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Evaluating Incentive-Driven Policies to Reduce Social Losses Associated with Wildfire Risk Misinformation

Ibtisam Al Abri

Department of Natural Resource Economics, Sultan Qaboos University, Muscat 123, Oman; ialabri@squ.edu.om

Abstract: Wildfires have caused significant ecological and social losses in terms of forest benefits, private dwellings, and suppression costs. Although great efforts have been made in wildfire policies and wildfire-mitigating strategies on private and public lands, devastating wildfires continue to occur. This implies there is a need for effective incentive-driven policies to encourage forest owners to undertake an increasing level of wildfire-mitigating actions. This study evaluates the effectiveness of alternative incentive-driven policies for the problem of two adjacent forest owners under various scenarios of misinformation about wildfire occurrence and spread using a stochastic dynamic model. The study also investigates how the implementation of these policies encourages wildfire-mitigating actions, yields larger reductions in social losses, and alleviates free-riding behavior. The outcomes of the analysis confirm that the effectiveness of incentive programs in reducing social losses and increasing forest value is influenced by the level of misinformation held by a forest owner when making wildfire prevention decisions. The results also revealed that fuel stock regulation is more effective at mitigating wildfire damages and associated costs than cost-share programs under all misinformation scenarios. It was also found that fuel stock regulation could correct free-riding behavior due to the restrictive nature of this policy. The findings provide additional motivation for educational programs that seek to improve forest owners' knowledge about the private benefits of fuel removal and collaboration efforts between neighboring forest owners. Collaborative efforts could yield substantial savings for the government through eliminating cost-share programs and reducing suppression costs.

Keywords: incentive programs; social losses; risk misinformation; wildfire management; forest benefits; stochastic dynamic model

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1. Introduction

The number of catastrophic, uncharacteristically severe, and uncontrollable wildfires has dramatically increased in recent years. Wildfires have continuously caused considerable ecological and social losses in terms of marketable and non-marketable forest benefits, private dwellings, and suppression costs [1,2]. Intense wildfires such as these are not unusual, especially for the United States. Although improvements have occurred over time in wildfire policies and wildfire-mitigating strategies on private and public lands, devastating wildfires continue to occur [3]. Despite warnings about wildfire threats, few forest owners preemptively use controlled fires to reduce the probability of wildfires [4]. In the U.S., wildfires burned more than 10 million acres in 2020 [5]. In addition to financial losses from damages, government wildfire protection costs have substantially risen from less than $1 billion annually in the 1990s to an average of $3 billion per year [6], with recent years on a trajectory to becoming the costliest years on record [5]. Unless policymakers develop more programs and tools to educate and encourage forest owners to make informed management decisions, wildfire suppression costs and wildfire damages will continue to rise in the future.

Two main factors play a significant role in increasing the intensity and size of wildfires in the U.S.: harsh weather conditions and accumulated fuels [7]. Accumulated surface fuels and the presence of ladder fuels increase the spread of wildfire, make crown wildfires more probable, and increase pine mortality [8]. If left unmanaged, the accumulation of these highly flammable fuels will create intense wildfires that are more likely to cause the death of economically valuable forests trees [9–13]. Furthermore, if a wildfire is ignited in the presence of high fuel loads, it is more likely to spread to neighboring stands even if those stands receive some fuel management [7]. Thus, the type, location, moisture content, and density of surface-level fuels as well as weather conditions drive the resulting damages from forest wildfires [14]. Since high temperatures and dry conditions increase the probability and severity of wildfires, some parts of the U.S. will likely experience an increasing climatic wildfire risk over the next 40 to 50 years [15,16].

Wildfire-mitigating activities, such as prescribed burns, can be used to mitigate damages from forest wildfires by reducing fuels in the understory [17]. Thinning and debris removal are also effective management tools, but they are usually more expensive than prescribed burns and are time-intensive [18]. In some regions of the U.S., forest owners can sell the harvested vegetation resulting from thinning to markets such as the woodchip market to offset management costs [19].

Motivations for owning tracts of forest are diverse, including aesthetics, privacy, hunting, recreation, and nature protection. About 16% of private forest owners hold forest for timber production, and this represents just over 40% of private forests [20]. With diverse reasons for owning forest, including many non-commercial reasons, one might expect wildfire prevention efforts to also vary substantially. Among the possible concerns that non-industrial private forest landowners (NIPFLs) have about their forest, wildfires are the most common concern, but still, 45% of NIPFLs do not see wildfires as a concern [20]. Only 8% of NIPFLs have a written forest management plan [21]. Based on studies, prescribed fires were implemented on about 6.5 million acres of southern forests in 2011, representing about 82% of all acres nationally with prescribed burns that year, but only about 0.03% of forested land in the south [21,22]. In this study, non-industrial private forest landowners (NIPFLs) are referred to as forest owners for clarity and simplicity.

Forests contribute a substantial portion of the nation's timber production, and forest owners play a large role in this production and forest management in the country [23]. Thus, improving individual forest owners' perceptions about forest wildfire risk and wildfire-mitigating strategies and increasing their overall fuel management effort has the potential to have a large impact on the timber industry's profitability and sustainability. These improvements would also decrease the public costs associated with forest wildfire damages and control. National agencies have recognized the need to implement increased fuel management across forested land in the U.S. to protect valuable timberland as well as rural communities and communities in the wildland–urban interface [24]. Therefore, there is a need to better understand forest owners' decision-making processes and potential reactions to wildfire management policies. This information would allow policymakers to implement programs that would reduce the severity of wildfires, the resultant damages, and wildfire suppression costs, and improve the region's ability to profitably and reliably supply timber. In addition, such programs could potentially reduce free-riding behavior among neighboring forest owners. A forest owner tends to free ride on the fire-mitigating actions of his neighboring forest owners, as these actions have positive cross-boundary externality [25–28]. Given the possibility of fire spread between two adjacent forests, a forest with sufficient fuel management may contribute to fire prevention in a neighboring forest. The presence of a positive externality of such preventative action suggests that individual forest owners may implement less wildfire-mitigating actions than is socially optimal when considering the benefits to the whole region [26].

Since wildfire-mitigating actions are costly, a forest owner may choose to participate in government-funded fuel management cost-share programs or collaborate with neighboring forest owners to mitigate the cost of fuel treatment. This study evaluates two main incentive-driven policies to reduce the social losses associated with wildfire risk misinformation about wildfire externalities. The first policy instrument is a cost-share program in which the government shares wildfire-mitigating actions' costs with forest owners or two adjacent forest owners share the wildfire-mitigating capital to reduce the cost, which is a form of collaboration effort [29–33]. The second policy instrument is the government regulating the fuel stock amount on an individual forest, preventing it from exceeding a certain level.

This study seeks to inform policymakers about possible incentive programs that would induce increased fuel management among forest owners and inform forest owners about their optimal fuel management decisions. Both of these features should encourage increased fuel management, reducing free-riding behavior, lessening the risk of catastrophic wildfires, and creating more resilient, wildfire-adapted forests. In addition, although the derived model in this study is parameterized for a standard forest in the U.S., it is applicable to many forests across the world that are prone to forest fire [34]; for example, the Mediterranean pine forests [35], the boreal conifers of Europe, Russia, and Canada [36], and Australian eucalypts [37].

The first objective was to utilize a stochastic dynamic model based on the models derived by Al Abri and Grogan [26,27] to assess the linkage of wildfire-mitigating decisions for two adjacent forest owners, considering heterogeneity in the forest owners' perceptions of the risk of wildfire occurrence and spread between adjacent forests. Misinformation about wildfires could occur due to incomplete knowledge about potential wildfire size and spread across borders [25] or a misunderstanding of the connection between wildfire behavior and forest vegetation [38]. Al Abri and Grogan [26] investigated how misinformation about wildfire externalities could result in fire-mitigating actions that are not in line with socially optimal levels; however, they did not consider incentive-driven programs to encourage increased wildfire-mitigating strategies to approximate optimal outcomes. Al Abri and Grogan [27] evaluated the effectiveness of incentive-based programs at reducing social losses for different forest ownership interests, but they assumed that the forest owners were perfectly informed about wildfire externalities. In addition, earlier models by Crowley et al. [39] and Busby et al. [25] accounted for parallel motivating policies for various misinformation about wildfire probability. However, Crowley et al. [39] used a Faustmann model that allows the forest owner to undertake wildfire-mitigating action only one time in a rotation. Further, their model presumed that the wildfire occurrence ratio is negatively related to the amount of fuel removal, not the fuel accumulation in the forest. On the other hand, Busby et al. [25] derived a dynamic model for neighboring forests and examined different causes of misinformation; however, the likelihood of wildfire occurrence was presumed fixed and their model reported the timing and frequency of fuel removal without considering the level of such treatment.

Unlike previous studies, this study contributes to the literature by evaluating the effectiveness of alternative incentive-driven policies for the case of two neighboring forest owners, considering various scenarios of misinformation about wildfire externalities (occurrence and spread), using a stochastic dynamic model. Moreover, this study models the wildfire occurrence and spread ratios while integrating the impact of fuel load on and across neighboring forests. The study also contributes by considering heterogenous forest owners in terms of different levels of misinformation while examining the effectiveness of a certain program.

The second objective of the study was to assess the effectiveness of implementing incentive-driven programs and investigate how the implementation of these programs encourages an increasing level of wildfire-mitigating actions, yields larger reductions in social losses, and alleviates free-riding behavior. This included analyzing which policies result in individually optimal decisions that most closely align with socially optimal decisions. Deriving individually optimal wildfire-mitigating strategies after implementing alternative incentive-driven programs would disclose which program is more likely to approximate the socially optimal strategy, thus controlling the free-riding potential and increasing the forest economic value.

The third objective of this study was to inform state and federal policymakers and agencies about categories of forest owners who may need larger incentives to adopt wildfire mitigation strategies and how various incentives are likely to affect private forest owners so that funds can be spent effectively and efficiently.

The study investigated a two-forest-owner problem for which forest owners have different levels of misinformation about wildfire externalities. The model accounted for forest owners who are perfectly and partially informed about wildfire occurrence and spread, as well as forest owners who are completely unaware of wildfire externalities. The study also considered two kinds of forest benefits: market gains such as priced recreation and hunting access, and non-market gains such as non-priced recreation and landscape amenity. The utilized model included a baseline that assumed both forests were jointly managed by a social planner to socially optimize the total rent across the forests. This baseline was utilized for comparison purposes so as to identify the gaps between the socially and individually optimal wildfire-mitigating actions, considering heterogeneous information levels held by forest owners in terms of wildfire occurrence and spread. Next, the analysis introduced incentive-driven programs to quantify the total social gain or loss for each program, and determine which incentive is more effective in approximating the socially optimal wildfire-mitigating strategies.

2. Materials and Methods

The utilized stochastic dynamic model reflects an interaction between two neighboring forest owners (labeled by $i \in [m, n]$) who manage wildfire-prone forests simultaneously and value both marketable and non-marketable forest benefits. Adjacent forests face the risk of wildfire occurrence as well as wildfire spread from one forest to an adjacent forest. The connections between forest owners occur through the probability of wildfire occurrence and the likely wildfire spread across forests. It is necessary to account for these channeling stochastic variables to determine the effectiveness of incentive-driven policies such as cost-sharing programs and fuel regulation where the gains from participation in a certain program would be attained. Disregarding such channels may not motivate participation in incentive-driven programs due to the underestimation of such programs' benefits, which would yield a suboptimal fuel treatment. This study simultaneously examined the behavior of two neighboring forests owners to derive the optimal reaction functions in a Nash equilibrium framework using a stochastic dynamic model. The derived reaction functions are capable of determining both the individually and socially optimal outcomes.

Stochastic Dynamic Model of a Wildfire-Prone Forest and Data Sources

The derived model included a continuous state variable, forest biomass s_{it}. The forest owner's wildfire-mitigating action was modeled by a continuous action variable, $x_{it} \in [0, s_{it}]$. Fire occurrence is a stochastic binary variable and was represented in the model as $\theta_{it} \in [0, 1]$. The spread rate of wildfires (φ_{it}) generated an externality between the two neighboring forests. The wildfire spread ratio specified the linkage between fuel load and wildfire-mitigating strategies across adjacent forests. Consistent with previous studies, the wildfire occurrence ratio was characterized by a Poisson distribution [39–41] and modeled as in the research by Al Abri and Grogan [26,27], as specified in Table 1.

The optimal solution to this forest optimization problem can be specified by linking the state variable (s_{it}), the action variable (x_{it}) for each forest owner (m, n), and the rent and transition functions into a set of simultaneous, discrete-time, stochastic dynamic Bellman equations for an infinite sequence of future periods:

$$V_m\{s_m, s_n, \theta, \varphi\} = \max_{x_m}\left(l_{mt}(s, \theta, \varphi, x) + \delta E_{\tilde{\theta}} V(s_{m,t+1}, s_{n,t+1})\right) \quad (1)$$

$$V_n\{s_n, s_m, \theta, \varphi\} = \max_{x_n}\left(l_{nt}(s, \theta, \varphi, x) + \delta E_{\tilde{\theta}} V(s_{n,t+1}, s_{m,t+1})\right) \quad (2)$$

The set of simultaneous Bellman equations characterizes a discrete-time Markov decision model in which the optimal policy path is a sequence of reactions the forest owner undertakes in period t if the process is in state j to maximize the expected value of current ($l_{mt}(s, \theta, \varphi, x)$) and future ($\delta E_{\tilde{\theta}} V(s_{m,t+1}, s_{n,t+1})$) net benefits. Bellman's Principle of Optimality [42] was applied to evaluate the discrete-time Markov decision type of problem and is expressed as follows: "An optimal policy has the property that, whatever the initial state and decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision." The Bellman equation describes the trade-offs between the immediate and expected future rents that a rational, forward-thinking forest owner faces in order to attain the dynamically optimal net benefit [43]. The risk of wildfire occurrence and spread externalities were integrated into Equations (1) and (2) by modeling the probability of wildfire arrival and the spread ratios as an increasing function of fuel accumulation, as shown in Table 1.

The socially optimal solution of wildfire-mitigating strategies can be derived by supposing that both neighboring forests are administered by a social planner who fully considers all benefits and expenses presented in the whole landscape according to:

$$V_{sp} = \max_{x_m, x_n} \left(l_{mt}(s,\theta,\varphi,x) + l_{nt}(s,\theta,\varphi,x) + \delta E_{\widetilde{\theta}} V(s_{m,t+1}, s_{n,t+1}) + \delta E_{\widetilde{\theta}} V(s_{n,t+1}, s_{m,t+1}) \right) \quad (3)$$

The current net rent received by forest owner i, $l_{it}(s,\theta,\varphi,x)$, comes from the total market ($u_{it}(s_{it})$) and non-market ($g_{it}(s_{it})$) benefits, depending on the fuel load present in the forest and the total costs, which include the cost of maintaining the forest (c_1), the cost of fuel removal (c_2), and the cost of replanting after wildfire (c_3).

The net rent was determined by the forest biomass, the wildfire occurrence, the wildfire spread ratio, and the wildfire-mitigating actions. If a wildfire occurs ($\theta = 1$), the forest owner obtains the salvaged forest value and replants immediately. In the absence of a wildfire ($\theta = 0$), the forest owner receives the following rent, which is impacted by the undertaken wildfire-mitigating treatments:

$$l_{it}(s,\theta,\varphi,x) = \begin{cases} [u_{it}(s_{it}) + g_{it}(s_{it})] - c_1 - c_2 & \theta_{it} = 0, \varphi_{it} = 0, x_{it} \in [0, s_{it}] \\ (1 - D_{it,total})[u_{it}(s_{it}) + g_{it}(s_{it})] - c_1 - c_2 - (D_{it,total})c_3 & \theta_{it} = 1 \; or \; \varphi_{it} = 1 \end{cases} \quad (4)$$

where $(1 - D_{it,total})$ is the salvaged proportion of the forest if a wildfire occurs, depending on the total potential wildfire damages to the forest ($D_{it,total}$), as detailed in Table 1. Considering the implementation of incentive-driven policies, if a forest owner participates in incentive-based cost-share programs and given the operating costs, this study assumes that engagement in collaborative efforts between two adjacent forest owners could save up to 50% of the total wildfire mitigation costs. This assumption is based on the reported costs associated with the fuel removal process by Schaaf et al. [44], Dubois et al. [45], and Bolding et al. [46]. On the other hand, if a forest owner follows fuel stock regulations, the fuel stock in the forest must not exceed a certain amount imposed by an authority or exogenous forest-owner association. Table 1 describes and lists the model parameter values and variable functional forms along with the sources used in the numerical analysis. The simulation was parameterized for a standard forest in the southeastern United States. The derived Bellman equations do not have a closed-form solution due to the specification of functional equations and endogeneity. Therefore, this study followed the work of Miranda and Fackler [38] and used a collocation method as an approximation to solve the Bellman equation; specifically, it implemented the *gamesolve* routine found in the COMPECON library using MATLAB_R2017a. The derivation of the model and the numerical solution of this study follows the work of Daigneault et al. [47], Al Abri and Grogan [26,27], and Al Abri [48].

Table 1. Optimization model specification, functional forms, and data sources for a forest in the Southeastern U.S.

Description	Specification	Parameter Value per Acre	Data Sources
Discount factor	δ	0.95	[40,41]
Annual forest biomass growth	$k(s_{it}) = \omega_0 {s_{it}}^{(\omega_1)}$	$\omega_0 = 1$, $\omega_1 = 0.93$	[26,47]
Value of amenities	$u_{it}(s_{it}) = \kappa_1(\omega(s_{it}) - \kappa_2)^2 + \kappa_3$	$\kappa_1 = -0.008, \kappa_2 = 80,$ $\kappa_3 = 50, \omega = 30$	[49]
Average consumer surplus (CS)	$CS_{it} = \alpha_0 + \alpha_1 s_{it} + \alpha_2 s_{it}^2$	$\alpha_0 = -2.97\$/UD,$ $\alpha_1 = 0.24,\ \alpha_2 = -0.00017$	[50]
Average user days (UD)	$UD_{it} = v_0 + v_1 s_{it} + v_2 s_{it}^2$	$v_0 = 9.32$ days/year, $v_1 = 0.24,\ v_2 = -0.0002$	[50]
Periodic maintenance cost	c_1	\$10	[51]
Replanting cost after wildfire	c_3	\$122.4	[40,41]
Fuel removal cost	$c_2 = c_{fix} + c_{\text{var}}(x_{it})$	$c_{fix} = \$5, c_{\text{var}} = \$100$	[40,41]
Individual damage function	$D_{it} = e^{-\left(\frac{0.1}{s_{it}}\right)}$		[26,27,39]
Total potential damage function	$D_{mt,total} = \theta_{mt} D(s_{mt}) + \theta_{nt} \varphi_{\mathbf{n}\rightarrow m,t}(s_{nt}) D(s_{mt})$		[26,27]
Wildfire probability	$\lambda(\gamma, s_{mt}, s_{nt}) = 1 - e^{-\gamma\left(\frac{k(s_{mt})+k(s_{nt})}{W}\right)}$	$\gamma = 0.04,\ W = 50$	[26,27,34]
Wildfire spread ratio	$\phi_{\text{n}\rightarrow m,t} = 1 - e^{-0.93(f_{n,t})^{0.93}}$		[26,27]

Notes: Specification and parameterization have been tested over the range of values observed in the simulation.

3. Results and Discussion

The result section is divided into three main parts. The first part presents the baseline scenario for different levels of misinformation for the two adjacent forest owners as well as the socially optimal levels of wildfire-mitigating strategies, social forest value, and resultant social losses. The second and third parts of this section respectively assess the effectiveness of the cost-share program and regulated fuel policy for motivating additional wildfire-mitigating activities, thus mitigating social losses. Each part successively discusses the optimal steady-state wildfire-mitigating strategies for all scenarios, private forest values, social losses associated with the individual forest owner's actions, and incentive-driven drop in social losses to determine the most effective incentive for approximating the best social solution. Furthermore, the discussion uses forest owner m as the primary forest owner and n as the adjacent forest owner. The reported residuals of the model were on the order of 10^{-10} times the value of the forest owner's net present value, thus signifying an accurate solution to the Bellman equation.

3.1. Baseline: Heterogeneity in Misinformation

This study investigates various sources of misinformation about wildfire spillover effects represented by the wildfire occurrence ratio (θ_{it}) and wildfire spread ratio (φ_{it}) between two adjacent forests. Four different groups of misinformation were considered in this study: (i) fully misinformed: forest owner m is completely misinformed about wildfire spillover effects, thus ignoring the actions of the neighboring forest owner; (ii) partially informed (1): forest owner m is aware of wildfire spillover effects through the probability of wildfire occurrence only; (iii) partially informed (2): forest owner m is aware of wildfire spillover effects through the probability of wildfire spread only; and (iv) fully informed: forest owner m is completely informed about wildfire spillover effects through both the wildfire occurrence ratio and the wildfire spread ratio. In summary, the first group represents a fully unaware forest owner about wildfire externalities, the second and third groups are partially aware forest owners, and the fourth group signifies a fully aware forest owner. In the following table headings, these various levels of misinformation are sorted to expose a gradual move from being fully misinformed to fully informed forest owners. By evaluating tables horizontally, each row represents a specific level of misinformation for forest owner m and compares how different misinformation alternatives of the adjacent forest owner n influences the optimal steady-state wildfire-mitigating strategy levels for forest owner m. In total, there are sixteen misinformation-pair scenarios based on the four groups of misinformation levels a forest owner may experience.

3.1.1. Optimal Steady-State Wildfire-Mitigating Strategy Levels

Table 2A illustrates the individually optimal steady-state wildfire-mitigating strategy levels for all sixteen potential scenarios of misinformation. To facilitate the comparison, the levels of wildfire-mitigating strategies are presented and discussed as a percentage of the total fuel present in the forest. Mainly, the results indicate that the responsiveness of forest owner m is more toward his own awareness level than to his neighboring forest owner n's level of awareness about wildfire externalities. Surprisingly, forest owner m tends to reduce his risk-mitigating actions as his information about wildfire spillover effects increases. This finding uncovers the free-riding potential between neighboring forest owners. Free riding between adjacent forest owners has been found in previous studies (see [26,39]). Risk-mitigating actions can be attributed as a public good; one forest owner's wildfire-mitigating strategies provide gains to neighboring forest owners. The utilized model in this study has clearly accounted for such gains through the wildfire occurrence ratio, the wildfire spread ratio, and the salvageable part of the forest after a wildfire. Consequently, Table 2 displays a lower risk-mitigating action level for completely informed forest owners relative to partially informed and non-informed. On the other hand, by examining Table 2 vertically, there is a slight increase in the risk-mitigating action level of forest owner m as his adjacent forest owner n becomes more informed about wildfire externalities, as the latter also tends to free ride. This indicates there is a mutual free-riding potential between forest owners, which forces both forest owners to undertake a slightly higher level of wildfire-mitigating strategies in order to offset to some extent the decline in the wildfire-mitigating actions in the adjacent forest. Another interesting result is that when a forest owner is completely misinformed about the cross-forest benefits, he does not react to any variations in his neighbor's actions. Although the changes in wildfire-mitigating strategies may seem small, such differences have a considerable impact on individual forest value, and thus social losses, as shown below.

Table 2. Baseline outcomes for forest owner m given different misinformation scenarios.

	Forest Owner n			
Forest Owner m	**Fully Misinformed**	**Partially Informed (1)**	**Partially Informed (2)**	**Fully Informed**
(A) Individually optimal steady-state wildfire-mitigating strategy levels				
Fully Misinformed	44.12%	44.11%	40.12%	40.12%
Partially Informed (1)	41.86%	41.82%	41.81%	41.81%
Partially Informed (2)	40.88%	40.88%	40.89%	30.90%
Fully Informed	37.61%	37.63%	37.64%	37.68%
(B) Individually optimal forest values ($/acre)				
Fully Misinformed	135.17	133.02	131.83	130.97
Partially Informed (1)	129.16	129.00	130.17	130.39
Partially Informed (2)	132.40	133.97	134.41	136.66
Fully Informed	140.09	141.23	143.04	146.50
(C) Social losses ($/acre)				
Fully Misinformed	28.96			
Partially Informed (1)	40.97	41.29		
Partially Informed (2)	34.50	31.35	30.48	
Fully Informed	19.12	16.84	13.22	6.31

Notes: fully misinformed: forest owner m is completely misinformed about wildfire spillover effects; partially informed (1): forest owner m is aware of wildfire spillover effects through the probability of wildfire occurrence only; partially informed (2): forest owner m is aware of wildfire spillover effects through the probability of wildfire spread only; and fully informed: forest owner m is completely informed about wildfire spillover effects.

3.1.2. Private Individual Forest Values

The private forest value for each misinformation scenario was found using a two-step process. First, the forest owner's optimal wildfire-mitigating strategy decisions, given the misinformation scenario, were determined. Second, the original Bellman equation was evaluated with both spatial externalities present, using the forest owner's optimal decisions obtained in the first step.

Table 2B shows individually optimal forest values for forest owner m given all combinations of misinformation scenarios on the two neighboring forests and assuming that the forest owners are interested in both marketed and non-marketed forest benefits. By investigating Table 2B horizontally, the findings reveal that the individually optimal forest value for forest owner m improves as his adjacent forest owner becomes more informed, except in the case of full misinformation due to the free-riding potential as discussed earlier. Similarly, with a vertical row comparison, the outcomes indicate that, on average, the forest value of forest owner m increases as he becomes more informed. Although the differences in the individually optimal forest values seem minimal, these differences are considerable given that non-industrial private forest landowners (NIPFLs) in the U.S. own about 300 million acres of forests [52].

The highest individual forest value was attained when both forest owners were fully informed. This best outcome demonstrated an 8.40% growth in individual value compared to the case when both adjacent forest owners are completely uninformed. Moreover, the highest forest value displayed a 13.60% rise in individual forest value relative to the lowest attained value. This emphasizes that failure to consider cross-stand gains of risk-mitigating strategies results in the lowest individual forest value.

3.1.3. Socially Optimal Risk-Mitigating Decision Level, Social Forest Value, and Social Losses

To determine the social losses related to individually managing a forest under wildfire externality, both neighboring forests were presumed to be jointly administered by a social planner who simultaneously maximizes joint forest values, considering all combinations of misinformation scenarios. The results showed that the socially optimal steady-state risk-mitigating level was observed to be 78.50% of the total fuel biomass of the forest and the optimal social forest value was $299.30 per acre. Based on optimal social outcomes, Table 2C shows the social losses associated with private forest owner actions for different misinformation scenarios, which was calculated based on the differences between the combined individually and socially optimal forest values. By examining Table 2C, on average, the results demonstrate that the social losses of a forest owner decrease as he becomes more knowledgeable about wildfire externalities and as his neighbor's knowledge about wildfire spillover effects increases. The social loss is minimized when both adjacent forest owners are completely informed about wildfire externalities. This minimum value led to a 78.20% decline in social losses compared to the full misinformation case (both forest owners are uninformed) and created an 85.50% decline in social losses relative to the highest attained social loss (forest owner m is misinformed about wildfire spread ratio). This result is vital for policymakers, implying that educating forest owners about wildfire spillover and particularly cross-forest effects of risk-mitigating actions could lead to a substantial diminishing of free-riding behavior and the resultant social losses. Beyond educational programs, and particular to misinformation issues, forest owners could become more incentivized to undertake an increasing level of risk-mitigating actions if they were offered financial incentives (cost-share program) or more firm regulations (fuel stock regulation). Next, this study examined the effectiveness of these incentive programs at inducing increased risk-mitigating actions and alleviating free-riding potentials, thus reducing social losses and increasing forest value, which is a novel contribution of this study.

3.2. Policy Instruments: Cost-Share Program

Policymakers tend to implement outcome-targeted programs to improve economic and social gains and minimize the consequences of contemporary risks. In an attempt to reduce economic and social losses from wildfire risk, policymakers could initiate programs and regulations intended to match individual and social optimal decisions. In this subpart, the study investigated incentive-based cost-share programs where the government shares risk-mitigating action costs with forest owners or forest owners are involved in collaborative efforts such as the sharing of wildfire-mitigating capitals. Consistent with previous studies, a cost-share program is designed to compensate forest owners for 50% of wildfire-mitigating action costs.

Table 3A shows the individually optimal steady-state risk-mitigating strategy levels under the cost-share program for all groups of misinformation scenarios. It is obvious that, relative to the baseline (Table 2A), the optimal levels of risk-mitigating actions noticeably increased after the implementation of the cost-share program under all scenarios. In addition, the increase was considerably higher when both forest owners were misinformed of wildfire spillover effects. The effectiveness of this program in incentivizing wildfire risk-mitigating actions increased as forest owner *m* became more misinformed, which is consistent with the free-riding behavior found in the baseline scenario. Similar to the baseline, it was also observed that the actions of a forest owner who is involved in a cost-share program were significantly induced by their own awareness level, but marginally influenced by their neighboring forest owner's awareness level.

Table 3. Optimal solutions with cost-share application for forest owner *m* for different misinformation scenarios.

	Forest Owner n			
Forest Owner m	**Fully Misinformed**	**Partially Informed (1)**	**Partially Informed (2)**	**Fully Informed**
	(A) Individually optimal steady-state wildfire-mitigating strategy levels			
Fully Misinformed	58.83%	58.81%	58.81%	58.81%
Partially Informed (1)	56.13%	56.18%	56.19%	56.18%
Partially Informed (2)	55.68%	55.69%	55.69%	55.69%
Fully Informed	51.13%	51.18%	51.21%	51.22%
	(B) Individually optimal forest values ($/acre)			
Fully Misinformed	136.58	134.92	133.85	132.99
Partially Informed (1)	131.59	130.92	132.31	132.96
Partially Informed (2)	134.82	136.14	136.55	139.18
Fully Informed	142.01	143.36	145.00	147.70
	(C) Social losses ($/acre)			
Fully Misinformed	26.13			
Partially Informed (1)	36.12	37.46		
Partially Informed (2)	29.66	27.01	26.20	
Fully Informed	15.28	12.58	9.29	3.91
	(D) Percentage reduction in social losses			
Fully Misinformed	9.77%			
Partially Informed (1)	11.84%	9.29%		
Partially Informed (2)	14.03%	13.84%	14.07%	
Fully Informed	20.11%	25.32%	29.75%	38.05%

Notes: fully misinformed: forest owner *m* is completely misinformed about wildfire spillover effects; partially informed (1): forest owner *m* is aware of wildfire spillover effects through the probability of wildfire occurrence only; partially informed (2): forest owner *m* is aware of wildfire spillover effects through the probability of wildfire spread only; and fully informed: forest owner *m* is completely informed about wildfire spillover effects.

By considering different misinformation scenarios, Table 3B presents individually optimal forest values for forest owner *m* when the cost-share program is implemented to the baseline. The individually optimal forest values for forest owner *m* moderately increased for all combinations of misinformation scenarios. Table 3C shows the social losses for different misinformation scenarios after the implementation of the cost-share program, which was derived by calculating the differences between the combined individually optimal forest values with the cost-share program and the socially optimal forest values without the cost-share program. When the cost-share program was introduced to the baseline, social losses clearly decreased. Moreover, Table 3D shows the percentage reduction in social losses after the implementation of the cost-share program. Generally, the reduction in social losses increased as a forest owner became more informed and as his adjacent forest owner became more informed about wildfire externality effects. The greatest reduction in social losses was 38.05% and was obtained when both forest owners had complete information about wildfire spillover effects. On the other hand, when both forest owners were fully misinformed about wildfire externalities, the obtained reduction in social losses was small (9.77%). The interesting result is that introduction of incentive-based cost-share programs has achieved greater social gains by more than 28% with fully informed forest owners compared to fully uninformed owners.

3.3. Policy Instruments: Fuel Stock Regulation

Fuel stock regulation is a forest-level standard that necessitates fuel accumulation in each forest to not exceed a specific amount in all periods. To study the effect of this policy and based on the literature, the fuel level was set to not exceed a fuel index of 40. Such a program could be introduced to encourage higher levels of risk-mitigating strategies by restricting the maximum fuel accumulation in a forest in all periods.

For all combinations of misinformation scenarios under fuel stock regulation, the individually optimal steady-state risk-mitigating action levels were homogeneous and constrained at 60% to conform to the regulation. Relative to the baseline (Table 2A), forest owner m nearly doubled their level of wildfire prevention actions with a regulated fuel policy. Moreover, the level of wildfire prevention actions under the regulated fuel policy was higher than the optimal wildfire prevention actions under the cost-share program, but remained suboptimal compared with the social optimum.

Considering fuel stock regulation, the increases in individually optimal forest values (Table 4A) for forest owner m were relatively higher than the case with the cost-share program (Table 3B), and both were higher than the baseline (Table 2B). Similarly, the reductions in social losses were greater with the application of a maximum allowed fuel policy (Table 4B) than with the cost-share program (Table 3C), and both policies yielded a reduction in social losses compared to the baseline (Table 2C). Correspondingly, Table 4C reports the percentage reduction in social losses after the application of fuel stock regulation for different misinformation scenarios. The level of reduction in social losses with a regulated fuel policy was greater than the case of a cost-share program for all considered scenarios in this study. The magnitude of reduction in social losses was influenced by the information held by the adjacent forest owner when making fuel removal decisions. It can be seen that the reduction in social losses increased as a forest owner became more informed and as his adjacent forest owner became more informed about wildfire externality effects. When both forest owners were uninformed about the cross-forest benefits of risk-mitigating strategies, the decrease in social losses was 10.32%, while the reduction in social losses was 44.40% when both forest owners were well informed about wildfire externalities. An interesting result is that the introduction of incentive-based fuel stock regulations achieved greater social gains by more than 34% with fully informed forest owners compared to fully uninformed owners. These results reveal that fuel stock regulation is more effective than cost-share programs under all misinformation scenarios.

Table 4. Optimal solutions with regulated fuel stock for forest owner m for different misinformation scenarios.

	Forest Owner n			
Forest Owner m	**Fully Misinformed**	**Partially Informed (1)**	**Partially Informed (2)**	**Fully Informed**
	(A) Individually optimal forest values ($/acre)			
Fully Misinformed	136.66	135.00	133.94	133.09
Partially Informed (1)	131.68	131.01	132.40	133.06
Partially Informed (2)	134.91	136.23	136.64	140.11
Fully Informed	142.30	143.46	145.10	147.90

Table 4. *Cont.*

Forest Owner m	Forest Owner n: Fully Misinformed	Partially Informed (1)	Partially Informed (2)	Fully Informed
	(B) Social losses ($/acre)			
Fully Misinformed	25.97			
Partially Informed (1)	35.94	37.28		
Partially Informed (2)	29.48	26.84	26.01	
Fully Informed	14.69	12.38	9.10	3.51
	(C) Percentage reduction in social losses			
Fully Misinformed	10.32%			
Partially Informed (1)	12.27%	9.71%		
Partially Informed (2)	14.54%	14.40%	14.66%	
Fully Informed	23.17%	26.51%	31.18%	44.40%

Notes: fully misinformed: forest owner *m* is completely misinformed about wildfire spillover effects; partially informed (1): forest owner *m* is aware of wildfire spillover effects through the probability of wildfire occurrence only; partially informed (2): forest owner *m* is aware of wildfire spillover effects through the probability of wildfire spread only; and fully informed: forest owner *m* is completely informed about wildfire spillover effects.

4. Conclusions and Policy Implications

Forests are a major contributor to the nation's timber industry. However, the country experiences regular wildfires that threaten timber and non-timber forest benefits. Drought conditions and a buildup of flammable vegetation in forests have resulted in more intense wildfires than normal recently. Wildfire damages result in significant financial losses to forest owners and high suppression costs to the government. Forest managers can better protect their land by understanding the behavior of wildfires in their region and the costs and benefits of fuel management. Thus, improving individual forest owners' perceptions about forest wildfire risk and increasing their wildfire prevention efforts through fuel management has the potential to bring about a large impact on the timber industry's profitability and sustainability, and decrease the public costs associated with forest wildfire control. This study provides valuable insights to policymakers about possible incentive programs, cost-share programs, and fuel stock regulations that would induce increased fuel management among forest owners and inform forest owners about their optimal fuel management decisions. Both of these features should encourage increased fuel management in the U.S., reduce the risk of catastrophic wildfires, and create more resilient forests.

Consistent with the findings of Busby, Amacher, and Haight [25] and Al Abri and Grogan [26], the simulation results of the baseline suggest that a forest owner tends to free ride on fire-mitigating treatments taken by his neighboring forest owner. Such a free-riding potential of a forest owner could be lightened to some extent by increasing their awareness of the wildfire spillover effects of a neighboring forest owner. Interestingly, this study uncovers that free-riding potential between adjacent forest owners persisted after cost-share program implementation; however, such behavior was alleviated due to the introduction of fuel stock regulation. Thus, to enhance better outcomes, incentive programs could also be complemented by information campaigns pertaining to wildfire externalities. Overall, our results provide an additional motivation for educational programs that seek to improve forest owners' knowledge about the private benefits of fuel removal and collaboration efforts between neighboring forest owners. Educational programs could be more effective in communities where collaborative planning is already in place [25]. Collaborative planning could serve as a substitute for a government cost-share program. Collaborative efforts could yield substantial savings for the government through eliminating cost-share programs and reducing suppression costs.

In examining the effectiveness of incentive programs at reducing social losses and increasing forest value, the novel finding of this study is that the effectiveness of an incentive-driven policy is influenced by the level of misinformation held by a forest owner when making wildfire prevention decisions. Social losses were further reduced after the implementation of a cost-share program and fuel stock regulation in the case of fully-informed adjacent forest owners compared to all other combinations of misinformation scenarios. Specifically, the introduction of incentive-based cost-share programs and fuel stock regulation achieved greater social gains by more than 28% and 34%, respectively, for fully informed forest owners compared to fully uninformed owners. Consistently, a maximum allowed fuel policy was revealed to sufficiently force forest owners to increase their level of fire-mitigating actions compared to the cost-share program. Therefore, these results indicate that fuel stock regulation is more effective at mitigating wildfire damages and the associated costs than cost-share programs under all misinformation scenarios. This could be attributed to the restrictive nature of the regulated fuel policy. Unlike previous studies, we found that the consequences of free riding on social losses were minor. In the context of a policy application, free riding does not yield an increase in social losses; rather, it limits the reduction in social losses that are associated with policy implementation.

This study assumes that the decisions of private forest owners to mitigate wildfire risk are largely based on the marketable and non-marketable benefits of the forest, fuel treatment rewards, and forest owners' level of understanding of wildfire risk on their own and neighboring properties. This specification can be extended to account for other factors that influence decisions regarding mitigating wildfire risk, including access to resources and tools; the risk of prescribed fire escape; access to liability insurance; past wildfire and treatment experiences; wildfire-related property damage; and awareness of wildfire prevention programs [53–55], which cannot be simply alleviated by increasing educational opportunities.

Furthermore, topic-wise, this study could be extended to account for renewable energy or other wood products that can be produced from fuel removal via thinning. The western U.S. has markets to support wood products such as woodchips and mulch that can be created from material removed with thinning and pruning [24]. The southern U.S., however, is largely missing markets for thinning materials that could encourage forest owners to participate in such activities and enhance the production of environmentally-friendly energy and wood products in the United States. Rubin et al. [56] studied the economic viability of biomass for biofuel production and concluded that policymakers could enhance the production of renewable biofuel energy by encouraging afforestation. In addition, this study mainly considered the fuel biomass as a determinant of risk and damages. Future studies could account for other factors related to the structure of the forest such as the height, diameter, spacing, age of the forest, and different rates of spread [3]. Modelling-wise, this study could be extended to include an investigation of spatial-dynamic ecological–economic linkages among forest owners in which wildfire spread is modeled within and across forestlands according to short- and long-distance dispersal mechanisms. This would reveal information regarding optimal strategies to mitigate the externality. The derived model could be applied to analyze the implications of the neighboring effect in light of natural disturbances such as windstorms [57,58]. Moreover, the two-adjacent-forest-owners model derived in this study forms a good foundation that can be applied to perennial agricultural crops, especially in under-researched parts of the world.

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