Wildland Fire Management and Willingness to Participate in Collaborative Efforts

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Abstract

In recent years, the dramatic increase in the number of severe and uncontrollable wildfires in the southern U.S. has become an important policy issue. While landowners, who predominantly utilize pine species, often cannot control the occurrence of wildfire, they can undertake fire prevention practices to mitigate fire losses. Previous literature has suggested that collaborative efforts between neighboring landowners is a potentially effective fire management approach. However, no previous studies have evaluated willingness to participate in collaborative efforts or investigated how collaborative planning encourages risk mitigation behavior. This study develops a stochastic dynamic model to examine two adjacent landowners who manage their stands simultaneously and seeks to understand how their risk mitigating decisions interact in the presence and absence of cooperative efforts. The derived model presents three main cases: no cooperative efforts exist, cooperative efforts exist and individuals choose to cooperate if doing so is individually optimal, and the socially optimal management with cooperative efforts. Then, the optimal fuel reduction actions from the second case are compared to the social optimum to evaluate whether landowner should participate or not. Results imply that government programs could be utilized to improve landowner's awareness and responses to cooperative efforts.

Key Words: Wildfires, Pine Species, Collaborative Efforts, Willingness to Participate, Stochastic Dynamic Model

Introduction

In recent years, the dramatic increase in the number of severe and uncontrollable wildfires in the southern U.S. has become an important policy issue (National Interagency Fire Center 2011). 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 on landscapes putting communities at risk (Busby, Amacher, and Haight 2013). While landowners, who predominantly utilize pine species, often cannot control the occurrence of wildfire, they can undertake fire prevention practices to mitigate the losses caused by fire. Fuel reduction actions, like thinning stands and prescribed burning, can be used to minimize fire damages as both the amount and configuration of forest fuels enhance the intensity and extent of wildfire (Agee and Skinner 2005; Amacher, Malik, and Haight 2005; Graham et al. 1999; Hirsch and Pengelly 1999; Pollet and Omi 2002; Yoder 2004). Fuel treatments create positive spatial externalities, especially in the case of crown fires, because fire easily spreads across property boundaries (Hann and Strohm 2003; Finney 2001; Gill and Bradstock 1998). Fuel management in an individual forest decreases the risk of fire and associated damages on neighboring forests and vice versa (Busby, Amacher, and Haight 2013). Studies by Brenkert-Smith, Champ, and Flores (2006) and Monroe and Nelson (2004) indicated that landowners consider fire prevention decisions undertaken by adjacent landowners when making decisions regarding fuel reduction actions.

Given the interaction of neighboring landowners' decisions, previous literature has suggested that collaborative efforts between neighboring landowners is a potentially effective fire management approach (Fleeger and Becker 2010, Grayzeck-Souter et al. 2009, Steelman 2008b). Involvement in collaborative efforts have cost-sharing incentives, like equipment-sharing among

participants, that could encourage landowners to undertake fuel treatment practices that mitigate wildfire losses (Reams et al. 2005; Sturtevant and Jakes, 2008). In 2001, Congress called for "close collaboration among citizens and governments at all levels" for the management of wildland fire, hazardous fuels, and ecosystem restoration (WGA 2001). Consistently, the Healthy Forests Restoration Act (HFRA) created an opportunity for communities/landowners to influence where/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 fuel reduction activities (Forests and Rangelands 2017).

Since cooperative efforts could result in undertaking increased fuel management, involvement in cooperative efforts could decrease the spread of fire and the associated damages to neighboring forests. This should encourage one forest manager to seek collaboration with his neighbor; the cost of sharing fuel treatment capital with an adjacent landowner could be covered by the benefits of preventing larger damages on his site as a result of fire spreading from his neighbor forest. Although several studies examined collaboration in the context of fire management (Reams et al. 2005; Sturtevant and Jakes 2008; Grayzeck-Souter et al. 2009; and Renner 2010; and others), none integrates collaborative planning into the process of making fuel reduction decisions or into a stochastic optimization of timber value. No previous studies have evaluated willingness to participate (WTP) in collaborative efforts or investigated the effectiveness of such incentives for different types of ownership (market-oriented and non-market driven ownerships).

The first objective of this study is to determine how, and under what scenarios of cost and fire damage mitigation, collaborative planning encourages risk mitigation behavior. The second

objective is to evaluate a landowner's WTP in collaborative efforts with his neighboring landowner; and estimate thresholds effects in landowner's WTP. The third objective is to present and compare the best responses to collaboration offers for different types of ownership (market-oriented and non-market driven). Different ownership types raise the question of how the WTP of each type diverges from the social optimum as, for example, the non-market driven landowners may be less interested in fire prevention actions as they enjoy the presence of fuel load on their landscape; therefore, they may be less likely to participate in cooperative efforts.

The benefits of collaborative efforts influence landscape-level fuel stocks, the spread rate of fire, fire damages, and potential salvage values in the event of a fire. This study examines two neighboring forest units and seeks to understand how their risk mitigating decisions interact in the presence and absence of cooperative efforts. The derived model will present three main cases: no cooperative efforts exist, cooperative efforts exist and individuals choose to cooperate if doing so is individually optimal, and the socially optimal management with cooperative efforts. Then, the optimal fuel reduction actions from the second case will be compared to the social optimum to evaluate whether landowner should participate or not.

This study models fire arrival rate as a function of the amount of flammable fuel stock present on the forest and assumes that fuel accumulation on the neighboring forest influences the fire spread rate from neighboring forest to own forest. Therefore, an increasing fuel stock presented on the neighboring forest increases the total potential fire damages and decreases the salvageable timber on own forest. This study develops a stochastic dynamic programming model in a game interaction framework based on the *solvegame* routine included in Miranda and Fackler (2002).

Model Formulation

This study models an interaction between two adjacent landowners who manage their

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stands simultaneously and potentially engage in collaborative planning to mitigate fire damages and reduce fire prevention costs. Landowners and their corresponding stands are indexed by $i \in [k, j]$. Each landowner is expected to account for the probability of forest fires while maximizing an infinite horizon of the net present value of current and future rents, thus, determining the optimal harvest age. As both adjacent forests are prone to fire, landowners may undertake some fuel management practices to prevent valuable stand losses; however, these practices are costly. The risk of fire increases as fuel stock increases in a forest.

The neighboring landowners also face the risk of fire spreading from one forest to an adjacent forest. A landowner with higher fuel stock will have a larger fire that is more likely to spread to neighboring forest. In addition, the total potential damage caused by the fire in own forest depends on probability of fire occurrence on own forest, probability of fire occurrence on adjacent forest, fire damages on own forest, and probability of fire spread from neighboring forest to own forest. Reducing fuel stocks leads to decreased fire damages and increased salvageable timber when the fire arrives within the rotation. The model then determines the rent-maximizing fuel management levels and rotation lengths, assuming that each landowner maximizes his own rents, and decisions are affected by the neighboring units through their effects on fire spread. In addition, the model investigates different scenarios when landowners receive benefits, e.g. cost reductions, from cooperating together to determine when it is beneficial to participate in such cooperative efforts. To do so, we first present a base case where there is no collaboration between the two landowners, and then, a second case where one landowner shows interest in sharing his fuel treatment capital with the adjacent landowner (cooperative efforts exist). A third case determines the socially optimal management of both adjacent lands in the presence of cooperation. This case, in comparison with the second case, helps to evaluate whether the adjacent owner should accept

the offer to maximize regional benefits.

The model allows each landowner to choose ownership interests. A landowner could be interested in timber sale revenues only or non-market benefits only or a combination of both. The non-market driven landowner earns non-market benefits that depend on fuel load present on the site (Donovan and Butry 2010) and on stand stock.

Rents Maximization, Fire Risk, and Collaborative Efforts

The stochastic dynamic problem contains two continuous state variables, stand biomass measured in cubic meters per hectare at the beginning of each period $s_{it} \in [s_{min}, s_{max}]$ and an index for fuel biomass ranges from 0 to 1 and defined at the beginning of each period $f_{it} \in [f_{min}, f_{max}]$; where $i \in [k, j]$[1]. To ensure a realistic simulation path, sit bounded between 1 and 1000 and fit bounded between 0.05 and 0.93. Although no study provides information regarding these boundaries explicitly, the selected minimum and maximum values are within the range of what have been estimated in literature[2]. The model also has a random binary variable represents fire occurrence $\theta_{it} \in [0,1]$ during each period. The model allows the landowners to make two decisions each period: clearcut the stand, $a_{it} = 1$, or wait, $a_{it} = 0$, and the level of fuel reduction $x_{it} \in [0, f_{it}]$. In the absence of fire, the landowner harvests his stands and replants immediately. In the presence of fire, the forest manager harvests the salvageable timber, cleans his site, and replants.

Consistent with literature, fire arrival is described as a Poisson distribution; however, unlike previous studies, this study models the fire arrival rate as an increasing function on fuel biomass accumulation $\lambda(\gamma, f_{it})$, where γ captures the incendiary events rate over a 100-year

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[1] For simplicity, *m* and *n* are also used in this chapter to refer to forest parcels owned by landowner *m* and landowner *n*, respectively.

[2] See Amacher, Malik, and Haight (2005); Daigneault, Miranda, and Sohngen (2010); and Busby, Albers, and Montgomery (2012).

period and f_{it} is the fuel stock. The fire arrival rate is increasing at a decreasing rate with the level of fuel stock:

$$\frac{\partial\left[\lambda(.)\right]}{\partial\gamma} > 0, \text{ and } \frac{\partial\left[\lambda(.)\right]}{\partial f_{it}} > 0,$$

$$\frac{\partial^2\left[\lambda(.)\right]}{\partial f_{it}^{\,2}} < 0.$$

Fire spread rate and Damage Function

Spread rate of fire creates an externality between the two adjacent forests. 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 k is influenced by the probability of fire starting on the parcel k (θ_{kt}), the resultant fire damage on parcel k as a function of its own fuel stock ($D(f_{kt})$), the probability of fire starting on parcel j (θ_{jt}), the probability of spread from neighbor j as a function of j's fuel stock ($\phi_{j\to k,t}\left(f_{jt}\right)$), and the resultant damage from fire spread on parcel k as a function of k's fuel stock ($D(f_{kt})$). Both the spread rate and the damage function are deterministic, increasing in fuel stock, ranging from 0 to 1, and continuous. The fire spread rate from j to k and the total potential damage function for forest k can be expressed as follows, respectively:

$$\phi_{j\to k,t} = \phi\left(f_{jt}\right) \tag{1}$$

$$D_{kt,total} = \theta_{kt}D(f_{kt}) + \theta_{jt}D(f_{kt})\phi_{j\to k,t}\left(f_{jt}\right) \tag{2}$$

Generally, the probability of fire spread from neighboring landowner $-i$ to landowner i can be expressed as $\phi_{-i\to i,t} \in \left[0,1\right]$.

Fuel Accumulation

The state of the fuel in period *t+1* depends on fuel reduction undertaken in period *t*. If fire does not occur and no fuel reduction is performed, fuel growths by $k(f_{it})$, the path of fuel accumulation in the stand over time. If fire prevention actions performed, x_{it}, fuel growths by $k(f_{it}) - x_{it}$. If the stand is harvested or destructed by fire, landowners clean and prepare the parcels for next rotation and consequently less-hazardous minimal fuels remains in the site3, f_0. The state of fuel on the stand the following period:

$$f_{i,t+1} = \begin{cases} k(f_{it}) - x_{it} & a_{it} = 0, \theta_{it} = 0, \phi_{-i \to i,t} = 0, x_{it} \in [0, f_{it}] \\ f_0 & a_{it} = 1\_or\_\theta_{it} = 1\_or\_\phi_{-i \to i,t} = 1 \end{cases} \quad [3]$$

Stand Management and Timber Growth

The state of merchantable timber in period *t+1* increase both as the stand grows naturally over time $y(s_{it})$ and with the level of fuel in the stand, $g(f_{it})$. If the stand is thinned, x_{it}, the timber yield increases from thinning by $s_{it} + y(s_{it})g(f_{it} - x_{it})$. If fire occurs, the amount of timber is characterized using a damage function, as discussed above, that gives the proportion of timber damaged on a parcel as a function of fuel accumulation on that parcel. If stand is harvested or if a fire occurs, the initial stand stock planted is s_o. The timber volume evolves across periods by:

$$s_{i,t+1} = \begin{cases} s_{it} + y(s_{it})g(f_{it} - x_{it}) & a_{it} = 0, \theta_{it} = 0, \phi_{-i \to i,t} = 0, x_{it} \in [0, f_{it}] \\ s_0 & a_{it} = 1\_or\_\theta_{it} = 1\_or\_\phi_{-i \to i,t} = 1 \end{cases} \quad [4]$$

Timber Revenue and Non-Timber Benefits

The net benefits received by landowner *i* from timber sales or non-market benefits or intermediate treatments in any given period, $l_{it}(s, f, \theta, a, x)$, will be influenced by the volume of

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[3] Consistent with Daigneault, Miranda, and Sohngen (2010) who assumes when a stand is thinned, harvested, or salvaged, the fuel stock is reset to an initial level such that the proportion of salvageable timber after fire is minimized.

merchantable timber s_{it}, the volume of combustible fuel f_{it}, the incidence of fire θ_{it}, and the action taken by the manager (a_{it}, x_{it}) in that period. In case of fire ($\theta_{it} = 1$), the landowner receives the discounted salvage value of the merchantable timber after the fire and replants the stand. If a fire does not occur in a given period ($\theta_{it} = 0$), the manager receives revenue that depends on the action taken:

$$l_{it}(s, f, \theta, a, x) = \begin{cases} (1 - D_{it,total})\varsigma \, p_t s_{it} - c_{\theta=1} & \theta_{it} = 1 \_ or \_ \phi_{-i \to i,t} = 1 \\ \beta_i u_{it}(f_{it}, s_{it}) - c_{per} & a_{it} = 0, \phi_{-i \to i,t} = 0, x_{it} = 0 \\ \beta_i u_{it}(f_{it}, s_{it}) - \eta_i c(x_{it}) & a_{it} = 0, \phi_{-i \to i,t} = 0, x_{it} \in (0, f_{it}] \\ \beta_i u_{it}(f_{it}, s_{it}) + (1 - \beta_i)(p_t s_{it} - c_{new}) & a_{it} = 1 \end{cases}$$

[5]

Where p is the deterministic price of the timber, ς is the fraction of the timber price that the market assigns to the ignited log, $(1 - D_{it,total})$ is the proportion of timber salvaged if a fire occurs, and $c_{\theta=1}$ is the cost of replanting the ignited stands. c_{per} and c_{new} are the costs of annually maintaining and replanting the stand, respectively. $c(x_{it})$ is the cost of thinning with fixed and variable components as landowners incur a fixed cost of setting up the fuel removal equipment regardless of the level of fuel removed; which depends on the amount of fuel removed and is affected by involvement in collaborative efforts. Involvement in collaborative efforts scales this cost down by η_i which is assumed to range from 0.19 to 1. The parameter η_i takes the value 1 when there is no collaboration (the cost $c(x_{it})$ is not scaled and incurred fully by the landowner if undertakes fuel removal practices) and 0.19 represents full collaboration. Full involvement in collaboration is proposed to scale the cost of fuel reduction by 0.19; full collaboration is not assumed to reduce the cost of fuel treatment to 0 due to operating costs which incorporate expenses like maintenance cost and labor wages associated with fuel reduction operation. Although a large literature discussed the cost

benefits of collaborative planning, no studies we are aware of has specified the magnitude of these benefits. Schaaf et al. (2004) reported that the overall average fuel removal cost is approximately $225 per acre ($555.98 per ha); fuel treatment cost reported by Dubois et al. (2001) are close to those found in Schaaf et al. (2004). Bolding, Kellogg, and Davis (2009) presented statistics for different types of costs associated with various fuel removal mechanisms, like maintenance and repair costs ($2.92 per acre on average) and labor overhead ($40 per care on average). The total of these expenses ($42.92 per acre or $106.06 per ha) relative to the overall average of fuel reduction treatment cost of $555.98 per ha gives the fraction of cost incurred by the landowner after involvement in collaborative planning, 0.19. Therefore, engagement in collaborative efforts between to adjacent landowners could save up to %81 of total fire prevention practices costs. Then, we perform sensitivity analysis with the scaling parameter, η_i, to determine how much costs need to be reduced to induce cooperation.

Based on ownership interest, landowners assign a weight, Beta, to timber and non-timber benefits. Consistent with what was assumed earlier, the non-timber benefits function, $u_{it}(f_{it}, s_{it})$, is concave and increasing in fuel loads and stand stock, where:

$$\frac{\partial u_{it}(.)}{\partial f_{it}} > 0, \text{ and } \frac{\partial u_{it}(.)}{\partial s_{it}} > 0,$$

$$\frac{\partial^2 u_{it}(.)}{\partial f_{it}^2} < 0, \text{ and } \frac{\partial^2 u_{it}(.)}{\partial s_{it}^2} < 0.$$

Stochastic Dynamic Optimization and Nash Equilibrium Framework

The interactions between landowners comes through the possible spread of fire across parcels. For a landowner to decide whether to engage in some sort of collaborative planning with a neighboring landowner, the landowner should account for fire spillover effect to and from parcels

in a landscape. Ignoring such effect may discourage a landowner from collaborating due to underestimation of collaborative efforts potential benefits. This also leads to widen the gap between individually optimal and socially optimal WTP in cooperative planning. This study simultaneously derives best response functions of each landowner, so-called 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 collaborative efforts as well as if it is socially optimal to participate.

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

$$V_k\{s, f_k, f_j, \theta\} = \max_{a_{kt}, x_{kt}} \left(l_{kt}(s, f, \theta, a, x) + \delta E_{\tilde{\theta}} V(f_{k,t+1}, f_{j,t+1}) \right) \qquad [6a]$$

$$V_j\{s, f_j, f_k, \theta\} = \max_{a_{jt}, x_{jt}} \left(l_{jt}(s, f, \theta, a, x) + \delta E_{\tilde{\theta}} V(f_{j,t+1}, f_{k,t+1}) \right) \qquad [6b]$$

Data Sources and Application

The study parameterizes the simulation by modelling loblolly pine (*Pinus taeda*) in the southeastern United States due to the availability of information about this tree species in the literature. We utilize parameter values and functional forms from Amacher, Malik, and Haight (2005 and 2006), Crowley et al. (2009), and Daigneault, Miranda, and Sohngen (2010). The functional forms and parameter values used in the numerical analysis for loblolly pine in the Southern U.S are presented in Table 1-1. The annual timber growth function used in this study was extracted from Chang (1984) and Amacher, Brazee, and Thompson (1991). The price of stumpage is assumed constant and taken from Timber Mart-South as $80 per 1000 boardfeet (TMS, 2010).

The existing literature does not provide information regarding incurred fuel reduction cost

in the presence of collaborative efforts; however, Amacher, Malik, and Haight (2005) assumed the fuel removal cost is a linear function of fuel removal actions. This function has been employed by this study as a base and, then, scaled the value down to represent cost reduction benefits associated with participation in collaborative efforts. The periodic maintenance (c_{per}) cost of $10 per hectare is found in Bair and Alig (2006), and the replanting cost after clearcut (c_{new} = $171.36 per hectare) is calculated based on Amacher, Malik, and Haight (2005). The cost of replanting after forest fire, $c_{\theta=1}$ =$122.4 per hectare, is taken from Daigneault, Miranda, and Sohngen (2010). In addition, fuel accumulation is assumed to follow an exponential growth process similar to the functions employed by Daigneault, Miranda, and Sohngen (2010), Brown, Reinhardt, and Kramer (2003), Omi and Martinson (2002), and Smith, Heath, and Jenkins (2003).

This study is the first attempt to model the direct effect of fuel accumulation on fire arrival rate. The assumed functional form is chosen to exhibit two main characteristics: increasing in both fuel loads f_{it} and the rate of incendiary events over a 100-year period γ, with the following probabilities:

$$\lambda(\gamma, f_{it}) = 1 - e^{-\gamma(\frac{k(f_{it})}{W})} \qquad [7]$$

W is a control factor used to scale the effect of fuel accumulation in expanding fire arrival rate. The values of γ and W are set to 0.02 and 50, respectively; these values are relatively similar to those found in Crowley et al. (2009) given the characteristics of our fire arrival rate function. Over the entire space of fuel stock f, the fire arrival rate function reports values that ranges from 1 to 8 fires every hundred years, which is a plausible given the nature of fire in the southern U.A. and fall within the range assumed in the literature.

The individual damage function is chosen to be strict convex in fuel load and has similar

characteristics to the function suggested by Crowley et al. (2009). The literature does not provide guidance that we are aware of regarding fire spread rate. Intentionally, the chosen specification is consistent with our assumption that one landowner's fire spread rate is increasing at a decreasing rate pattern with fuel stock presents on the stand owned by a neighboring landowner and bounded between 0 and 1.

Results

Preliminary results suggest that the pattern of fuel accumulation substantially affects the optimal pattern of efforts for both landowners. In the base case, the socially optimal treatment pattern is to treat both parcels more frequently than individually optimal. Fuel reduction on an individual parcel reduces expected damage on the adjacent parcel. Figure 1 shows fire prevention actions for both landowners before engagement in in collaborative efforts; and Figure 2 illustrates fire prevention actions after engagement in collaborative efforts. It is clear that involvement in collaboration increases both the level and frequency of fuel removal in both adjacent parcels. In addition, Figure 1 and Figure 2 indicate that forest managers should control fuel accumulation starting earlier on in the rotation. Further, the optimal pattern of fire prevention action increases in level and frequency as the value of the trees increases. Additional economic and risk parameters will be considered to determine if there are cases where effort should remain constant and to further explore the patterns of the timing of fuel removal efforts over different fire probabilities and fire spread rates.
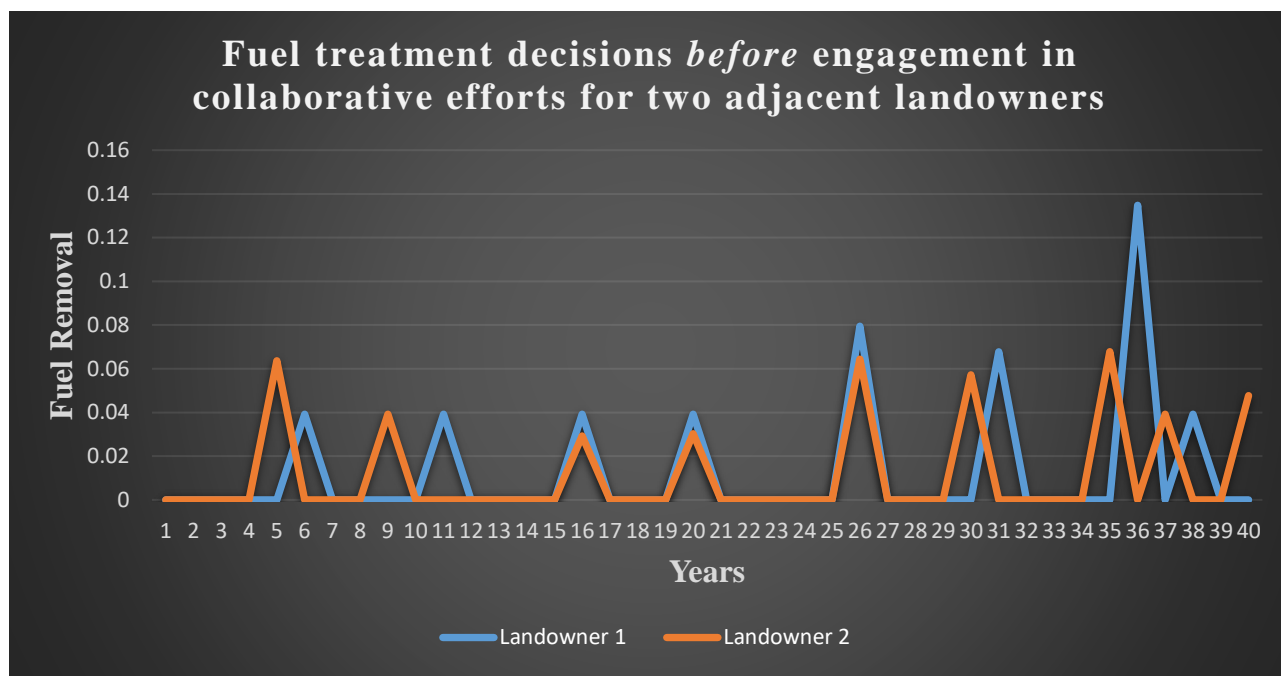
FIGURE 1
Fuel treatment decisions *before* engagement in collaborative efforts for two adjacent landowners
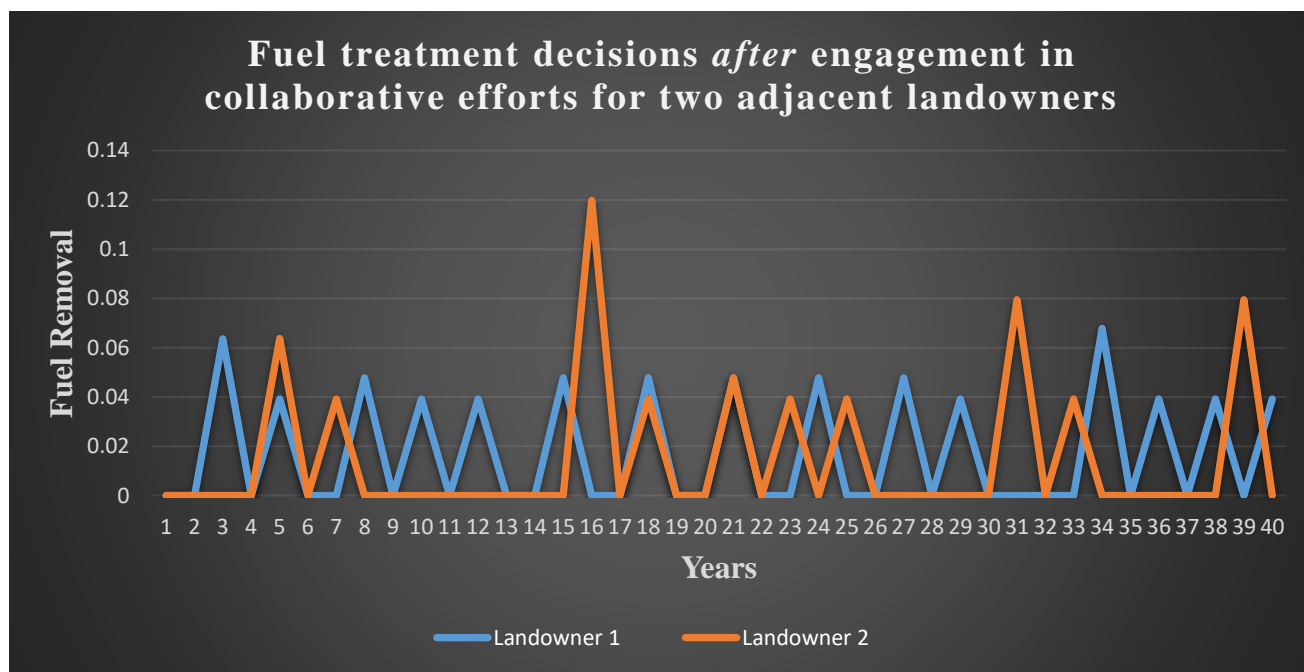
FIGURE 2
Fuel treatment decisions *after* engagement in collaborative efforts for two adjacent landowners

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Policy Implication and Conclusion

The number and intensity of megafires in the U.S. is growing due to harsh weather conditions and accumulated fuels. In addition to financial losses to timber growers, Government suppression costs have been significantly increasing and reached an average of $3 billion in recent years. For this reason, government designs more programs to educate and encourage landowners to take informed fire management decisions. Involvement in collaborative efforts between neighboring landowners is one of the potentially effective fire management approaches that could lead to decrease the spread of fire and the associated fire damages among participants. This study develops a stochastic dynamic model for two adjacent landowners to investigate the potential effects of collaborative planning on mitigating fire damages and associated costs; hence, fire prevention decisions. The study evaluates whether landowner should participate in collaborative planning from individual and social perspectives. Results imply that government programs could be utilized to improve landowner's awareness and responses to cooperative efforts.

Table 1-1. Optimal Management Model Specification for Loblolly Pine in the Southern U.S.

Description	Specification	Parameter Value Per Hectare
Discount factor	δ	0.95
Amenities benefits	$u_{it}(f_{it}, s_{it}) = \kappa_1 \left(\omega(f_{it} + s_{it}) - \kappa_2 \right)^2 + \kappa_3$	$\kappa_1 = -0.008, \kappa_2 = 80, \kappa_3 = 50, \omega = 30$
Stumpage price	p_t	$80
Periodic Maintenance cost	c_{per}	$10
Replanting cost after harvest	c_{new}	$171.36
Replanting cost after fire	$c_{\theta=1}$	$122.4
Fuel removal cost	$c(x_{it}) = \eta_i (c_{fix} + c_{var}(x_{it}))$	$c_{fix} = 5, c_{var} = 100, 0.19 \leq \eta_i \leq 1$
Fraction of stumpage price for salvage sales	ς	0.75
Individual damage function for landowner i	$D_{it} = e^{-(\frac{0.1}{f_{it}})}$	
Fuel accumulation function	$k(f_{it}) = 15^{(1+f_{it}^{0.93})}$ or $f_{it}^{0.93}$	
Fire arrival rate	$\lambda(\gamma, f_{it}) = 1 - e^{-\gamma(\frac{k(f_{it})}{W})}$	$\gamma = 0.02, W = 50$
Fire spread rate for landowner i	$\phi_{-i \rightarrow i,t} = 1 - e^{-0.93(f_{-i,t})^{0.93}}$	

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