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# The Impact of Heterogeneous Management Interests in Reducing Social Losses from Wildfire Externalities

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**Abstract:** The United States has experienced an even longer and more intense wildfire season than normal in recent years, largely resulting from drought conditions and a buildup of flammable vegetation. The derived stochastic dynamic model in this study was utilized to evaluate the interaction of wildfire risk mitigation policies for two adjacent landowners under various scenarios of forest benefits while accounting for full awareness of fire externalities. This study also evaluated the effectiveness of cost-share programs and fuel stock regulation and investigated under which scenarios of forest management interests the implementation of these policies encourages risk mitigation behaviors and yields larger reductions in social costs. The findings revealed that social costs significantly reduced after the implementation of cost-share programs and fuel stock regulation. Market-oriented adjacent landowners were more responsive to policy instruments compared to other types of neighboring landowners, and their responsiveness was greater for fuel stock regulation policies than for cost-share programs. Policymakers may introduce extra financial incentives or more rigorous fuel stock regulations to induce nonmarket-oriented landowners to undertake increased fuel management activities.

**Keywords:** wildfire risk; fuel treatment; social losses; forest management interests; misinformation

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## 1. Introduction

In recent years, the United States has experienced record-breaking wildfires that have increased the importance of reducing private and social losses from fire damages. Wildfires burned a total of about 8.8 million acres in 2018 and 10 million in 2017 [1]. Federal agencies spend billions of dollars on fire suppression, and this suppression, in combination with a lack of fuel management on the part of individual landowners, results in a large accumulation of hazardous forest fuels (dried pine needles or leaves, scrubby understory vegetation, etc.) on landscapes, putting communities at risk [2]. While nonindustrial private landowners, who are often poorly informed about fire risk [3], often cannot control the occurrence of wildfires, they can undertake fire prevention practices to reduce forest damage in the event of a wildfire. Fuel reduction actions, such as prescribed burning and some forms of thinning, can be used to minimize fire damages [4,5] as both the amount and composition of forest fuels impact the intensity and extent of wildfires [6–11]. Nevertheless, landowners may ignore warnings to manage fuels or may engage in minimal fuel reduction efforts due to differences in forest management interests, the costs associated with these practices, and/or misinformation about the importance of such actions in reducing fire damages. Previous research has raised the question of whether policymakers should introduce financial incentives or fuel regulations to induce individual landowners to undertake increased fuel management activities [12–16]. Prior studies have suggested that cost-share programs and fuel stock regulation could reduce social costs and encourage increased fuel management [2].

This study considered two main policy instruments that were examined for different forest management interests. The first instrument is a fuel treatment cost-share program that could take two forms: a traditional form under which the government shares fuel reduction costs with landowners or a relatively new form where two adjacent landowners engage in collaborative efforts that require the sharing of fuel reduction capital. Using qualitative methods, studies in the literature have suggested that collaborative efforts between neighboring landowners is a potentially effective fire management approach [17–20]. Such collaboration has cost-sharing incentives, such as equipment-sharing among participants, which could encourage landowners to undertake fuel treatment practices that mitigate wildfire losses [21–30]. In 2001, Congress called for the "close collaboration among citizens and governments at all levels" for the management of wildland fire, hazardous fuels, and ecosystem restoration [31]. In 2003, the Healthy Forests Restoration Act (HFRA) created an opportunity for communities and landowners to influence where and how federal agencies apply fire prevention projects on federal lands. One effective approach to gain benefits from this opportunity is to create and participate in a Community Wildfire Protection Plan (CWPP). Local communities with active CWPP are granted priority for funding related to forestry cost-sharing programs, such as fuel removal and tree planting [32]. Alternatively, the government could implement fuel stock regulations that prohibit fuel stocks on an individual parcel from exceeding a certain amount [2].

The first objective of this study was to build upon the stochastic dynamic model derived by Al Abri and Grogan [33] to evaluate the interaction of fuel treatment decisions for two adjacent landowners under various scenarios of forest benefits. The model is capable of determining optimal steady-state fuel management decision levels as a function of fire risk and fuel biomass dynamics. The model assumes that neighboring landowners understand the spillover effects of fuel accumulation on both fire arrival rate and fire spread rate; landowners are fully aware of the cross-stand effects of wildfires and are fully informed about the cross-stand benefits of fuel treatment. The second objective of this study was to use the derived model to examine how different forest management interests might yield privately optimal outcomes that deviate from socially optimal decisions. Externality costs that result from suboptimal fuel management decisions may differ based on the individual landowner's characteristics [34,35], and their economic parameters. Furthermore, differing landowner uses for and perceived values of forests may lead to divergent privately optimal decisions. The third objective of this study was to evaluate the effectiveness of alternative policy instruments for the problem of two adjacent landowners and investigate under what scenarios of forest management interests the implementation of these policies encourages risk mitigation behaviors and yields larger reductions in social costs. Examining variations in individually optimal fuel treatment paths that result from employing financial incentives or fuel regulations would reveal which policy is more effective in approximating the socially optimal outcome. Previous studies by Amacher et al. [3] and Busby et al. [2] evaluated similar incentives for different misinformation regarding fire risk, with no consideration to different forest management interests.

The analysis that follows examines a two-landowner problem for which landowners differ based on their forest management interests. While previous work has only considered heterogeneity in landowner knowledge, this study considered differences in economic parameters and landowner characteristics that may affect decisions. Such parameters are impossible to alleviate simply by educating landowners. This study considered two kinds of forest uses: market-oriented, i.e., valuing market forest benefits such as hunting leases and forest recreations benefits, and nonmarket-oriented, i.e., valuing nonmarket forest benefits such as natural amenities and nonmarket ecosystem services. To our knowledge, no previous work has included an investigation of adjacent landowners with different ownership or management purposes. Differing management objectives (market-oriented and nonmarket-oriented) beg the question of how the decision pattern of each type deviates from the social optimum, and if heterogeneity across landowners yields larger or smaller spatial externalities relative to a homogeneous landscape. We might expect that the landowner who values total forest volume and its associated amenities may be less likely to remove hazardous fuels on their sites, relative to a landowner who values specific kinds of forest biomass [35,36]. Forest managers who are interested in hunting leases and other forest recreation activities (such as hiking, camping, sightseeing, and fishing) may be more proactive about mitigating risk if they derive income from the forest. Additionally, the demand for their forests' services by hunters and forest recreationists may be influenced by fuel reduction techniques and the occurrence and frequency of wildfires [37]. Unlike Al Abri and Grogan [33], the derived model introduces a weight parameter such that a landowner could assign different weights to market and nonmarket forest benefits based on their forest management interests. Therefore, the model allows a landowner to value either type of forest benefits or a combination of both.

## 2. Materials and Methods

This study employed a stochastic dynamic programming model in a game interaction framework based on the *solvegame* routine included in Miranda and Fackler [38] to examine two neighboring forest parcels. The derived model presents, first, a base case representing the traditional private landowners' maximization problems when no policy exists and, second, the socially optimal management assuming both forest parcels are jointly managed in the socially optimal manner to maximize combined rents across parcels. A comparison of these two problems allows us to identify the differences between the socially and individually optimal fuel reduction outcomes. Next, we introduce specific policies to evaluate the social gain (or reduction in social costs) from each policy, and assess the deviations between the socially optimal outcome and the individually optimal outcome derived under these policies to reveal if it is economically worthwhile to invest in a certain program. This procedure is studied under a variety of scenarios of heterogeneous management preferences. Consistent with Al Abri and Grogan [33], this study modeled the fire arrival rate as a function of the amount of flammable fuel stock present on the forest and assumed that fuel accumulation on the neighboring forest influences the fire spread rate from the neighboring parcel to an individual's own parcel. The analysis that follows further contributes to the literature by accounting for heterogeneity across landowners in terms of management preferences while evaluating the effectiveness of a policy or regulation.

### 2.1. Model Formulation

The derived stochastic dynamic model considers an interaction between two adjacent landowners (labeled by $i \in [j, k]$) who manage their parcels simultaneously and potentially participate in incentive-based programs or engage in collaborative planning to mitigate fire damages and reduce fire prevention costs. The model allows each landowner to choose management interests. A landowner could value either nonmarket or market forest benefits, or a combination of both. This study investigated various combinations of ownership purposes to determine how different types of ownership may influence fire prevention actions and associated social costs. As both adjacent parcels are prone to fire, each landowner maximizes an infinite horizon of the net present value of current and future rents and considers full information regarding fire externalities. Consequently, landowners may undertake some fuel management practices to prevent or minimize fire damages.

In addition to the risk of fire occurrence, the neighboring landowners face the risk of fire spreading from one parcel to an adjacent parcel. A landowner with higher fuel stock will have a larger fire that is more likely to spread to the neighboring parcel. Therefore, the total potential damage caused by the fire on an individual's own parcel depends on the probability of fire occurrence on the parcel, fire damages on one's own parcel, the probability of fire occurrence on the adjacent parcel, and the probability of fire spread from the neighboring parcel to one's own parcel. Reducing fuel stocks leads to decreased fire damages and increased salvageable site value when the fire arrives. The model then determines the rent-maximizing fuel management levels, assuming that each landowner maximizes their own rents, and decisions are affected by the neighboring units through their effects on fire occurrence and spread. In addition, the model investigates different scenarios when landowners receive benefits, e.g., cost reductions, from government compensation or cooperating together to determine when it is beneficial to participate in such programs.

### 2.2. Model Structure and Fire Risk

The stochastic dynamic problem contains a continuous state variable: forest biomass index $f_{it}$, where $i \in [j, k]$, measured in cubic meters per acre at the beginning of each period and ranging from $f_0$ to $f_{max}$. The model allows the landowners to make decisions regarding the level of fuel reduction each period, $x_{it} \in [0, f_{it}]$. The model also has a random binary stochastic variable representing fire occurrence, $\theta_{it} \in [0, 1]$, during each period. In the absence of fire ($\theta_{it} = 0$), the landowner gains rent based on their forest activities. In the presence of fire ($\theta_{it} = 1$), the landowner sustains the unburned portion of the forest, cleans the burned portion, and replants immediately.

Consistent with previous literature, the fire arrival is characterized by a Poisson distribution; moreover, consistent with Al Abri and Grogan [33], this study modeled the fire arrival rate, $\lambda(\gamma, f_{jt}, f_{kt})$, as an increasing function of landscape-level historical average fire arrival rate, $\gamma$, and landscape-level fuel biomass, ($f_{jt}$, $f_{kt}$). The fire arrival rate is increasing at a decreasing rate with the level of fuel stocks:

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

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

### 2.3. Fire Spread Rate and Damage Function

The spread rate of fire creates an externality between the two adjacent parcels. The fire spread rate characterizes how fuel accumulation and intermediate fuel treatment on one forest parcel impacts fire damages on a neighboring parcel. Therefore, for example, the total potential fire damages on parcel $j$ is influenced by the probability of a fire starting on parcel $j$, $\theta_{jt}$, the resultant fire damage on parcel $j$ as a function of its own fuel stock, $D(f_{jt})$, the probability of a fire starting on parcel $k$, $\theta_{kt}$, and the probability of spread from neighbor $k$ as a function of $k$'s fuel stock, $\phi(f_{kt})$. Both the spread rate and the damage function are continuous, increasing in fuel stock, and ranging from 0 to 1. The fire spread rate from $k$ to $j$ and the total expected damage function for parcel $j$ can be expressed as follows, respectively:

$$\varphi_{jt} = \phi(f_{kt}) \quad (3)$$

$$D_{jt,total} = \theta_{jt} D(f_{jt}) + \theta_{kt} \varphi_{jt}(f_{kt}) D(f_{jt}) \quad (4)$$

### 2.4. Forest Biomass Accumulation

The state of the forest biomass in period $t$+1 depends on fuel reduction undertaken in period t. If a fire does not occur and no fuel reduction is performed, the forest biomass grows by $k(f_{it})$. If fire prevention actions are performed, $x_{it}$, the forest biomass grows by $k(f_{it}) - x_{it}$. If a fire destroys the forest in a given period, in the next period, the forest biomass is reset to its minimum value, $f_0$. If the forest is partially destroyed, the salvageable forest is determined by the total potential damage function; accordingly, the state of forest biomass the following period is given by:

$$f_{i,t+1} = \begin{cases} f_{it} + k(f_{it}) - x_{it} & \theta_{it} = 0, \varphi_{it} = 0, x_{it} \in [0, f_{it}] \\ (1 - D_{it,total})[f_{it} + k(f_{it}) - x_{it}] + (D_{it,total}) f_0 & \theta_{it} = 1 \; or \; \varphi_{it} = 1 \end{cases} \quad (5)$$

*2.5. Site Value, Program Evaluation, and Different Management Interests*

Landowner $i$'s valuation of their trees could be derived from only amenities on their site, $u_{it}(f_{it})$, from only marketed forest benefits such as hunting leases and other forest recreation, $g_{it}(f_{it})$, or from a combination of both. $\beta_i$ is a weighting parameter associated with nonmarket-oriented forest benefits, while market-oriented benefits are weighted by $(1 - \beta_i)$. $\beta_i$ is based on ownership interests, and its value can range from 0 to 1.

Given the different types of management interests, landowners assign a weight $\beta_i$ to nonmarket forest benefits and $(1 - \beta_i)$ to market forest benefits. Consistent with what was assumed earlier, the nonmarket-oriented landowner earns nonmarket benefits that depend on fuel load present on the site, $u_{it}(f_{it})$. Consistent with Donovan and Butry [39], the chosen functional form is concave and increasing in fuel loads, where:

$$\frac{\partial u_{it}(.)}{\partial f_{it}} > 0 \text{ and } \frac{\partial^2 u_{it}(.)}{\partial f_{it}^2} < 0 \text{ where } i \in [j,k] \quad (6)$$

The market-oriented landowners earn rents based on the economic value of recreation activities on their site, such as hunting leases. The value of marketable recreation can be calculated as the product of consumer surplus (CS) per recreation day and average user days (UD), as in Rosenberger et al. [40] who assumed that the total marketable recreation value is a function of forest biomass each period and increases at a decreasing rate, such that:

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

The net rent received by landowner $i$ from market or nonmarket benefits or intermediate treatments in any given period, $l_{it}(f, \theta, \phi, x)$, will be influenced by the volume of forest biomass, $f_{it}$, the incidence of fire, $\theta_{it}$, the fire spread rate, $\varphi_{it}$, and the fuel reduction action, $x_{it}$, in that period. In the case of fire ($\theta_{it} = 1$), the landowner receives the discounted salvageable site value after the fire and replants the forest. If a fire does not occur in a given period ($\theta_{it} = 0$), the landowner receives rent that depends on the action taken:

$$l_{it}(f, \theta, \varphi, x) = \begin{cases} [\beta_i\, u_{it}(f_{it}) + (1-\beta_i)\, g_{it}(f_{it})] - c_{per} - \rho_i\, c(x_{it}) & \theta_{it} = 0, \varphi_{it} = 0, x_{it} \in [0, f_{it}] \\ (1 - D_{it,total})[\beta_i\, u_{it}(f_{it}) + (1-\beta_i)\, g_{it}(f_{it})] - c_{per} - \rho_i\, c(x_{it}) - (D_{it,total})c_{\theta=1} & \theta_{it} = 1 \textit{ or } \varphi_{it} = 1 \end{cases} \quad (8)$$

where $(1 - D_{it,total})$ is the proportion of salvageable site value if the forest ignites, and $c_{\theta=1}$ is the cost of replanting the ignited part of the forest. $c_{per}$ is the cost of maintaining the forest parcel each period. $c(x_{it})$ is the cost of fuel reduction with fixed and variable components ($c_{fix}$ and $c_{\text{var}}(x_{it})$, respectively) as landowners incur a fixed cost of setting up the fuel removal equipment regardless of the level of fuel removed. Total cost depends on the amount of fuel removed and is scaled down by $\rho_i$ if a landowner participates in incentive-based cost-share programs or is involved in collaborative efforts. To determine the extent to which cost-sharing could reduce costs, the literature was reviewed for reported costs of fuel removal. Schaaf et al. [41] reported that the overall average fuel removal cost is approximately USD 225 per acre; fuel treatment costs reported by Dubois et al. [42] are close to those found in Schaaf et al. [41]. Bolding et al. [43] presented statistics for different types of costs associated with fuel removal mechanisms, such as maintenance and repair costs (USD 2.92 per acre on average) and labor overhead (USD 40 per acre on average). Given the operating costs associated with the fuel removal process, this study assumed that engagement in cost-share programs could save up to 50% of total fire prevention practices costs.

The second policy instrument is a fuel stock regulation requiring that fuel stock on an individual parcel does not exceed a specified level, $\dot{\text{F}}$, an amount quantified by a land management agency or an exogenous forest-owner association. For example, the Firewise program, which empowers neighbors within communities to collaborate in order to reduce wildfire risk and damages, and protect their properties, specifies fuel standards for 628 participating communities in 40 states within the U.S. [44].

### 2.6. Stochastic Dynamic Optimization and Nash Equilibrium Framework

The interactions between landowners come through the probability of fire occurrence and the possible spread of fire across parcels. Accounting for both stochastic variables in the process of investigating the effectiveness of cost-sharing programs and fuel regulation is important because both variables represent channels through which the benefits from participation in a certain program would be obtained. Ignoring such effects may discourage a landowner from participating due to underestimation of such program's potential benefits, thus leading to less than the socially optimal fuel treatment. This study simultaneously derived best-response functions for each landowner (dynamic reaction function) in a Nash equilibrium framework. These best-response functions include whether or not it is individually optimal for each landowner to participate in the government cost-sharing program or collaborative efforts, as well as if any policy instrument is preferred in approximating the socially optimal outcomes.

The optimal management path can be solved by combining the state variable, the action variable for each group of participants ($j$, $k$), and the rent and transition functions into the following set of simultaneous Bellman equations for an infinite sequence of future periods:

$$V_j\{f_j, f_k, \theta, \varphi\} = \max_{x_j}\left(l_{jt}(f, \theta, \varphi, x) + \delta E_{\tilde{\theta}} V\left(f_{j,t+1}, f_{k,t+1}\right)\right) \quad (9)$$

$$V_k\{f_k, f_j, \theta, \varphi\} = \max_{x_k}\left(l_{kt}(f, \theta, \varphi, x) + \delta E_{\tilde{\theta}} V\left(f_{k,t+1}, f_{j,t+1}\right)\right) \quad (10)$$

The socially optimal path of fuel treatment is obtained by assuming that both adjacent parcels are managed by a social planner who accounts for all returns and costs across the entire landscape according to:

$$V_{sp} = \max_{x_j, x_k}\left(l_{jt}(f, \theta, \varphi, x) + l_{kt}(f, \theta, \varphi, x) + \delta E_{\tilde{\theta}} V\left(f_{j,t+1}, f_{k,t+1}\right) + \delta E_{\tilde{\theta}} V\left(f_{k,t+1}, f_{j,t+1}\right)\right) \quad (11)$$

### 2.7. Data Sources and Application

This study parameterized the simulation by modeling a standard forest parcel in the southeastern United States. The functional forms and parameter values used in the numerical analysis are presented in Table 1 and utilized from Amacher et al. [3,7], Crowley et al. [45], Busby et al. [2], and Rosenberger et al. [40]. The annual forest growth function used in this study exhibits similar characteristics to the one employed by relevant studies found in the literature, Busby et al. [2] and Daigneault et al. [46].

The periodic maintenance ($c_{per}$) cost of USD 10 per acre is found in Bair and Alig [47] and the cost of replanting after a forest fire, $c_{\theta=1}$ = USD 122.4 per acre, is calculated based on Amacher et al. [5]. The model assumes the cost of fuel removal is a linear function of fuel removal actions based on Amacher et al. [5]. This cost is scaled down when incentive-based programs are included in the model.

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

| Description | Specification | Parameter Value Per Acre |
|---|---|---|
| Discount factor | $\delta$ | 0.95 |
| Annual forest biomass growth | $k(f_{it}) = \omega_0\left(\omega_1 + f_{it}\right)(\omega_2 f_{it}{}^{(\omega_3)})$ | $\omega_0 = 0.25, \omega_1 = 5,\ \omega_2 = 1\ , \omega_3 = 0.47$ |
| Minimum forest biomass | $f_0$ | 0.05 |
| Maximum forest biomass | $f_{max}$ | 100 |
| 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) | $UD_{it} = v_0 + v_1 f_{it} + v_2 f_{it}^2$ | $v_0 = 9.32 days/year,$ $v_1 = 0.24, v_2 = -0.0002$ |
| Periodic maintenance cost | $c_{per}$ | \$10 |
| Replanting cost after fire | $c_{\theta=1}$ | \$122.4 |
| Fuel removal cost | $c(x_{it}) = c_{fix} + c_{\text{var}}(x_{it})$ | $c_{fix} = \$5, c_{\text{var}} = \$100$ |
| Individual damage function for landowner $i$ | $D_{it}=e^{-\left(\frac{0.1}{f_{it}}\right)}$ | |
| Fire arrival rate | $\lambda\left(\gamma, f_{jt}, f_{kt}\right) = 1 - e^{-\gamma\left(\frac{k(f_{jt})+k(f_{kt})}{W}\right)}$ | $\gamma = 0.02,\ W = 50$ |
| Fire spread rate for landowner $i$ | $\phi_{-i\to i,t}= 1 - e^{-0.93(f_{-i,t})^{0.93}}$ | |

Notes: Functional forms have been examined over the range of values observed in the simulation.

Consistent with Al Abri and Grogan [33] and Al Abri [48], this study modeled the direct effect of fuel accumulation on the fire arrival rate. The assumed functional form is chosen to exhibit two main characteristics: a rate that is increasing in both fuel loads ($f_{jt}, f_{kt}$) and the historical average rate of incendiary events over a 100 year period $\gamma$, yielding:

$$\lambda\left(\gamma, f_{jt}, f_{kt}\right) = 1 - e^{-\gamma\left(\frac{k(f_{jt})+k(f_{kt})}{W}\right)} \tag{12}$$

$W$ is a control factor used to scale the effect of fuel accumulation in the fire arrival rate. The values of $\gamma$ and $W$ are set to 0.02 and 50, respectively; these values are based on those found in Crowley et al. [30] and Al Abri [33] given the characteristics of our fire arrival rate function. Over the entire space of fuel stocks, the fire arrival rate function reports values that range from 1 to 8 fires every hundred years, which falls within the range assumed in the literature and recorded for the southeastern U.S.

The individual damage function is chosen to be strictly convex in fuel load and has similar characteristics to the function suggested by Crowley et al. [30]. Al Abri and Grogan [18] provided guidance regarding the specification of fire spread rate that is consistent with our assumption that one landowner's fire spread rate is increasing at a decreasing rate as a function of fuel stock present on the parcel owned by a neighboring landowner and bounded between 0 and 1.

## 3. Results and Discussion

The results are presented in three main sub-sections. The first subsection presents the outcomes of the base case and it also discusses the socially optimal fuel management level, social site value, and social costs under various forest management interests. The second and third subsections, respectively, evaluate the effectiveness of the cost-share program and regulated fuel policy in stimulating fire-mitigating strategies and reducing social costs. Each subsection successively describes the optimal steady-state fuel treatment path for an individual landowner, private site values for all scenarios, social costs associated with the individual landowner's decisions, and incentive-driven reduction in social costs to reveal which incentive is more effective in approximating the socially optimal outcome. In what follows, the description of the results uses landowner $j$ as the primary landowner and $k$ as the neighboring landowner. The results of the dynamic programming model show that the maximum residuals were on the order of $10^{-11}$ times the value of the landowner's net present value, indicating that the numerical solution to the Bellman equation is accurate.

### 3.1. Base Case: Heterogeneity in Management Interests

This study considered five types of management interests ranging from being fully nonmarket-oriented to fully market-oriented. These five types are stated in this study as follows: (1) $\beta_i$ = 1: the landowner is only interested in nonmarket forest benefits, (2) $\beta_i$ = 2/3: the landowner is mostly interested in nonmarket forest benefits and partially engages in market forest benefits, (3) $\beta_i$ = 1/2: the landowner considers both forest benefits equally, (4) $\beta_i$ = 1/3: the landowner is partially interested in nonmarket forest benefits and mostly interested in marketable forest benefits, (5) $\beta_i$ = 0: the landowner is only market-oriented. With five different possible management interests for each landowner, there are twenty management-pair scenarios.

#### 3.1.1. Optimal Steady-State Risk-Mitigating Decision Level

Table 2A shows the individually optimal steady-state fuel removal levels under all twenty possible scenarios of management interests. In this table, management interests are sorted to reflect a gradual move from nonmarket- to market-oriented landowners. By reading Table 2A horizontally, each row assumes a fixed management type for landowner *j* and compares how different management options of the adjacent landowner *k* influence the optimal steady-state fuel removal levels for landowner *j*. For example, the top row of Table 2A contains the individually optimal steady-state fuel removal levels for landowner *j* who is interested only in nonmarket forest benefits given all five possible management types of the adjacent landowner *k*. Moreover, we present and discuss the level of fuel treatment as a percentage of total fuel present to facilitate the comparisons.

**Table 2.** Base case outcomes for landowner *j* given different management interests.

| | | | *k* | | |
|---|---|---|---|---|---|
| ***j*** | **$\beta$ = 1** | **$\beta$ = 2/3** | **$\beta$ = 1/2** | **$\beta$ = 1/3** | **$\beta$ = 0** |
| | (A) Individually optimal steady-state fuel treatment levels | | | | |
| $\beta$ = 1 | 29.24% | 30.31% | 30.01% | 30.08% | 30.30% |
| $\beta$ = 2/3 | 30.00% | 30.32% | 30.30% | 30.17% | 30.31% |
| $\beta$ = 1/2 | 30.03% | 30.32% | 30.33% | 30.23% | 30.53% |
| $\beta$ = 1/3 | 30.30% | 30.33% | 30.37% | 30.40% | 30.87% |
| $\beta$ = 0 | 30.45% | 30.35% | 30.49% | 30.40% | 30.98% |
| | (B) Individually optimal site values (USD/acre) | | | | |
| $\beta$ = 1 | 131.85 | 132.25 | 132.40 | 132.48 | 133.00 |
| $\beta$ = 2/3 | 132.39 | 132.53 | 132.74 | 132.81 | 133.04 |
| $\beta$ = 1/2 | 132.42 | 132.75 | 132.77 | 132.73 | 133.15 |
| $\beta$ = 1/3 | 132.73 | 132.77 | 132.81 | 133.07 | 133.44 |
| $\beta$ = 0 | 132.90 | 132.98 | 133.00 | 133.98 | 136.08 |
| | (C) Socially optimal steady-state fuel treatment levels | | | | |
| $\beta$ =1 | 78.95% | | | | |
| $\beta$ = 2/3 | 79.31% | 79.62% | | | |
| $\beta$ = 1/2 | 79.38% | 79.69% | 79.88% | | |
| $\beta$ = 1/3 | 79.38% | 79.70% | 79.83% | 80.89% | |
| $\beta$ = 0 | 79.77% | 80.04% | 80.28% | 80.84% | 80.89% |
| | (D) Socially optimal site values (USD/acre) | | | | |
| $\beta$ = 1 | 292.55 | | | | |
| $\beta$ = 2/3 | 292.71 | 293.44 | | | |
| $\beta$ = 1/2 | 292.75 | 293.86 | 294.01 | | |
| $\beta$ = 1/3 | 293.39 | 293.90 | 294.08 | 294.40 | |
| $\beta$ = 0 | 293.80 | 294.31 | 294.38 | 295.48 | 296.99 |

**Table 2.** *Cont.*

| | k | | | | |
|---|---|---|---|---|---|
| *j* | **$\beta$ = 1** | **$\beta$ = 2/3** | **$\beta$ = 1/2** | **$\beta$ = 1/3** | **$\beta$ = 0** |
| | (E) Social costs (USD/acre) | | | | |
| $\beta = 1$ | 28.84 | | | | |
| $\beta = 2/3$ | 27.93 | 28.39 | | | |
| $\beta = 1/2$ | 27.91 | 28.36 | 28.47 | | |
| $\beta = 1/3$ | 27.92 | 28.36 | 28.45 | 28.25 | |
| $\beta = 0$ | 28.00 | 28.35 | 28.39 | 27.51 | 24.82 |

Notes: $\beta$ = 1: nonmarket forest benefits only; $\beta$ = 2/3: 2/3 nonmarket forest benefits and 1/3 market forest benefits; $\beta$ = 1/2: 1/2 nonmarket forest benefits and 1/2 market forest benefits; $\beta$ = 1/3: 1/3 nonmarket forest benefits and 2/3 market forest benefits; $\beta$ = 0: market forest benefits only.

For all management types of landowner *k* and by reading Table 2A vertically, the pattern of the decision levels reveals that the differences between landowner *j*'s fuel removal rate increases as they become more market-oriented. This supports past empirical literature that found that market-oriented landowners value fuel reduction more than nonmarket-oriented landowners because of the demand for their forests' services by hunters and forest recreationists who also value fire-mitigating strategies [22]. In addition, by reading Table 2A horizontally, landowner *j*, on average, tends to increase the level of fuel removal as the management interest of their neighboring landowner *k* becomes more market-oriented. It is clear that the responsiveness of landowner *j* to decisions resulting from different management interests of their adjacent landowner is not as strong as the responsiveness toward their own management interests. Therefore, it is found that the fuel treatment decision of a landowner is more influenced by their own forest management interests than by their adjacent landowner's management interests.

### 3.1.2. Private Site Values

Table 2B reports individually optimal site values for landowner *j* given all combinations of management interests on the two adjacent parcels and assuming that landowners are fully informed about fire spillover effects. By examining Table 2B vertically, it is noticeable that the individually optimal site value for landowner *j* moderately increases as they move from being interested in nonmarket benefits only to market benefits solely, given any management interest of the neighbor *k*. However, by examining Table 2B horizontally, landowner *j*'s individual optimal site value considerably increases as the neighboring landowner *k* becomes more interested in the marketable benefits of their forest. Although the variations in the individually optimal site values are small, these variations represent a considerable amount of money for nonindustrial private landowners in the U.S. who own approximately 300 million acres of forests [32].

The highest individual site value is obtained when both landowners are totally market-oriented (the bottom right cell of Table 2B). This best outcome represents a 3.20% increase in individual value relative to the lowest obtained site value when both landowners are fully interested in nonmarket forest benefits only. This finding is consistent with our previous finding that market-oriented landowners value fuel reduction more than nonmarket-oriented landowners because of the demand for their forests' services by hunters and forest recreationists who also value fire-mitigating strategies, which results in a higher site value.

### 3.1.3. Socially Optimal Fuel Management Level, Social Site Value, and Social Costs

In order to calculate the social costs associated with individually managing a forest in the presence of wildfire risk, both adjacent parcels are assumed to be jointly managed by a social planner who simultaneously maximizes joint net returns to both parcels for all combinations of management interests. The model still assumes full information regarding fire externalities. Table 2C reports the socially optimal steady-state fuel removal levels for all combinations of landowners under different management interests. It is clear that the socially optimal levels are higher than the individually optimal levels (Table 2A) for all scenarios. However, the differences between socially and individually optimal fuel treatments do not show a clear trend, as adjacent landowners move from being interested in nonmarket forest benefits to market forest benefits.

Table 2D shows socially optimal site values for both landowners when both parcels are jointly managed by a social planner given different combinations of management purposes. Consistent with individually optimal behaviors, Table 2D shows that the socially optimal site values increase as both adjacent landowners become more market-oriented. It demonstrates that the highest social site value for the two landowners is obtained when both parcels are used for market forests benefits only, while the lowest value is attained when both parcels are utilized for nonmarket forests benefits only. Moreover, the site values under joint management are all strictly higher than the combined individually optimal site values, which confirms the existence of social costs associated with individually and separately managing forest parcels.

Table 2E reveals social costs associated with private landowner decisions considering different management preferences and is derived based on the differences between combined individually and socially optimal site values. By examining Table 2E vertically, the findings specify that social costs decrease as a landowner becomes more market-oriented given all management types of the adjacent landowner. This may be attributed to the previous finding that market-oriented landowners undertake a relatively higher level of fuel removal. On the other hand, by examining Table 2E horizontally, it is noticeable that social costs, on average, decrease as the neighboring landowner becomes more market-oriented under all scenarios of forest management interests. Therefore, the results reveal that social costs associated with the private actions of a landowner are influenced by different management interests of a neighboring landowner. The lowest social cost is obtained when both neighboring landowners are only interested in the marketable benefits of their forests. This best outcome brings about a 16.19% reduction in social cost relative to the case when both adjacent landowners only involve nonmarket-oriented forest activities, where the latter case is the highest obtained social cost.

### *3.2. Policy Instruments: Cost-Share Program*

The purpose of a policy or program is to improve outcomes or gain social benefits. In the context of fire-mitigating strategies, the government may introduce programs and regulations aimed at harmonizing individually and socially optimal fuel management choices, therefore minimizing social costs. An effective implementation of these policies could also reduce government suppression spending [2]. In this subsection, we examine incentive-based cost-share programs such as government cost-share programs where the government shares fuel treatment costs with landowners or collaborative efforts that include sharing of fuel reduction capital between the two adjacent landowners. Consistent with similar studies, a cost-share program is assumed to compensate landowners for fifty percent of fuel reduction costs.

Table 3A reports the individually optimal steady-state fuel removal levels under the cost-share program for all combinations of landowners under different management interests. It is clear that the optimal levels are considerably higher than the base case, individually optimal (Table 2A), for all scenarios. Moreover, the effectiveness of this program in encouraging fire prevention actions increases as landowner $j$ becomes more market-oriented, as well as when their neighboring landowner becomes more interested in marketable benefits of their forest. Unlike the base case and the fuel stock regulations, it is found that the fuel treatment decision of a landowner who participates in a cost-share program is significantly influenced by their own forest management interests and by their adjacent landowner's management interests.

**Table 3.** Outcomes with cost-share application for landowner *j* given different management interests.

| | | | *k* | | |
|---|---|---|---|---|---|
| *j* | **$\beta = 1$** | **$\beta = 2/3$** | **$\beta = 1/2$** | **$\beta = 1/3$** | **$\beta = 0$** |
| | (A) Individually optimal steady-state fuel treatment levels | | | | |
| $\beta = 1$ | 51.49% | 52.08% | 52.23% | 52.49% | 52.63% |
| $\beta = 2/3$ | 52.07% | 52.18% | 52.36% | 53.62% | 53.82% |
| $\beta = 1/2$ | 52.11% | 52.20% | 53.40% | 53.68% | 53.84% |
| $\beta = 1/3$ | 52.11% | 52.72% | 53.51% | 53.82% | 53.89% |
| $\beta = 0$ | 52.45% | 52.54% | 53.56% | 54.83% | 54.98% |
| | (B) Individually optimal site values (USD/acre) | | | | |
| $\beta = 1$ | 132.90 | 133.28 | 133.55 | 133.62 | 134.15 |
| $\beta = 2/3$ | 133.45 | 133.57 | 134.01 | 134.02 | 134.74 |
| $\beta = 1/2$ | 133.47 | 134.05 | 134.04 | 134.19 | 134.95 |
| $\beta = 1/3$ | 133.78 | 134.03 | 134.21 | 134.58 | 135.07 |
| $\beta = 0$ | 134.04 | 134.10 | 134.36 | 135.51 | 137.73 |
| | (C) Social costs (USD/acre) | | | | |
| $\beta = 1$ | 26.75 | | | | |
| $\beta = 2/3$ | 25.82 | 26.30 | | | |
| $\beta = 1/2$ | 25.81 | 25.76 | 25.93 | | |
| $\beta = 1/3$ | 25.82 | 25.83 | 25.66 | 25.25 | |
| $\beta = 0$ | 25.72 | 26.10 | 25.66 | 24.46 | 21.52 |
| | (D) Percentage reduction in social costs | | | | |
| $\beta = 1$ | 7.24% | | | | |
| $\beta = 2/3$ | 7.55% | 7.38% | | | |
| $\beta = 1/2$ | 7.52% | 9.16% | 8.95% | | |
| $\beta = 1/3$ | 7.54% | 8.90% | 9.82% | 10.64% | |
| $\beta = 0$ | 8.14% | 7.92% | 9.61% | 11.07% | 13.31% |

Notes: $\beta = 1$: nonmarket forest benefits only; $\beta = 2/3$: 2/3 nonmarket forest benefits and 1/3 market forest benefits; $\beta = 1/2$: 1/2 nonmarket forest benefits and 1/2 market forest benefits; $\beta = 1/3$: 1/3 nonmarket forest benefits and 2/3 market forest benefits; $\beta = 0$: market forest benefits only.

Table 3B reports individually optimal site values for landowner *j* under all management interests when the cost-share program is applied to the base case. With the cost-share program, there is an increase in the individually optimal site values for landowner *j*. Table 3C reveals social costs after compensating landowners for 50% of fuel treatment costs; these social costs are calculated based on the differences between combined individually optimal site values with the cost-share program and socially optimal site value without the cost-share discussed earlier. Findings show that social costs decrease as a result of the cost-share program. Similar to the base case, social costs decrease as a landowner becomes more market-oriented given all management types of the adjacent landowner. In addition, Table 3D reports the percentage reduction in social costs after the application of the cost-share program. The highest achieved reduction in social cost is 13.31%, which is obtained when both landowners are only interested in marketable benefits of their forests, while the lowest reduction is 7.24%, which is observed when both landowners only value natural amenities and nonmarket ecosystem services of their forests. It is obvious that, on average, the reduction in social costs increases as a landowner becomes more market-oriented. Forest managers who are interested in market forest benefits, such as hunting leases, are more likely to mitigate fire risk as they depend on their forests for income, and the demand for their forest services is influenced by fire prevention actions [22]. The interesting result is that the introduction of incentive-based cost-share programs has reaped greater social benefits with market-oriented landowners compared to nonmarket-oriented landowners.

### 3.3. Policy Instruments: Maximum Allowed Fuel Policy

A maximum allowed fuel regulation would be a parcel-level standard that requires fuel stocks on an individual parcel to not exceed a specified level in each time period. To examine this policy and based on what has been discussed in the literature, fuel stock is set not to exceed a fuel index of 40. This policy is proposed to motivate a higher level of fuel treatment through restricting the maximum fuel stock on a parcel in each time period.

For all pairs of management interests under regulated-fuel policy, the individually optimal steady-state fuel treatment levels are found constrained at 60% to comply with the regulation. Compared to the base case (Table 2A), landowner *j* almost doubles the level of fuel treatment on their parcel with fuel stock regulation. Interestingly, the level of fuel treatment under fuel stock regulation is also higher than the optimal fuel removal levels under the cost-share program; and it is closer to the social optimum but remains suboptimal. Unlike the cost-share program, and due to the homogeneous fuel removals under fuel stock regulation, there is neither a clear responsiveness of landowner j toward their own management interests nor toward decisions resulting from different management interests of their adjacent landowner.

With fuel stock regulation, the increases in individually optimal site values (Table 4A) for landowner j are higher than the case with the cost-share program (Table 3B), and both are higher than that of the base case (Table 2B). Consistently, the decline in social costs is greater with the application of a maximum allowed fuel policy (Table 4B) than with the cost-share program (Table 3C), and both policies yield a reduction in social costs compared to the base case (Table 2E).

**Table 4.** Outcomes with regulated fuel stock for landowner *j* given different management interests.

| | | | *k* | | |
|---|---|---|---|---|---|
| ***j*** | **$\beta = 1$** | **$\beta = 2/3$** | **$\beta = 1/2$** | **$\beta = 1/3$** | **$\beta = 0$** |
| | (A) Individually optimal site values (USD/acre) | | | | |
| $\beta = 1$ | 132.98 | 133.36 | 133.64 | 133.71 | 134.25 |
| $\beta = 2/3$ | 133.54 | 133.66 | 134.10 | 134.10 | 134.84 |
| $\beta = 1/2$ | 133.56 | 134.14 | 134.13 | 134.28 | 135.88 |
| $\beta = 1/3$ | 133.88 | 134.13 | 134.30 | 134.68 | 135.17 |
| $\beta = 0$ | 134.14 | 134.25 | 134.46 | 135.63 | 138.03 |
| | (B) Social costs (USD/acre) | | | | |
| $\beta = 1$ | 26.59 | | | | |
| $\beta = 2/3$ | 25.64 | 26.12 | | | |
| $\beta = 1/2$ | 25.64 | 25.58 | 25.74 | | |
| $\beta = 1/3$ | 25.63 | 25.63 | 25.47 | 25.05 | |
| $\beta = 0$ | 25.52 | 25.80 | 25.46 | 24.22 | 20.92 |
| | (C) Percentage reduction in social costs | | | | |
| $\beta = 1$ | 7.80% | | | | |
| $\beta = 2/3$ | 8.20% | 8.00% | | | |
| $\beta = 1/2$ | 8.15% | 9.78% | 9.59% | | |
| $\beta = 1/3$ | 8.20% | 9.61% | 10.49% | 11.35% | |
| $\beta = 0$ | 8.85% | 8.98% | 10.31% | 11.95% | 15.72% |

Notes: $\beta = 1$: nonmarket forest benefits only; $\beta = 2/3$: 2/3 nonmarket forest benefits and 1/3 market forest benefits; $\beta = 1/2$: 1/2 nonmarket forest benefits and 1/2 market forest benefits; $\beta = 1/3$: 1/3 nonmarket forest benefits and 2/3 market forest benefits; $\beta = 0$: market forest benefits only.

Table 4C reports the percentage reduction in social costs with fuel stock regulation for different management interests. The highest achieved reduction in social cost is 15.72%, which is obtained when both landowners are only interested in marketable benefits of their forests, while the lowest reduction is 7.80%, which is observed when both landowners only value natural amenities and nonmarket ecosystem services of their forests. Similar to the case of the cost-share program, the reduction in social costs increases as a landowner becomes more market-oriented. However, the reduction in social costs is considerably greater after a maximum allowed fuel policy is applied to the base case compared to the cost-share program application. For example, considering market-oriented landowners, there is a 13.31% reduction in social costs with the application of the cost-share program, while the reduction in social costs with fuel stock regulation is 15.72%. Therefore, market-oriented adjacent landowners are more responsive to policy instruments compared to other types on neighboring landowners, and fuel stock regulations can guarantee lower fuel stocks than standard cost-share programs can incentivize.

## 4. Conclusions

Spatial externalities link neighboring forest landowners; specifically, fire prevention actions on an individual parcel decreases expected fire damages on the individual and adjacent parcel. This study developed a stochastic dynamic model for two adjacent landowners to evaluate the interaction of fuel treatment decisions for two adjacent landowners under various scenarios of forest benefits and to examine how different forest management interests might yield private outcomes that deviate from socially optimal decisions. The study then investigated the potential effects of a cost-share program and fuel stock regulation on mitigating fire damages and associated costs through motivating higher levels of fuel treatment. The derived model in this study adds insight into how different forest management interests affect fuel management decisions, associated social costs, and the effectiveness of policies. Examining the effectiveness of policies under a wide variety of scenarios regarding management interests is a unique contribution of this study. While previous studies have only accounted for differences in landowner knowledge, this study considered heterogeneity in economic parameters and landowner characteristics that influence decisions, which are impossible to alleviate simply by educating landowners.

The analysis revealed that different types of forest valuation (market and nonmarket forest benefits) influence fire prevention actions. Broadly, the market-oriented landowner tends to implement a higher level of fuel removal. This tendency increases when their adjacent landowner also becomes market-oriented. Market-oriented landowners have an extra incentive to undertake fuel treatment from hunters and forest recreationists who also value fire-mitigating strategies. Therefore, social costs associated with adjacent market-oriented landowners are lower relative to landowners who only consider nonmarket value.

The findings indicated that forest management interests significantly affect the outcomes of policies. Social costs are significantly reduced after the implementation of a cost-share program and maximum allowed fuel policy in the case of market-oriented landowners. In addition, a maximum allowed fuel policy was revealed to sufficiently force landowners to increase the level of fuel removal compared to the cost-share program. In the context of heterogeneous landowners, a uniform maximum fuel stock helps to mitigate some of the impacts of heterogeneous incentives, unlike the cost-share program that has greater social benefits with market-oriented landowners compared to nonmarket-oriented landowners. Policymakers may introduce extra financial incentives or more rigorous fuel regulations to induce nonmarket-oriented landowners to undertake increased fuel management activities.

This study could be extended to investigate the effectiveness of incentive-based policies and fuel regulation in the context of multiple landowners, or different landscape attributes such as wind speed and parcel size, or insurance programs. Additional research is needed to examine the interaction between nonindustrial and industrial landowners, and to simultaneously account for fire and hurricane risks. Lastly, this modeling exercise assumed perfect enforcement of the fuel stock regulation. In reality, monitoring and enforcement would be costly. In such circumstances, the cost-share program could be as effective as the fuel stock regulation because it incentivizes removal with less dependence on enforcement.

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