with regulation and cost-share.

insight into how insurance, misinformation, initial fuel stock, and Government suppression influence landowner fuel treatment decisions, social costs, and the effectiveness of policy. The combination of different initial conditions, insurance, and misinformation is a unique aspect of our study.

We uncover two interesting results concerning insurance. First, even with risk-adjusted insurance, we find that when there is a program of Government suppression, landowners do not have sufficient incentive to increase fuel treatment to the socially optimal level. Despite reducing the cost of insurance when fuel stocks are lower and confronting landowners with the risk of being dropped from their insurance program, fuel treatment remains suboptimal because landowners know that Government suppression will protect values at risk when there is a fire, thereby limiting damage and preventing insurance drops from occurring. Although risk-adjusted insurance is advocated as a way to increase fuel treatment levels in the WUI, we do not find evidence to support this position. Instead, we find that in the presence of an active program of publicly funded fire suppression severely constrains the ability of market insurance to induce fuel treatment on private land.

Given the limited amount of treatment that occurs when landowners have insurance, we considered how observed outcomes compare to the level of treatment among landowners without insurance. Surprisingly, we find that insurance may delay fuel treatment on private land. When the fuel treatment game is played between two landowners without insurance, both undertake fuel treatment in the first rather than the second time period. Treatment occurs earlier because when a fire is realized and landowners are uninsured, individual losses are substantial, especially when fuel loads are high. To avoid these potentially costly outcomes, landowners without insurance undertake fuel treatment earlier to maintain lower fuel stocks overtime. Insurance programs may delay fuel treatment and inhibit this behavior. Together, these findings indicate that the effectiveness of efforts to increase fuel treatment and constrain suppression spending through insurance programs may be limited.

Landowners have incentives to reduce fuel stock in order to reduce expected wildfire damages, but removing natural vegetation simultaneously reduces on-site amenity value. For our chosen parameters, we do not find evidence of strategic interaction in amenity value and for our chosen parameters find that the incentive to forgo fuel treatment in order to maintain amenity value is weak. This is partially due to the fact that although higher fuel loads are associated with higher amenity values, these conditions also increase fire damage and, in fact, greater amenity value losses in the case of a wildfire. Landowners are willing to accept short-term reductions in amenity value following fuel treatment in order to mitigate the risk of a damaging fire and more severe amenity value losses in the future.

Our modeling framework also allows us to examine the source of social costs from the wildfire problem. Based on the results described in Figs. 4 and 6, we find that a larger fraction of social costs can be attributed to free riding off of government suppression rather than spatial externalities between landowners. A similar conclusion was reached in Crowley et al. (2009), but here we are able to gain additional insight through our examination of misinformation and unequal starting fuel levels. We find that of the three misinformation cases, social costs are the greatest for cases where landowners underestimate fire damage and the probability of fire; over a range of parameter values we find that landowners undertake no fuel treatment. Furthermore, for these two cases of misinformation, a cost-share program is unable to provide landowners with sufficient incentive to undertake fuel treatment. This partly due to the fact that when fuel treatment goes to zero, Government responds by increasing suppression.

Additionally, a novel feature of our model is consideration of the social costs from misinformation under an asymmetric versus a symmetric fuel landscape across landowners. For the game with asymmetric starting fuel, social costs from misinformation persist over a greater range of fire probability and damage function parameter values. This is because when one landowner's fuel stock is greater, the landowner with the smaller starting fuel stock is better able to free-ride on treatment undertaken on the parcel with the higher fuel stock than when starting fuel is the same on both parcels. This suggests that as information about wildfire improves, through education programs for example, the social costs of misinformation will be more persistent on landscapes where fuel differs across ownerships.

Table 5
Heterogeneous fuel and misinformation sensitivity analysis.

Probability of fire parameter	
0.3% or less	No fuel treatment
0.4% to 0.7%	Landowner with high fuel undertakes fuel treatment in period 1 only.
0.8% to 2%	Landowner with high fuel undertakes fuel treatment in period 1 only and neighboring landowner undertakes fuel treatment in period 2 only.
3.0% up to 5% (base case parameter)	Landowner with high fuel undertakes fuel treatment in periods 1 and 3 and neighboring landowner undertakes fuel treatment in period 2 only. (Base case with heterogeneous fuel treatment level.)
Damage function parameter	
.07 or less	No fuel treatment
0.08 to 0.16	Landowner with high fuel undertakes fuel treatment in period 1 only.
0.19 to 0.56	Landowner with high fuel undertakes fuel treatment in period 1 only and neighboring landowner undertakes fuel treatment in period 2 only.
0.57 up to .95 (base case parameter)	Landowner with high fuel undertakes fuel treatment in periods 1 and 3 and neighboring landowner undertakes fuel treatment in period 2 only. (Base case with heterogeneous fuel treatment level.)

We find that when landowners are misinformed and unaware of the spatial externality, the outcome is actually closer to the social optimum than when landowners have perfect information about the spatial externality, as in Crowley et al. (2009). Rather than suggesting a policy of promoting misinformation, this result suggests that in settings where spatial externalities are a significant determinant of fire damage and landowners are aware of these relationships, inefficiencies in fuel treatment and suppression will be greater. These settings might include areas with high wind speeds, steep slopes, or where ownership units are small relative to wildfire size. In these types of settings, wildfire is more likely to travel across ownership boundaries, affecting more than one landowner in a single fire event and making fuel treatment decisions on adjacent ownership units relevant to fire damage on the individual parcel. Social costs resulting from misinformation about the probability of fire and fire damage might be reduced using education programs. These types of education programs may be particularly effective in areas where frameworks for wildfire education are already in place through community fire planning efforts.

Our analyses of the fuel treatment regulation and cost-share program indicate that the effectiveness of each policy will depend on the presence and type of misinformation. In the base case, the cost-share program did nothing to increase fuel treatment when there was misinformation about the probability of fire or fire damage. For the asymmetric fuel case, however, the cost-share program increased fuel treatment on the parcel with the lower fuel loading only, but not on the neighboring parcel. With misinformation about the spatial externality, the cost-share program increases fuel treatment on both parcels for the base case and on the heterogeneous landscape.

In all cases, the fuel stock regulation achieves reductions in fuel loads across the landscape. However, the present analysis does not include an examination of the costs of implementing, monitoring, and enforcing this type of regulation, which may be nontrivial given that the federal government is primarily accountable for suppression spending while municipal governments have jurisdiction over private land management ordinances. Nonetheless, given the significant suppression cost savings that would certainly result from the associated increase in fuel treatment, it seems likely that even with these costs substantial reductions in social costs would be possible.

The results of this study provide insight into wildfire risk management and the fuel treatment decision on a landscape where landowners interact through spatial externalities. Additionally, our approach may serve as a platform for additional research on wildfire risk management in more complex settings, with additional landowners or more nuanced landowner and landowner–Government interaction, or for other aspects of the problem such as alternative insurance programs or other risk-mitigating management options available to landowners. The wildfire problem is undoubtedly complex and because of the growing number of people living in and around the fire-prone WUI, this issue is one of continued importance.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2013.02.019.

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