

Article

The Interaction of Wildfire Risk Mitigation Policies in the Presence of Spatial Externalities and Heterogeneous Landowners

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Abstract: The dramatic increase in the number of uncontrollable wildfires in the United States has become an important policy issue as they threaten valuable forests and human property. The derived stochastic dynamic model of this study is capable of determining optimal fuel treatment timing and level simultaneously and as a function of fire risk and fuel biomass dynamics. This study develops a stochastic dynamic model to evaluate the interaction of fuel treatment decisions for two adjacent landowners under various scenarios of misinformation about fire occurrence and spread. Findings indicate that a landowner tends to free ride on fuel treatment undertaken by his adjacent landowner. However, the study finds that the free riding potential of a landowner could be alleviated to some extent by having a neighboring landowner who is aware of fire spillover effects. In addition, the study reveals that the social cost resultant from free riding behavior is lower than the social cost associated with complete absence of fire externality awareness for both landowners. These findings imply that governments could introduce more effective educational programs to ensure that all landowners are fully aware of cross-parcel benefits of fuel treatment in order to align socially and privately optimal decisions, thus minimizing externality costs.

Keywords: fire behavior; risk mitigation; nash equilibrium; stochastic dynamic model; misinformation

1. Introduction

Wildfires are an interesting example of a natural hazard with potentially large negative externalities on regions surrounding the initial start of the fire. Private and public financial losses due to fire damage in the United States have risen and reached billions of dollars in recent years. Concurrently, government suppression costs have increased from less than \$1 billion per year in the 1990s to an average of \$3 billion yearly recently [1]. While landowners often cannot control the likelihood of fire (e.g., risk of fire from lightning strikes or human activity), they can affect the severity of the wildfire, and consequently the externality experienced by neighboring landowners, by thinning stands and by using prescribed fires to reduce the amount of fuel present for the wildfire [2]. Therefore, fuel reduction practices could significantly reduce fire-related losses incurred by landowners and substitute for fire suppression efforts made by the government. However, factors like imperfect information about risk, cross-stand effects, and forest management options, or the cost of preventative practices may discourage landowners from adopting fuel management activities at all or, at a minimum, reduce efforts below the socially optimal amount. Identifying cases with the greatest divergence between individually and socially optimal management and the greatest externality costs would help government agencies develop more effective education programs in order to align socially and privately optimal decisions and minimize externalities.

The first purpose of this study is to derive a stochastic dynamic model to evaluate the interaction of fuel treatment decisions for two adjacent landowners under various scenarios of fire behavior in the presence of flammable vegetation, forest benefits, and misinformation about spatial externalities associated with fire spread. The second objective of this study is to use the derived model to examine how different misinformation types might yield private outcomes that deviate from socially optimal decisions. The magnitude of the externality that results from suboptimal fuel management decisions may differ based on the individual landowner's characteristics, including their individual beliefs regarding risk and spillover effects [3], and their economic parameters.

A landscape's spatial configuration of forest across space could play an important role in risk interdependencies, via the extent of cross-boundary externalities. Shared boundaries between forests allow for fire spread between two adjacent forest parcels. Thus, a parcel's lack of fuel management may contribute to fire damage on neighboring parcels. In addition, common boundaries of neighboring parcels may be a source of inefficiencies as they may cause a landowner to free ride on his adjacent landowner's fuel management effort. Consistent with Busby, Albers, and Montgomery [4], we assume that land parcels that share common boundaries influence each other's fire risk, while parcels that share no boundaries do not. Consistently, studies by Brenkert-Smith, Champ, and Flores [5] and Monroe and Nelson [6] stated that landowners account for fuel management actions of adjacent forests when making decisions regarding intermediate fuel treatment.

This study combines and builds on the work of Crowley et al. [7] and Busby, Amacher, and Haight [8]. Crowley et al. [7] modeled two neighboring stands and classified the landowners by their preferences and information sets relative to the adjacent neighbor. They framed their analysis using a Faustmann-style model, and do not allow the landowner to undertake fuel reduction more than once during a rotation. In addition, they assumed the fire arrival rate facing both parcels is reduced by total fuel treatment; thus, modeling the fire arrival rate as a function of the level of fuel removal. On the other hand, Busby, Amacher, and Haight [8] developed a dynamic model for two adjacent stands and analyzed three sources of misinformation: Underestimating the probability of fire, undervaluing fire damages, and failure to consider spillover effects. They modeled fire damage as a function of fuel load each period; however, the probability of fire arriving is assumed to be independent of fuel load and is fixed each period. Moreover, their model allows landowners to decide on the timing and frequency of fire prevention actions, but not the level of these actions.

This study examines a two-landowner problem for which landowners differ based on their perceptions of risk and fire spread. The model also assumes that fuel biomass accumulation influences the probability of spread of fire from the originally ignited parcel to the neighboring parcel. Specifically, total potential fire damage on parcel j is influenced by the probability of fire occurrence on parcel j , the probability of fire occurrence on adjacent parcel k , and the probability of fire spread from parcel k to parcel j . Additionally, this study accounts for direct effects of fuel stocks on the salvage value after a forest ignites.

Reed [9] and Yoder [10] assume that fuel reduction influences fire arrival only, while Amacher, Malik, and Haight [11] assume fuel reduction efforts impact the salvageable value only. Crowley et al. [7] assume that fuel reduction affects both the probability of fire and the damage from the fire. In this study, we improve on previous literature by explicitly accounting for fuel stocks on both parcels, and model fire arrival, fire damage, and fire spread as a function of the fuel stock itself, not as a function of fuel removal efforts, which only indirectly affect the probability of fire, damage, and spread from fire in reality.

This study investigates heterogeneity in landowner information or beliefs about risk of fire spread between parcels. The model considers landowners with perfect information about fire occurrence and spread, landowners who are partially aware of fire externalities, and landowners who do not consider fire occurrence and spread. Incomplete beliefs may exist due to imperfect knowledge regarding fire scale and spread across boundaries [8] or limited understanding of the linkage between fire behavior and surface fuel accumulation [12]. The analysis also considers two kinds of forest uses: Market

oriented, i.e., valuing market forest benefits like hunting leases and forest recreation benefits, and non-market oriented, i.e., valuing non-market forest benefits like natural amenities and non-market ecosystem services. Considering both types of forest management interests gives a more comprehensive framework to the analysis of the interaction of landowners' actions in the presence of misinformation.

The derived models include a base-case that assumes both forest parcels are jointly managed in the socially optimal manner to maximize combined rent across parcels. This baseline is then compared to the decisions made by individual private landowners, under a variety of scenarios of landowners who are heterogeneous with respect to fire spread information.

2. Materials and Methods

2.1. Modeling Framework

This study models two adjacent landowners who manage their parcels simultaneously and independently in a fire prone region. Landowners and their corresponding forest parcels are indexed by $i \in [j, k]$. Each landowner maximizes the expected net present value of their own site value for an infinite time horizon, in the presence of fire, by choosing the level of fuel reduction practices each period. Possible levels in fuel reduction include zero to represent years for which the landowner does not reduce fuels. Both parcels face a risk of fire that depends on the amount of fuel stock present on the landscape and a likelihood of fire spread from the adjacent parcel. This latter risk is the only way that the neighboring landowner enters into the individual landowner's decisions. Lower fuel stocks on the individual parcel result in less fire damages and higher salvageable forest biomass or site value when the fire arrives in a certain period. The model then determines the rent maximizing fuel management path (a dynamic reaction function).

In the base case, a social planner is assumed to manage both sites jointly so as to maximize combined net benefits across both parcels which allows us to identify the socially optimal levels of fuel management and to calculate the social losses associated with the private landowners' management. Unlike Amacher, Malik, and Haight [11,13], and Crowley et al. [7] who followed the standard Faustmann model in their analysis, this study builds up a stochastic dynamic model which allows us to determine periodic level, frequency, and timing of intermediate fire prevention practices.

2.2. Rent Maximization and Endogenous Fire Probability

The maximization problem is composed of one continuous state variable, total forest biomass f_{it} ; where $i \in [j, k]$ (For simplicity, j and k are also used to refer to forest parcels owned by landowner j and landowner k , respectively). Total forest biomass is measured in cubic meters per acre at the beginning of each period.

To prevent catastrophic wildfire, each landowner chooses the level of fuel removal activities $x_{it} \in [0, f_{it}]$ each period. The landowner can choose not to engage in any fuel reduction practices ($x_{it} = 0$). Conversely, the maximum amount of fuel reduction possible is the total forest biomass that period (f_{it}).

A stochastic binary variable represents fire occurrence, $\theta_{it} \in [0, 1]$. Fire arrival is characterized as a Poisson distribution; however, unlike previous studies, we model the fire arrival rate, $\lambda(\gamma, f_{jt}, f_{kt})$, as a function of landscape-level fuel biomass f_{jt} and f_{kt} , and a landscape-level historical average fire arrival rate γ . The arrival rate increases as the historical average arrival rate increases and as the level of fuel stock increases:

$$\frac{\partial[\lambda(.)]}{\partial\gamma} > 0 \text{ and } \frac{\partial[\lambda(.)]}{\partial f_{it}} > 0 \quad (1)$$

However, we assume that the arrival rate is concave with respect to landscape-level fuel:

$$\frac{\partial^2[\lambda(.)]}{\partial f_{it}^2} < 0 \text{ where } i = (j, k) \quad (2)$$

2.3. Fire Spread Rate and Damage Function

The fire spread rate represents the contribution of one parcel's post-treatment fuel accumulation to fire losses on the neighboring parcel. The probability of fire spread from neighboring landowner k to landowner j can be expressed as $\varphi_{jt} = \phi(f_{kt})$, and the reverse for spread from j to k . The spread rate of fire is increased by increasing fuel accumulation on the neighboring parcel, where:

$$\frac{\partial \varphi_{jt}}{\partial f_{kt}} > 0 \text{ for landowner } j. \quad (3)$$

For both fires that ignite on parcel j and those that spread from parcel k to parcel j , the fuel stock on parcel j impacts fire damages on the parcel, represented by $(D(f_{jt}))$, where we assume:

$$\frac{\partial D}{\partial f_{it}} < 0 \text{ and } \frac{\partial^2 D}{\partial f_{it}^2} > 0 \text{ where } i = (j, k). \quad (4)$$

In the presence of a neighboring forest parcel, the expected fire damage on parcel j includes: (1) the probability of fire occurring on parcel j and the associated damage and (2) the probability of fire occurring on parcel k and spreading to parcel j and the associated damage. This yields the following expected damage function:

$$D_{jt, \text{total}} = \theta_{jt} D(f_{jt}) + \theta_{kt} \varphi_{jt}(f_{kt}) D(f_{jt}). \quad (5)$$

2.4. The Path of Forest Biomass

Total forest biomass, and consequently the change in the forest biomass, is determined by management decisions. In the absence of fuel treatment or fire, forest biomass growth is given by $k(f_{it})$. If the landowner engages in fuel reduction, x_{it} , total forest biomass changes by $k(f_{it}) - x_{it}$. In the event of a fire, the landowner maintains the remaining unburned trees on the site and cleans the ignited part of the site in preparation for replanting. For the burned portion of the parcel, next period forest biomass is reset to its minimum value, f_0 , representing the starting biomass when the whole field is replanted. In the presence of salvaged forest, only the damaged portion is replanted. Combining all possibilities, the state of forest biomass evolves across periods by:

$$f_{i,t+1} = \begin{cases} f_{it} + k(f_{it}) - x_{it} & \theta_{it} = 0, \varphi_{it} = 0, x_{it} \in [0, f_{it}] \\ (1 - D_{it, \text{total}})[f_{it} + k(f_{it}) - x_{it}] + (D_{it, \text{total}})f_0 & \theta_{it} = 1 \text{ or } \varphi_{it} = 1 \end{cases} \quad (6)$$

2.5. Site Value: Marketed and Non-Market Forest Benefits

Landowner i 's valuation of his trees is derived from amenities on his site $u_{it}(f_{it})$ and from marketed forest benefits like hunting leases and other forest recreations $g_{it}(f_{it})$. Following Busby, Amacher, and Haight [8], and Donovan and Butry [14], the chosen functional form for non-market oriented benefits (amenity value) is concave and increasing in fuel loads, where:

$$\frac{\partial u_{it}(\cdot)}{\partial f_{it}} > 0 \text{ and } \frac{\partial^2 u_{it}(\cdot)}{\partial f_{it}^2} < 0 \text{ where } i \in [j, k] \quad (7)$$

The choice of the marketed forest benefits functional form, $(g_{it}(f_{it}))$, is based on studies by Walsh and Olienyk [15], Rosenberger et al. [16], and Hesseln et al. [17]. The economic value of market activities per acre each time period is the product of the consumer surplus (CS) per recreation day and average user days (UD). Demand for marketed forest used is linked to total forest biomass present on the site which in turn is influenced by wildfire occurrence and intermediate fuel treatments that reduce

the probability of fire [17]. Therefore, both consumer surplus and average user days are assumed to be nonlinear functions of forest biomass each period and increase at a decreasing rate, such that:

$$\frac{\partial g_{it}(\cdot)}{\partial f_{it}} > 0 \text{ and } \frac{\partial^2 g_{it}(\cdot)}{\partial f_{it}^2} < 0 \text{ where } i \in [j, k] \quad (8)$$

The total net rent received by landowner i from marketed and non-marketed forest benefits in any given period, $l_{it}(f, \theta, \phi, x)$, directly depends on the volume of forest biomass f_{it} , the incidence of fire θ_{it} , the fire spread rate ϕ_{it} , and the action, x_{it} , taken by the landowner in that period. If a fire occurs ($\theta_{it} = 1$), the landowner receives the salvageable site value based on the total potential damage function and replants the burned portion of the site. If a fire does not occur in a given period ($\theta_{it} = 0$), the landowner receives rents or incurs costs that depend on the action taken:

$$l_{it}(f, \theta, \phi, x) = \begin{cases} u_{it}(f_{it}) + g_{it}(f_{it}) - c_{per} - c(x_{it}) & \theta_{it} = 0, \phi_{it} = 0, x_{it} \in [0, f_{it}] \\ (1 - D_{it, total})[u_{it}(f_{it}) + g_{it}(f_{it})] - c_{per} - c(x_{it}) - (D_{it, total})c_{\theta=1} & \theta_{it} = 1 \text{ or } \phi_{it} = 1 \end{cases} \quad (9)$$

where c_{per} is the cost of annually maintaining the site in the absence of fire. $c(x_{it})$ is the cost of fuel treatment which depends on the amount of fuel removed, and this cost is assumed to have fixed (c_{fix}) and variable ($c_{var}(x_{it})$) components as there is a fixed cost of setting up the treatment capital regardless of fuel removal level. $(1 - D_{it, total})$ is the proportion of forest biomass salvaged if a fire occurs and is a function of fuel stock as defined earlier by the total potential damage function. $c_{\theta=1}$ is the cost of replanting the site after the fire which depends on the proportion of forest that is burned.

2.6. Stochastic Dynamic Nash Equilibrium and Numerical Optimization

The connections between landowner j and landowner k come through the fire arrival rate, the fire spread from one parcel to another, and thus, the total potential fire damages. The failure of one landowner to account for possible fire spread to a neighboring landowner and the resultant losses leads to a wedge between socially optimal fire prevention and the individually optimal fuel reduction decisions. To address this, the current study solves for the Nash equilibrium to derive a dynamic reaction function which represents the best response of one landowner to the fuel reduction activities of the other landowner every period. Simultaneously deriving the dynamic reaction functions for both forest landowners in each time period yields a subgame perfect Nash equilibrium (SPNE) path of fire prevention decisions.

For our two adjacent landowners problem, we develop a value function (or Bellman equation) for each landowner for an infinite sequence of future periods that is calculated by combining the optimal current rent earned at year t and the optimal expected discounted future rents from year $t+1$ onward. The Bellman equations are given by Equations (10) and (11) representing landowners j and k , respectively, for an infinite time horizon:

$$V_j\{f_j, f_k, \theta, \phi\} = \max_{x_j} (l_{jt}(f, \theta, \phi, x) + \delta E_{\theta} V(f_{j,t+1}, f_{k,t+1})) \quad (10)$$

$$V_k\{f_k, f_j, \theta, \phi\} = \max_{x_k} (l_{kt}(f, \theta, \phi, x) + \delta E_{\theta} V(f_{k,t+1}, f_{j,t+1})) \quad (11)$$

This study follows Miranda and Fackler [18] and Judd [19] and uses a collocation method as an approximation to solve the Bellman equations due to the absence of a closed-form solution. This study solves the Bellman equations by implementing Chebyshev basis functions in MATLAB_R2017a using the gamesolve routine included in the Miranda and Fackler [18] COMPECON library.

2.7. Social Optimum

A social planner is assumed to solve for the optimal path of fuel reduction across the entire landscape in each time period to derive the maximum joint net returns to both landowners:

$$V_{sp} = \max_{x_j, x_k} (l_{jt}(f, \theta, \varphi, x) + l_{kt}(f, \theta, \varphi, x) + \delta E_{\bar{\theta}} V(f_{j,t+1}, f_{k,t+1}) + \delta E_{\bar{\theta}} V(f_{k,t+1}, f_{j,t+1})). \quad (12)$$

The solution derived from Equation (12) gives the socially optimal path of fire prevention actions in each period. This study then compares and contrasts the derived privately optimal fuel treatment paths from Equations (10) and (11) to the socially optimal path from Equation (12).

2.8. Data Sources and Application

To parameterize the simulation, we model a standard forest parcel in the Southeastern United States that consists of trees, shrubs, and ground cover; and is operated or utilized for marketed forest benefits (like hunting, hiking, camping, and other forest recreation activities) as well as non-marketed forest benefits (such as household recreation). We utilize parameter values and functional forms from Amacher, Malik, and Haight [13], Crowley et al. [7], Busby, Amacher, and Haight [8], Rosenberger et al. [16], and Daigneault, Miranda, and Sohngen [20], as listed in Table 1. The selected annual forest growth function used in this study exhibits similar characteristics to the one used by most relevant studies; Busby, Amacher, and Haight [8] and Daigneault, Miranda, and Sohngen [20].

The periodic maintenance (c_{per}) of the stand is assumed to be \$10 per acre, consistent with Daigneault, Miranda, and Sohngen [20] and Bair and Alig [21]. The cost of establishing new forest after a wildfire, $c_{\theta=1}$ is assumed to be \$122.4 per acre, is based on Amacher, Malik, and Haight [11] using the derived optimal planting density and Dubois et al. [22]. Intermediate treatment cost varies by the level of fuel removal. Consistent with Amacher, Malik, and Haight [11], the cost function of intermediate actions $c(x_{it})$ is assumed to be a linear function of fuel removal efforts.

The fraction of the salvageable site value, $(1 - D_{it,total})$, as discussed above is a function of the surface fuel stocks. A severe forest fire such as the one that ravaged Florida in 1998 reveals that the mortality rate of trees on non-treated stands was more than twice that of trees on treated stands on average [23]. In addition, silvicultural practices like prescribed burning have been shown to mitigate tree mortality rates in fire prone regions [23–25]. Consequently, the damage function assumes that damages increase as fuel stocks increase.

The selected amenities value (non-marketed forest benefits) function was found in Busby, Amacher, and Haight [8] and assumed to depend on the forest biomass on an individual parcel. Moreover, Walsh, and Olienyk [15] provided reduced form functions for average consumer surplus (CS) and average user days (UD), as listed in Table 1.

No published work could be found in the literature that models the fire arrival rate as a function of fuel accumulation process. This study chooses a functional form that exhibits similar desired characteristics like the one presented by Crowley et al. [7] who modeled fire arrival probability as a function of fuel removal for the case of adjacent landowners. Consistent with our previous assumption, we assume that fire arrival rate is an increasing function in fuel stock accumulation, implying the following probabilities:

$$\lambda(\gamma, f_{jt}, f_{kt}) = 1 - e^{-\gamma \left(\frac{k(f_{jt}) + k(f_{kt})}{W} \right)}. \quad (13)$$

The parameter γ represents the rate of incendiary events over a 100-year period. W is a scaling factor and used to control the influence of fuel stock accumulation in increasing the probability of fire. The values of γ and W are set to 0.02 and 50, respectively; these values are based on those found in Crowley et al. [7] given the characteristics of our fire arrival rate function. The assumed functional form for the fire arrival rate takes on values ranging from 1 to 8 fires every hundred years over the range of possible fuel accumulation. This range falls within ranges found the literature and approximates the natural fire cycle in the southeastern U.S.

The individual damage function for an individual landowner i exhibits similar characteristics to the function proposed by Crowley et al. [7]; specifically, it is strictly convex in fuel load. No precedents could be found in the literature for fire spread rate, so the functional form for landowner i was purposely chosen to be an increasing and concave function with respect to fuel stock present on the site owned by the neighboring landowner, and bounded between 0 and 1.

Table 1. Optimal management model specification for a forest parcel in the Southeastern U.S.

Description	Specification	Parameter Value Per acre
Discount factor	δ	0.95
Annual forest biomass growth	$k(f_{it}) = \omega_0(\omega_1 + f_{it})(\omega_2 f_{it}^{\omega_3})$	$\omega_0 = 0.25, \omega_1 = 5, \omega_2 = 1, \omega_3 = 0.47$
Amenities value	$u_{it}(f_{it}) = \kappa_1(\omega(f_{it}) - \kappa_2)^2 + \kappa_3$	$\kappa_1 = -0.008, \kappa_2 = 80, \kappa_3 = 50, \omega = 30$
Average consumer surplus (CS)	$CS_{it} = \alpha_0 + \alpha_1 f_{it} + \alpha_2 f_{it}^2$	$\alpha_0 = -2.97\$/UD,$ $\alpha_1 = 0.24, \alpha_2 = -0.00017$
Average user days (UD)	$UD_{it} = v_0 + v_1 f_{it} + v_2 f_{it}^2$	$v_0 = 9.32\text{days/year},$ $v_1 = 0.24, v_2 = -0.0002$
Periodic maintenance cost	c_{per}	\$10
Replanting cost after fire	$c_{\theta=1}$	\$122.4
Fuel removal cost	$c(x_{it}) = c_{fix} + c_{var}(x_{it})$	$c_{fix} = \$5, c_{var} = \100
Individual damage function for landowner i	$D_{it} = e^{-\left(\frac{0.1}{f_{it}}\right)}$	
Fire arrival rate	$\lambda(\gamma, f_{jt}, f_{kt}) = 1 - e^{-\gamma\left(\frac{k(f_{jt}) + k(f_{kt})}{W}\right)}$	$\gamma = 0.02, W = 50$
Fire spread rate for landowner i	$\phi_{-i \rightarrow i, t} = 1 - e^{-0.93(f_{-i, t})^{0.93}}$	

Notes: Values without specified units are unitless.

3. Results

This study explores different sources of misinformation regarding fire spillover effects represented by the fire arrival rate (λ) and fire spread rate (ϕ) between the two adjacent parcels. Four different categories of misinformation are analyzed in this study: (1) $(\lambda(j), \phi(j))$: the landowner j is totally unaware of fire spillover effects; thus, he does not account for his neighbor's fuel stock in either fire arrival rate or fire spread rate, (2) $(\lambda(j, k), \phi(j))$: the landowner j accounts for his neighbor's fuel loads in the probability of fire arrival but fails to recognize cross-stand benefits of fuel treatment through the fire spread rate between the two adjacent parcels, (3) $(\lambda(j), \phi(j, k))$: the landowner j is uninformed about the effect of interdependency of the two adjacent parcels through the fire arrival rate; however, he recognizes the effect of such interdependency on the spread rate of fire, (4) $(\lambda(j, k), \phi(j, k))$: the landowner j is fully informed about cross-stand benefits of fuel treatment and understands the effects of his neighbor's fuel accumulation on both fire arrival rate and fire spread rate. In summary, the first category represents a completely uninformed landowner with regards to fire externalities, the second and third characterize partially informed landowners, and the fourth category represents a fully informed landowner. In the table headings, these different levels of misinformation are sorted to reflect a gradual move from being uninformed to fully informed landowners. With these four possible categories of misinformation levels a landowner may experience, there are sixteen misinformation-pair scenarios.

The results are presented in three sub-sections. We successively describe the optimal steady-state fuel treatment path for an individual landowner; the private site values for all scenarios; and socially optimal fuel management path, social site values, and social costs.

3.1. Optimal Steady-State Risk-Mitigating Decision Path

In this sub-section onward, we present and discuss the level of fuel treatment as a percentage of total fuel present to facilitate the comparisons. In order to have a general understanding of the optimal risk-mitigating decision path, Figure 1 shows the individually optimal fuel management decision path for landowner j in the case of landowners who are fully informed about fire externalities (All other

combinations regarding the type of the adjacent landowners bring about a similar fuel removal path to the one shown in Figure 1, but different removal levels as shown in Table 2. For simplicity, we discuss one combination to give a general understanding of the shape of the optimal path). In general, the optimal path of fuel management dramatically increases in the first ten years and then reaches a steady-state level at about 30% of fuel removal (Figures display the optimal decision path for 30 years to conserve space. The horizontal axis represents forest rotations in year). This result implies that the individually optimal fuel management path tightly follows the nature of the fuel accumulation on the forest at the beginning ten years and before reaching the steady-state level. Reaching a steady-state level in later years is expected given the biological growth feature of trees in the forest; due to an increasing variable cost associated with increasing fuel removal efforts; and given the on-site post-treatment amenity value as discussed below. This indicates that the landowner fuel treatment decision depends of the level of fuel accumulated on his parcel, and there is a tight relationship between fuel accumulation on a parcel and the fuel removal.

Table 2 shows the individually optimal steady-state fuel removal level under all sixteen possible misinformation scenarios. The main result is that landowner j is more responsive to his own level of misinformation regarding fire spillover effects than to his adjacent landowner k 's misinformation level. For all levels of misinformation of landowner k , landowner j decreases his fuel management as he gets more informed about fire externalities. This is an evidence of free riding potential between adjacent landowners. Fuel management can be considered a public good because one landowner's fuel treatment produces benefits to neighboring landowners [7]. These benefits are represented, in our model, through the fire arrival rate, the fire spread rate, and consequently the salvageable part of the forest after fire. The landowner is more likely to reduce fuel removal as he gains more information about the complex cross-parcel externality; for this reason, Table 2 shows lower level of fuel removal in the case of fully informed landowners compared to the case of partially informed and non-informed.

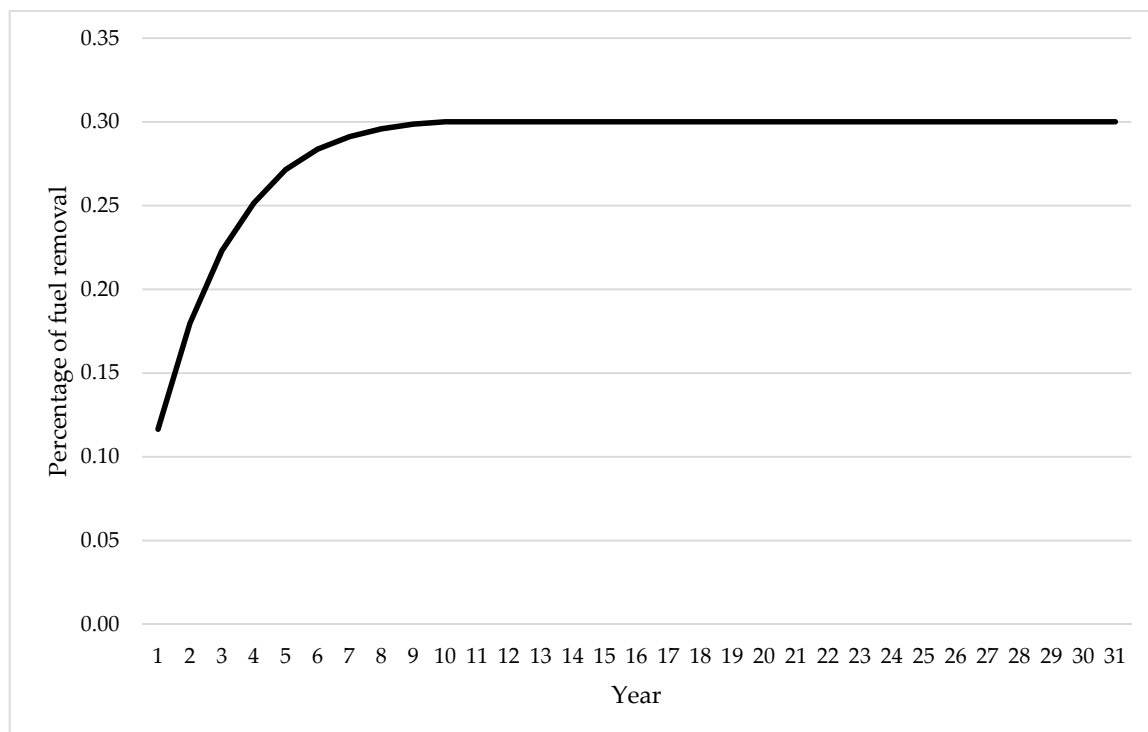


Figure 1. Individually optimal fuel management decision path for landowner j in the case of fully informed landowners (j, k) about fire externality.

Table 2. Individually optimal steady-state fuel management decision path for landowner j given all combinations of misinformation scenarios.

j	k			
	$\lambda(k), \varphi(k)$	$\lambda(k, j), \varphi(k)$	$\lambda(k), \varphi(k, j)$	$\lambda(k, j), \varphi(k, j)$
$\lambda(j), \varphi(j)$	40.60%	40.60%	40.60%	40.60%
$\lambda(j, k), \varphi(k)$	36.09%	36.08%	36.11%	36.11%
$\lambda(j), \varphi(j, k)$	30.88%	30.88%	30.91%	30.91%
$\lambda(j, k), \varphi(j, k)$	30.30%	30.33%	30.39%	30.81%

Notes: λ : Fire arrival rate, φ : Fire spread rate; for landowner j , $\lambda(j), \varphi(j)$: considers own fuel stock on both the fire arrival rate and the fire spread rate (uninformed landowner); $\lambda(j, k), \varphi(j)$: considers own and adjacent fuel stocks on the fire arrival rate and only own on the fire spread rate (partially informed landowner); $\lambda(j), \varphi(j, k)$: considers own fuel stock on the fire arrival rate, and own and adjacent on the spread rate (partially informed landowner); $\lambda(j, k), \varphi(j, k)$: considers own and adjacent fuel stocks on both the fire arrival rate and the fire spread rate (informed landowner).

In addition, by comparing the four columns of Table 2, landowner j slightly increases the level of fuel removal as his neighboring landowner k becomes more informed about cross-stand benefits of fuel treatment. This indicates that landowner k also tends to reduce his level of fuel removal once he becomes informed about cross-parcel benefits of fuel treatment, which incentivizes landowner j to marginally increase his fuel removal to offset to some degree the decrease in fuel removal on the neighboring parcel. Moreover, when landowner j is partially informed, there is relatively limited reactivity of landowner j to his neighbor's misinformation level. Consistently, the uninformed landowner does not alter decisions when his neighbor's information level changes. This landowner is unaware of the cross-parcel benefits of fuel treatment, and does not decrease the level of fuel removal when his adjacent landowner undertakes some fuel removal. Although the differences among fuel removal decisions shown in Table 2 may seem small, such small differences have greatly affected the individual site value, and thus social costs, as indicated below.

3.2. Private Site Values

Table 3 reveals individually optimal site values for landowner j given all combinations of misinformation scenarios on the two adjacent parcels. The private site value for each misinformation scenario is found by evaluating the original Bellman equation at the landowner's optimal actions under each misinformation scenario. Specifically, landowner's fuel treatment decisions are obtained with the misinformation scenario; then, using the obtained decisions, the original Bellman equation is evaluated with both sources of externalities present. Table 3 is structured similarly to Table 2 and can be read horizontally and vertically. Except the case when landowner j is completely uninformed, we see that the individually optimal site value for landowner j increases as his neighboring landowner gets more informed (horizontal value comparison), and also increases as he becomes more informed (vertical value comparison). When landowner j is completely uninformed, the individually optimal site value for landowner j does not follow this general pattern. The individual site value for landowner j decreases as his adjacent landowner k gets more informed. This finding is consistent with the previously discussed free riding potential between the two adjacent landowners. A similar result can be observed if Table 3 is examined vertically.

Table 3. Individually optimal site values for landowner j given different misinformation scenarios.

j	k			
	$\lambda(k), \varphi(k)$	$\lambda(k, j), \varphi(k)$	$\lambda(k), \varphi(k, j)$	$\lambda(k, j), \varphi(k, j)$
$\lambda(j), \varphi(j)$	132.73	130.05	128.20	127.05
$\lambda(j, k), \varphi(k)$	126.48	126.43	126.81	127.59
$\lambda(j), \varphi(j, k)$	128.71	130.15	131.86	133.82
$\lambda(j, k), \varphi(j, k)$	136.00	138.40	140.98	143.74

Notes: λ : Fire arrival rate, φ : Fire spread rate; for landowner j , $\lambda(j), \varphi(j)$: considers own fuel stock on both the fire arrival rate and the fire spread rate (uninformed landowner); $\lambda(j, k), \varphi(j)$: Considers own and adjacent fuel stocks on the fire arrival rate and only own on the fire spread rate (partially informed landowner); $\lambda(j), \varphi(j, k)$: considers own fuel stock on the fire arrival rate, and own and adjacent on the spread rate (partially informed landowner); $\lambda(j, k), \varphi(j, k)$: considers own and adjacent fuel stocks on both the fire arrival rate and the fire spread rate (informed landowner).

Although the differences in the individually optimal site values are small, especially with partially informed landowners, these differences represent a significant amount of money for non-industrial private landowners in the U.S. who own approximately 300 million acres of forests (Alig et al. 2003). The highest individual site values are obtained when landowner j is fully informed (the bottom row of Table 3); and the maximum is obtained when both landowners are fully informed (the bottom right cell of Table 3). This best outcome represents an 8.30% increase in individual value relative to the two uninformed landowners. This latter case is equivalent to landowners assuming each parcel is managed in isolation with no adjacent parcel. In addition, the best outcome shows a 13.69% increase in individual site value compared to the lowest obtained outcome (both landowners are uninformed about fire spread rate). This indicates that failure to recognize cross-stand benefits of fuel treatment through the fire spread rate between the two adjacent parcels brings about the lowest individual site value. This finding highlights the importance of accounting for fire spread rate in this context which is a novel contribution of this study.

3.3. Socially Optimal Fuel Management Path, Social Site Values, and Social Costs

In order to derive the social costs associated with individually managing a forest and in the presence of fire externality, we assume that both adjacent parcels are jointly managed by a social planner who simultaneously maximizes joint net returns to both parcels and who is fully informed about fire spillover effects. Socially optimal steady-state fuel treatment is found to be 45.20% of fuel biomass present and the associated social site value is \$293.30 per acre. For a better understanding of the wedge between socially and individually optimal fuel treatment paths, Figure 2 illustrates socially and individually optimal decision paths in the case of fully informed landowners. In this case, the socially optimal level is higher than the individually optimal by about 14.39%.

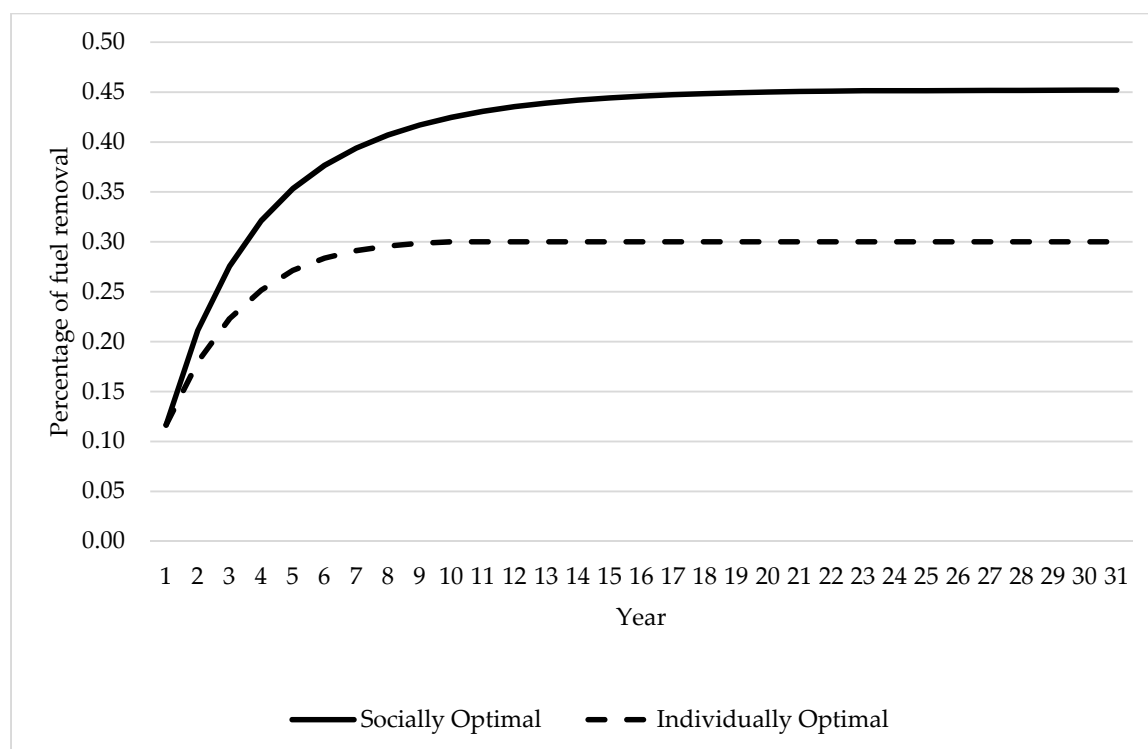


Figure 2. Socially vs. individually optimal fuel management decision paths for landowner j in the case of fully informed landowners (j, k) about fire externality.

Table 4 displays combined individually optimal site values for different misinformation levels which is needed in driving associated social costs. Considering different misinformation scenarios, Table 5 is calculated based on the differences between combined individually optimal site values (Table 4) and the socially optimal site value. Holding the completely uninformed case constant, results reveal that social costs, on average, decrease as a landowner gets more informed and wholly recognizes the spillover effects of fire between his own parcel and the neighboring parcel. The most interesting result is that the highest social costs are obtained when landowner j is uninformed about fire spread rate which strengthen our previous statement regarding the significant role of fire spread awareness in influencing landowners' decision making. Another interesting result is that the social cost resulting from free riding behavior (the bottom left cell of Table 5) is lower than the social cost associated with complete absence of fire externality awareness for both landowners (the top left cell of Table 5). This means that the case when each parcel is managed in isolation with no adjacent parcel is more socially costly than free riding potential. This study is consistent with the work of Crowley et al. [7] and Busby, Amacher, and Haight [8] in that free riding influences social costs. However, this study examines additional sources of misinformation covering a wider range of possible fire spillover effects which provides additional insight regarding potential consequences of the interactions between the two adjacent landowners.

Table 4. Combined individually optimal site values for different misinformation scenarios.

<i>j</i>	<i>k</i>			
	$\lambda(k), \varphi(k)$	$\lambda(k, j), \varphi(k)$	$\lambda(k), \varphi(k, j)$	$\lambda(k, j), \varphi(k, j)$
$\lambda(j), \varphi(j)$	265.45			
$\lambda(j, k), \varphi(j)$	252.96	252.85		
$\lambda(j), \varphi(j, k)$	257.43	260.29	263.71	
$\lambda(j, k), \varphi(j, k)$	272.01	276.79	281.96	287.47

Notes: λ : Fire arrival rate, φ : Fire spread rate; for landowner *j*, $\lambda(j), \varphi(j)$: considers own fuel stock on both the fire arrival rate and the fire spread rate (uninformed landowner); $\lambda(j, k), \varphi(j)$: considers own and adjacent fuel stocks on the fire arrival rate and only own on the fire spread rate (partially informed landowner); $\lambda(j), \varphi(j, k)$: considers own fuel stock on the fire arrival rate, and own and adjacent on the spread rate (partially informed landowner); $\lambda(j, k), \varphi(j, k)$: considers own and adjacent fuel stocks on both the fire arrival rate and the fire spread rate (informed landowner).

Table 5 shows also that social costs of a landowner decreases as his neighbor's information about fire externality improves. The lowest social cost is reached when both neighboring landowners are fully aware of cross-parcel fire externality effects. This best outcome brings about a 79.07% reduction in social cost relative to the completely uninformed case (both landowners are uninformed), and generates a 85.60% reduction in social costs compared to the highest obtained social cost (landowner *j* is uninformed about fire spread rate). This finding is important for policy makers as it implies that improving landowners' knowledge about fire spillover and specifically cross-parcel effects of fuel treatment could result in a considerable alleviation in the act of free riding and the associated social costs.

Table 5. Social costs for different misinformation scenarios.

<i>j</i>	<i>k</i>			
	$\lambda(k), \varphi(k)$	$\lambda(k, j), \varphi(k)$	$\lambda(k), \varphi(k, j)$	$\lambda(k, j), \varphi(k, j)$
$\lambda(j), \varphi(j)$	27.85			
$\lambda(j, k), \varphi(j)$	40.33	40.45		
$\lambda(j), \varphi(j, k)$	35.87	33.01	29.59	
$\lambda(j, k), \varphi(j, k)$	21.29	16.50	11.34	5.83

Notes: λ : Fire arrival rate, φ : Fire spread rate; for landowner *j*, $\lambda(j), \varphi(j)$: considers own fuel stock on both the fire arrival rate and the fire spread rate (uninformed landowner); $\lambda(j, k), \varphi(j)$: considers own and adjacent fuel stocks on the fire arrival rate and only own on the fire spread rate (partially informed landowner); $\lambda(j), \varphi(j, k)$: considers own fuel stock on the fire arrival rate, and own and adjacent on the spread rate (partially informed landowner); $\lambda(j, k), \varphi(j, k)$: considers own and adjacent fuel stocks on both the fire arrival rate and the fire spread rate (informed landowner).

4. Discussion and Conclusions

This study developed a model for a two-landowner problem and solved for the Nash equilibrium in a stochastic dynamic framework to derive the individually optimal response of one landowner to the fire risk mitigation policies of the adjacent landowner under different sources of misinformation about fire spillover effects. The existence of spatial externalities on a landscape via fire risk and fire spread between two neighboring forests can cause substantial inefficiencies if ignored by landowners when making decisions regarding fire risk mitigation activities. The novelty of our work follows from introducing and endogenously integrating the probability of fire spread from the original parcel to the neighboring parcel as a function of accumulated fuel into the modeling framework which more accurately portrays the link between the two adjacent forests relative to previous literature.

The analysis reveals that fuel accumulation on the forests directly influences fuel reduction practices undertaken by adjacent landowners. Risk-mitigating practices are found to reduce fire-related losses incurred by landowners and substitute for fire suppression efforts made by the government. However, such practices simultaneously remove natural vegetation on forests which reduce on-site

amenity value. For our model and chosen parameters, as shown in Table 2, the small differences in the level of fuel removal could be attributed to the negative effect of such actions on amenity value. Like in Busby, Amacher, and Haight [8], landowners are more willing to adopt an increasing level of fuel reduction in the short run (the first 10 years as shown in Figure 1) in order to reduce long-run fire losses which could result in more severe amenity value losses in the future. However, this study gives a clearer picture as it shows that in the long run (year 10 onward), landowners are not willing to maintain the same increasing level of fuel removal as they did in the short run. It seems that a landowner has an incentive to forgo some level of fuel management in order to maintain amenity value on his forest. Therefore, a landowner tends to maximize the benefits of fuel reduction (mitigating fire damages) while considering the loss in amenity value.

In addition, this study discloses that different levels of information about fire externalities held by landowners when making decisions could discourage landowners from adopting fuel management activities or reduce efforts below the socially optimal amount. When investigating the interaction of wildfire risk mitigation policies for the two adjacent parcels, results show that a landowner is more reactive to his own level of misinformation regarding fire spillover effects than to his adjacent landowner's misinformation level. Simulation results indicate that a landowner tends to free ride on fuel removal actions undertaken by his adjacent landowner. Consistent with Al Abri [26], we found that an informed landowner tends to reduce fuel treatment when his neighboring landowner is unaware of cross-parcels effects of fuel treatment. A similar result was found in Crowley et al. [7] and Busby, Amacher, and Haight [8], but in this study we provide richer insight regarding free riding potential through consideration of multiple levels of misinformation, especially undervaluing fire spread between the two adjacent parcels. One of the interesting results is that the free riding potential of a landowner could be alleviated to some extent by a neighboring landowner who is aware of fire spillover effects. The idea of mutual free riding may encourage a landowner to increase fuel removal to offset the expected decrease in fuel removal of the neighbor [26]. Although free riding behavior may seem hard to correct through government policies, our finding implies that governments could introduce more effective educational programs to insure that all landowners are fully aware of cross-parcel benefits of fuel treatment, which may reduce the free riding potential.

Another interesting result and the novelty of our model is that failure to recognize cross-stand benefits of fuel treatment through the fire spread rate between the two adjacent parcels brings about the lowest individual site value and the highest social costs. This finding does not only validate our model setting, but ensures the importance of accounting for fire spread rate in this context. The most important result in this study is that the social cost resultant from free riding behavior is lower than the social cost associated with complete absence of fire externality awareness for both landowners. Although previous studies conclude that free riding behavior causes inefficiencies in fuel treatment, this study contributes by revealing that managing each parcel with no adjacent parcel increases inefficiencies in fuel treatment and is more socially costly than free riding potential. Identifying such cases with the greatest divergence between individually and socially optimal management and the greatest externality costs would help government agencies develop more effective education programs in order to align socially optimal and private decisions and minimize externalities.

In summary, common boundaries between forests allow for fire spread between adjacent forest parcels. Thus, a parcel's lack of fuel management may contribute to fire damage on neighboring parcels. This study investigates fire-mitigating fuel treatment behaviors of neighboring landowners to evaluate the interaction of fuel treatment decisions for adjacent landowners under various scenarios of misinformation about fire occurrence and spread. The study also determines optimal fuel treatment and examines how individual beliefs regarding fire risk and fuel accumulation could influence these results. Although the derived model of this study is capable of determining optimal fuel treatment timing and level simultaneously on adjacent forest parcels, it does not consider housing development in fire-prone areas (the wildland–urban interface) where neighboring property owners are expected to behave differently. In this case, the urban landowner could maintain an asset protection zone (APZ) to

lessen the potential impact of spatial externalities. This buffering action could influence fuel treatment level on one's own and adjacent property, and these effects could be analyzed in future work.

This study could serve as a platform for future research on forest fire management with two or multiple neighboring landowners. Given the conclusion that misinformation influences risk-mitigating behaviors and social costs, it would be interesting to examine scenarios when landowners could revise or change beliefs over time. Past experience regarding fire occurrence and spread, or past applied fuel removal strategies could impact future fire-mitigating decisions.

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