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Title: Wildfire Risk Management: Strategic Interaction and Spatial Interdependence

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In this dissertation, I examine how the spatial configuration of forest ownership influences the risk-mitigating behavior of public and private forestland owners over time. I determine whether or not the predicted equilibrium outcomes are socially optimal and, if not, whether the introduction of regulation, liability, or private insurance would lead to socially optimal outcomes. Because both individual and collective actions affect wildfire risk, this problem is well suited to game theory and the analysis of strategic behavior. I use a game theoretic framework to examine how the public landowner's investment in fuel management influences, and is influenced by, decisions made by private forestland owners. I find that spatial configuration and location affect the timing and amount of fuel treatment on the landscape. There is less investment in fuel management on landscapes characterized by fragmented ownerships. I also find that the nature of the strategic interaction between landowners depends on whether there are constant, increasing, or decreasing returns to investment in fuel management. To address the inefficiencies in fire risk management, I find that a fuel stock regulation offers the greatest potential to improve outcomes on a landscape with mixed ownership.

Wildfire Risk Management: Strategic Interaction and Spatial Interdependence

by

Gwenlyn M. Busby

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Gwenlyn M. Busby, Author

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1. INTRODUCTION

Large populations on the earthquake-prone Pacific coast, the hurricane-prone Gulf and Atlantic coasts, in flood plains across the country, and in the fire-prone areas of the interior and western U.S. present serious concerns and make natural hazard risk analysis a timely issue. While little can be done to prevent tectonic shifts, lightning strikes, heavy rain events, or low pressure ocean storm systems, individuals living in threatened areas can undertake self-protective actions to reduce the amount of damage caused when a natural hazard occurs. To protect against earthquake and hurricane damage, structures can be reinforced and fortified; dams and levees protect structures from rising flood waters; and removing forest fuels reduces the severity of wildfire damage. And for each hazard, the spatial pattern of protective measures determines the effectiveness of protection on the affected landscape.

Wildfire is an intrinsic ecosystem process throughout much of the western U.S. (Pyne, 1996); however, recent years have seen an increase in the number of catastrophic and uncontrollable fires. Statistics from the past five years on suppression cost and acres and homes burned (Table 1) provide a stark illustration of the impact these fires have had on the landscape. In 2003, for example, 4,508 homes in the United States were destroyed by wildland fires, many of them during the October fires in southern California, resulting in more than two billion U.S. dollars in damages (NIFC, 2008). These fires have continued to burn in spite of the millions of dollars federal agencies spend on fire suppression every year.

TABLE 1.1: Wildfire statistics

Year	Suppression Cost (billions)	Acres Burned	Homes burned
2002	$1.66	6,937,584	4,184
2003	$1.32	4,918,088	4,508
2004	$.89	6,790,692	315
2005	$.87	8,686,153	402
2006	----	9,873,745	750
2007	$1.84	9,321,326	5,401

Source: National Interagency Fire Center (2008).

Recent years have also seen a steady increase in the number of individuals living in and around forested areas (Stewart et al., 2005), which has added to the complexity and immediacy of the wildfire problem. Areas where private property is adjacent to or intermixed with fire-prone public land is often referred to as the wildland urban interface (WUI). As the number of individuals living in the WUI increases, the greater the potential wildfire damage. If wildfire risk[1] is not considered by individuals and communities in these fire-prone areas, values at risk of damage and destruction by wildfire will continue increasing and public expenditures on fire suppression will remain ineffective.

Because wildfire responds to changes in the amount and configuration of fuels, a forest stand can be managed through the use of various hazardous fuel reduction treatments[2] to minimize wildfire risk (van Wagtendonk, 1996; Graham et al., 1999; Hirsch and Pengelly, 1999; Pollet and Omi, 2002; Agee and Skinner, 2006). The objective of fuel treatments for hazard reduction is to reduce fuel

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[1] Throughout the dissertation, wildfire risk is defined as expected loss: the product of the value in the fire-prone area and the probability of fire. This is the standard definition of risk used throughout the economics literature.

[2] I do not distinguish between different types of fuel reduction treatments and consider only “fuel removal” generally.

loads (i.e., the quantity of fuel) and/or change the spatial arrangement of fuels. Through the removal and manipulation of fuels, managers can effectively reduce the severity and intensity of wildland fires.[3] However, the landscape pattern of wildfire risk depends both on the actions taken by the individual forest owner and those taken by neighboring forest owners. The positive spatial externalities created by fuel reductions have been documented (Hann and Strohm, 2003) and found to be especially significant in the case of large wildfires (Finney, 2001; Gill and Bradstock, 1998). Because both individual and collective actions affect wildfire risk, this problem is well-suited to game theory and the analysis of strategic behavior.

The spatial pattern of ownership in the western U.S. is characterized by a mix of privately owned and publicly managed land. The wildland urban interface (WUI) is the area where structures and other human development, often privately owned, meet or intermingle with undeveloped, often publicly managed, wildlands (National Fire Plan, 2007). Each landowner considers the state of neighboring forests when making decisions about undertaking self-protective activities, such as removing forest fuels (Monroe and Nelson, 2004; Brenkert-Smith et al., 2006). Good management on neighboring forests decreases the risk of fire damage on the individual ownership whereas poor management on neighboring forests increases the risk of fire damage on the individual ownership. However, it is often the case that neither the benefits nor costs of these *spatial externalities* are considered by the individual when making forest management decisions.

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[3] Fire severity is a measure of damage caused and intensity is a measure of fire temperature (Sousa 1984).

The nature of these spatial externalities, whether positive or negative, is influenced by state and federal wildfire and land management policies. Government regulations and market mechanisms, such as insurance and liability rules, can be used to manage risk and create incentives for fuels reduction. Policies that cause an individual to reduce fuel decrease wildfire risk on the individual property as well as neighboring properties, through the positive spatial externalities. Under consideration in many states are regulations requiring property owners to manage forest fuel loads. An audit (UDSA 2006) released by the U.S. Department of Agriculture's Inspector General in November 2006 argued that because state and local governments regulate development in areas where cities meet forests, they should bear a greater share of wildfire costs or else limit development in areas of high wildfire risk, suggesting a public liability rule.

The objective of this dissertation is to examine how spatial configuration and location affect fire risk management decisions on a landscape with mixed ownership and to explore policies intended to promote efficient fire risk management. In particular, this research will provide timely insight into private fire risk management decisions and inform public policy. By predicting the strategic interaction of public land managers and private landowners over a range of typical ownership patterns, settings, and in the presence of a land management regulation, a liability rule, and a private insurance program, policy-makers will gain greater insight into the wildfire problem and increase their ability to craft more effective wildfire management policies.

A summary of the relevant economics and forestry literature is provided in chapter 2. In chapter 3, a spatially explicit model of the fire risk management problem with multiple decision makers is described. Results from the model for the base case and a range of real-world scenarios are described in chapter 4. The sensitivity analysis, used to test the robustness of the model, is presented in chapter 5. Finally, a discussion of the results and concluding remarks are offered in chapter 6.

2. LITERATURE REVIEW

I develop a stylized model of wildfire risk management decisions that incorporates the spatial and strategic interaction between public land managers and private land owners. The development of the model builds on previous work grounded in the spatially explicit modeling of resource management decisions with risk. A thorough analysis of wildfire risk management decisions requires consideration of literature in the areas of wildfire and natural hazard risk, game theory, models of land management with spatial interdependence, and wildfire policy.

In the area of hazard economics, I glean insight from economic models of endogenous risk and more traditional research on optimal rotation forestry with risk. Basic game theory provides the framework for the strategic interaction developed in the dissertation. Models of land management with spatial interdependence illustrate the increasing complexity of this type of problem. Finally, the wildfire policy literature provides insight into the current and potential role of government regulation, liability, and insurance to address wildfire risk. Within each literature, and in the context of the wildfire problem, I describe where advances have been made, conclusions have been drawn, and where opportunities exist for future research. Broadly speaking, the innovations to the wildfire problem I develop in this dissertation relate to strategic interaction of landowners with different management objectives on a spatially explicit landscape with mixed ownership.

2.1 Wildfire and Natural Hazard Risk

A rich economics literature models decisions in the face of natural hazard risk, which can inform a discussion about forest management under fire risk. Within much of this literature, risk is endogenously determined. That is, individuals can influence the risk they face through their behavior. In their seminal work, Ehrlich and Becker (1972) provide a framework for endogenous risk and model self-protection decisions, which reduce the probability of an undesirable state, and self-insurance decisions, which reduce the severity of damage resulting from the undesirable state. Though the distinction between self-protection and self-insurance is often made for analytical convenience (e.g., Berger et al. (1987) model health-risk self-protection whereas Lewis and Nickerson (1989) model self-insurance decisions), the implications of an endogenous risk framework are significant and failure to incorporate individuals' ability to influence the risk they face through their behavior will lead to sub-optimal management decisions (Shogren and Cocker, 1990; Archer and Shogren, 1996; Finnoff et al., 2005). In the model presented here, individuals have the ability self-protect with fuel management, thereby reducing the severity of wildfire damage, but the probability of fire is exogenous.

The forestry literature emphasizes the optimal forest rotation length for timber production and fire-risk has been addressed primarily within this context. The more recent studies within this literature use an endogenous risk framework (Konoshima et al. 2006; Amacher et al., 2005; Crowley et al. 2008), while earlier studies assume fire risk is exogenous (Reed, 1984; Routledge, 1980; Martell, 1980). These stand-level studies, however, focus on a single ownership and only Konoshima et al. (2006) and Crowley et al. (2008) addresses the spatial dimension of the hazard across more than one stand. Konoshima (2006) explicitly accounts for the spatial externalities associated with fuel treatments across stands and uses a spatially explicit stochastic dynamic optimization model to provide insight into the optimal spatial allocation of fuel treatment effort. The implications of mixed ownership on the optimal fuel treatment effort remain unexplored.

2.2 Game Theory

Game theory is the study of multi-person decision problems (Gibbons, 1992). Game theoretic models are different from typical economic agent-based models in that an individual's payoff is determined not only by their decision, but also by the decisions of the other player(s). A game consists of: players or individual decision-makers; strategies or the possible choices for each of the players; and payoffs, or outcomes, from the combination of chosen strategies for each player. Games are often differentiated by the information available to each player, whether players move simultaneously or sequentially, and whether or not the game is repeated. I consider a finitely repeated, simultaneous-move game of complete information, which means that the timing, feasible moves, and payoffs of the game are common knowledge (Gibbons, 1997).

Game theory has been applied to a range of problems in the field of environmental and resource economics including: species preservation (Palmini, 1999), land conservation (Albers et al., 2006), ecological restoration (Buckley and Haddad, 2006), common property renewable resource use (Polasky et al., 2006; Hannesson, 1997; Dutta, 1995), and emissions decisions (Maler and de Zeeuw, 1998). Game theory is often applied to problems of public good provision where the free rider problem exists. Because fire risk depends on the effort of many individuals, fuel management as a form of hazard mitigation is a public good; it is, to a certain degree, non-rival and non-excludable. If an individual reduces the fuel load on his or her property, then wildfire risk is reduced on both the individual's property and on neighboring properties; the individual cannot exclude neighbors from benefiting, or "free riding," on her effort.

Reddy (2000) examines hurricane damage mitigation as a public good and identifies the institutional characteristics that minimize free riding and promote sustainable development. Varian (2004) and Hirshleifer (1983) use game theory to examine public good provision and evaluate alternative technologies that relate individual effort to improvements in provision of the public good. Because fuel reduction effort both on an individual unit and on the surrounding landscape affects wildfire risk (Hann and Strohm, 2003), especially in the case of large wildfires (Finney, 2001; Gill and Bradstock, 1998), I employ the total effort technology. In my model, public good provision will depend on the weighted sum of the efforts exerted by individuals and, more specifically, fuel reduction in nearby areas will have a greater influence on wildfire risk than fuel reduction in areas further away.

Despite the characteristics of fire-risk management that make game theory appropriate (i.e., both individual and collective actions affect wildfire risk), only Amacher et al. (2006) and Crowley et al. (2008) use a stand-level models to analyze the strategic interaction between government and a private land owner, in their choice of suppression level and fuel reduction effort level, respectively. Amacher et al. (2006) models a single stand and focus on the strategic interaction between the individual land owner's fuel management decision and the government's suppression decision. Crowley et al. (2008) model two adjacent stands and examine the interaction between two private land owners' fuel management decisions and government's suppression decision. In both studies the landscape is composed of private land only.

In this paper, I consider a more complex system of public and private land ownership where both the private land owner and the public land manager to make fuel management decisions. With this framework I am able to explore how the spatial configuration of ownership and location affect fuel management decisions. Crowley et al. (2008) find that the inefficiencies in fire risk management result primarily from publicly funded fire suppression. However, because public suppression and fuel treatment and decisions are typically unrelated in practice,[4] I focus on the interaction between public and private land owners and free riding.[5]

2.3 Models of land management with spatial interdependence

In many cases, optimal land management requires explicit consideration of landscape pattern and location. Models of land management with spatial interdependence can be broadly grouped into those with a single decision maker and those with multiple decision makers. The primary difference between these two frameworks is that when there are multiple decision makers, the strategic interaction between individuals must be incorporated into the analysis.

2.3.1 A single decision-maker

Swallow and Wear (1993), Swallow et al. (1997), and Albers (1996) examine optimal forest management decisions under sole ownership in spatially discrete dynamic frameworks. Both Swallow and Wear (1993) and Swallow et al. (1997) begin with standard optimal rotation Faustmann type models. Swallow and Wear (1993) model forest management decisions on a focal plot in a landscape with spatial interactions, but where management on surrounding plots is exogenous. Swallow et al. (1997) extend this model and examine a landscape with spatial interaction where the management of all stands is endogenous. Both Swallow and Wear (1993) and Swallow et al. (1997) conclude that when spatial

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[4] This is evidenced by the separation of budgets and personnel with respect to suppression and fuels management programs in federal agencies.

[5] If a social planner made the fuel treatment and suppression decisions jointly, then the tradeoff (i.e., the benefit of reduced suppression cost from increases in fuel reduction) between the two would be an important consideration.

interactions are incorporated into the model, optimal management differs substantially from the traditional Faustmann (and Hartman) type forest management models. Extending these models, Albers (1996) examines the spatial interdependence of tropical forest management in the presence of uncertainty where irreversibilities exist and, given these assumptions, finds that optimal management favors preservation and flexible management.

2.3.2 Multiple decision-makers

When there are multiple decision-makers, models of land management with spatial externalities must include an analysis of the strategic interaction among individuals. In the literature, this has been done within both experimental economic and theoretical frameworks. In the field of experimental economics, Parkhurst et al. (2002) and Parkhurst and Shogren (2007) analyze the effectiveness of an agglomeration bonus at reducing habitat fragmentation (Parkhurst et al., 2002) and creating stylized conservation patterns (Parkhurst and Shogren, 2007). In both studies, the players act as private land owners with essentially identical benefit functions. And in the spatially explicit Parkhurst and Shogren (2007) model, the players' land units are identical. In both studies players move simultaneously and the game is repeated many times, allowing non-cooperative players to make observations and form opinions about each others' behavior. In this way, the history of play informs decisions made in the current period. In the model developed here, the history of play does not matter; only fuel stock matters.

Buckley and Haddad (2006) model a sequential game between two land managers, a restorationist and a farmer, but theirs is not spatially explicit. In the single period of play, the farmer observes the restorationist's action before deciding which action to take. Buckley and Haddad find that strategic restoration requires consideration of others reaction to restoration and, in some settings, additional restoration elicits a response from others that offsets restoration gains.

Albers et al. (2006) develop a spatially explicit model of a game between different types of conservation agents, each with a unique benefit function. Each agent must choose their desired level of conservation and benefits from the total area conserved, where adjacency of conserved plots matters. Albers et al. find that both the amount and pattern of conservation depend on the differences (or similarities) between the conservation agents. In the model presented here, differences between public land managers and private landowners will similarly influence management decisions and outcomes. However, while agents can conserve any unit in the grid landscape presented in Albers et al. (2006), in the present analysis agents can make fuel management decisions on their individual unit only.

2.4 Wildfire policy: Regulation, insurance and liability

Many of the environmental and natural resource issues facing the western U.S. involve public land management, with increasing emphasis on the interaction between private and public lands. In keeping with that focus, this work is directly relevant to the current policy discussion over how best to manage wildfire in areas where public and private lands meet and intermingle. The Healthy Forests Restoration Act of 2003 (HFRA) was the legislative response to increasing threats posed by catastrophic wildfire, but economic analysis has not yet informed the implementation of the Act. The primary objective of HFRA is to increase hazardous fuels reduction projects on National Forest, Bureau of Land Management, and other federal lands in order to protect communities and private property in the WUI, municipal watersheds, and endangered species habitat. The U.S. Government Accountability Office (GAO) emphasized the need for research in this area arguing that the tradeoffs between wildfire risk reduction benefits and cost must be made explicit (GAO, 2005). The nature of these tradeoffs will be determined by the spatial configuration of ownership, land management regulations, and liability rules in place. This dissertation will inform decisions regarding hazardous fuels reduction projects on public land and have a direct impact on the effective implementation of HFRA and the choice and implementation of other state level regulations.

When market failures exist,[6] government intervention is necessary in order to move toward the efficient solution and the optimal allocation of resources. For example, to protect against hurricanes, another natural hazard, Dehring (2006) describes two market failures that justify residential construction codes: information asymmetries and externalities. When information asymmetries exist, home buyers do not have the technical expertise to evaluate the structural integrity of a house (Oster and Quigley, 1977). In the presence of externalities, building codes are required to prevent market participants from developing land in a way

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[6] Markets fail when they don't achieve the efficient or desired outcome.

that endangers adjacent property (Oster and Quigley, 1977). I assume that private land owners are able to evaluate the fuel conditions and accurately estimate fire-risk,[7] and focus only on the market failure created by externalities.

Land management regulation is one tool with the potential to correct for this market failure. For example, a regulation establishing a maximum fuel load on each land unit would require individual land owners to manage their fuel load. This would limit the fire-risk on the individual unit and the fire-risk imposed on neighbors. Montana, Minnesota, New Mexico, and Washington statutory law require landowners to reduce excessive fuel loads to reduce the possibility of wildfires (Yoder et al., 2003). In a similar move, Oregon passed the Oregon Forestland-Urban Interface Fire Protection Act in 1997 and the associated administrative rules in 2002, which require fuel removal on private land in at-risk areas and became effective in 2007.

As an alternative to government regulation, market-based mechanisms provide economic incentives to individuals to guide individuals' behavior. Private insurance is a market-based mechanism that could be applied to the wildfire problem. At present, standard homeowner insurance contracts cover wildfire damage without consideration for the probability of fire or the impact of actions taken to reduce expected damage in the case of a fire.[8] Therefore, current

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[7] There are many state and federal wildfire awareness and education programs throughout the western U.S. suggesting that this might not be the case. Crowley et al. (2008) examine the impact of information asymmetries on fuel management and find that the greatest increases in the social cost of fire management occur when landowners are unaware of the benefits of fuel treatment.

[8] In November 2006, Oregon Department of Forestry and the Oregon State Fire Marshal's Office met with insurance agents to try and convince agents to offer incentives on homeowners' policies to induce self-protective measures, as described in the Oregon Forestland Urban Interface Fire Protection Act (1997). At present, however, there is only limited interest on the part of the insurance industry to adjust premiums to reflect the true, in almost all cases higher, wildfire risk.

insurance contracts implicitly encourage individuals to build in fire-prone areas and eliminate their incentive to engage in self-protection. Even in the presence of government subsidies for wildfire risk reduction, with a standard insurance contract,[9] individuals will undertake zero self-protective actions (Lankoande, 2005). Public disaster relief following a fire is also found to reduce private expenditures on both insurance and self-insurance (Brunette and Couture, 2006). Finally, it must be noted that private insurance and fuel treatment are not perfect substitutes because, unlike fuel removal, private insurance does not generate positive spatial externalities. For this reason, policies which promote or require insurance, such as the National Flood Insurance Program (NFIP), will have a different impact than those which require self-insurance.

Liability is another market-based mechanism that could be applied to the wildfire problem. Liability rules can be divided into two types: strict liability and negligence. Strict liability requires that one party compensate for losses regardless of precaution. A negligence rule only requires compensation if an individual is proven negligent; otherwise the owner of the damaged property bears the cost of fire damage. Twenty-two states in the U.S. have negligence rules for prescribed fire and the spread of wildfire and four states have strict liability rules (Yoder et al., 2004). Because the model presented here does not include fire spread—when a fire occurs it burns across the entire landscape—including an analysis of strict liability and negligence rules would require an assumption about the wildfire ignition location.

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[9] Lankoande (2005) derives this result for a standard pooling contract following Laffont (1990), which assumes a perfectly competitive insurance market, actuarially fair contracts, and risk averse individuals who insure themselves completely.

2.5 Summary

The research presented here is representative of how economics can inform wildfire risk management in the presence of spatial externalities. In recent years, significant advances have been made in the modeling of land management decisions with spatial interdependence. These models addressed management decisions on a single ownership with spatial independence and interdependence, across multiple ownerships with spatial independence and interdependence, on a landscape with multiple decision-makers. The next step in this progression of research is the study of management decisions on landscapes with mixed ownership where individual decision-makers have different management objectives. Each nuance in these increasingly complex land management decision models provides new insight into optimal land management. Taking the next step within this body of work will provide timely insight into fire risk management decisions on landscapes with mixed ownership and aid in the design of policy to address wildfire risk.

3. FRAMEWORK

3.1 General Model

I approach the wildfire problem using a spatially explicit, dynamic game theoretic model. The game is set on a forested landscape with mixed ownership—public and private. Similar in spirit to Swallow and Wear (1993), Swallow et al. (1997), and Albers (1996), all spatial interactions between adjacent units are considered and a dynamic setting is examined. In the model, spatial interactions include the effect that the fuel load on an individual unit has on neighboring units and vice versa. These effects are included by their explicit consideration in landowners' fuel management decisions. The setting is dynamic because individuals consider the future when making fuel management decisions. That is, decision-makers account for the fact that fuel management decisions in one period affect the fuel stock and, therefore, the expected loss from wildfire in later time periods. Unlike Swallow and Wear (1993), Swallow et al. (1997), and Albers (1996), all of which model land management decisions under sole ownership, I examine these decisions on a landscape with mixed ownership and owners with different objectives.

3.1.1 Fire, Fuels, and Suppression

I assume the probability of a fire on the landscape in each period is constant and that when a fire occurs it burns across the entire landscape. These assumptions obviate the need to model fire behavior and allow me to focus on the strategic interaction between landowners and the ownership pattern. Although the fire affects the entire landscape, its effect is not felt equally across ownership units. Value loss from fire is an increasing function of fuel stock on the individual unit and on neighboring units. This is because when fuel stocks are high, fire intensity is also high, but when fuel stocks are low the opposite is true. To illustrate, a high-intensity fire might kill all the standing trees and completely destroy structures thereby eliminating all environmental service values and destroying private property values. On the other hand, a low-intensity fire might kill only the low shrubs and debris, cause very little damage to existing structures, and leave environmental service values largely intact.

Forest fuels include trees, shrubs and other vegetation that grows over time. There are three basic types of forest fuels: surface fuels, ladder fuels, and canopy fuels. Surface fuels include forest litter, grasses, and fine woody material. Ladder fuels create continuity between surface fuels and canopy fuels. Finally, canopy fuels are made up of the forest canopy and are measured in terms of canopy bulk density. Ladder fuels and canopy fuels are important factors contributing to stand-replacing fires whereas surface fuels contribute to surface fires. I focus only on surface fuels, which determine the intensity of a surface fire. Of the three fuel types, surface fuels grow the fastest. After a surface fire, total surface fuel stock decreases as surface fuel is consumed.

Fire suppression reduces fire damage by protecting both private property and public lands where environmental service and public good values are present. I assume that an attempt is made to suppress all fires, but that the effectiveness of suppression decreases with fuel stock. Once a fire starts, I assume that full force suppression occurs and that the level of suppression is not a choice variable. Because suppression effort is exogenous, its effectiveness is included implicitly in the model. Taking a different approach, Crowley et al. (2008) focus their analysis on the tradeoff between fuel treatment and suppression and, as a result, find that the greatest inefficiencies in fire management are caused by free-riding on public provision of fire suppression effort.

The assumption that fire suppression effort is exogenous is consistent with the absence of consideration for the tradeoff between fuels treatment and suppression in practice. In state and federal land management agencies, fire suppression decisions are made by different groups of people, at different points in time, and using different budgets. Once suppression policy improves, managers might be able to consider this tradeoff, but, for now, modeling suppression as exogenous is a reasonable representation of current fire management.

3.1.2 The Game

There are $i=(1,\ldots,N)$ land units owned by either a private individual or a public agency and $t=(0,\ldots,T)$ time periods. Land units are located in the fire-prone WUI and contain flammable forest fuels. Both public and private owners must make fuel management decisions, but the values each owner considers when making fuel management decisions are different.

I assume the private individual's land unit contains a structure which might serve as a primary residence or vacation home. The private owner's values at risk of wildfire damage include structure value and amenity value. Structure value is simply the value of the physical structure. Amenity value includes scenic views and proximity to recreation, for example, which are location dependent and depend on the attributes of neighboring sites. The sum of structure value and amenity value on each unit can be thought of as total private property value. Such amenity values are capitalized into the market value of the property.

The public manager's value at risk of wildfire damage includes public good amenity values only.[10] Public good amenity value may include existence, biodiversity, ecosystem function, and carbon sequestration values, for example. Because pure public goods are non-rival and non-excludable, the spatial location of both local and non-local individuals does not influence the amount any one individual benefits from the public good. However, while location of the individual may not matter for public good amenity value, location may matter in terms of public good generation. For example, highly productive forest sites will sequester greater amounts of carbon than less productive sites thus providing greater carbon sequestration public good benefits. For this reason, a public good value is assigned to each unit representing its individual contribution to total public good value. Because my focus is not on timber value, which increases in value over time, I assume that, unless damaged by fire, structure, amenity, and public good amenity values remain constant over time.

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[10] The public manager will consider private property value if liability rules, which will be introduced later, are in place and require they do so.

The uncertainty in each period of the game is from fire and is completely resolved at the end of the period. There are two states of the world in each period: 'fire' and 'no fire.' The 'fire' state of the world occurs with frequency ρ and the 'no fire' state of the world occurs with frequency $1-\rho$. If a fire occurs, fuel stock and values on the entire landscape are affected. Specifically, the fuel stock decreases as surface fuels are consumed and both private and public landowner's values are lost. The extent of damage to private property and public good values on individual units is an increasing function of pre-fire fuel stock on the individual unit and surrounding units. If a fire does not occur, damage to private property and amenity values on all units is zero and the fuel stock continues to grow, unabated by fire.

At the beginning of each period, public and private owners simultaneously choose their level of fuel treatment effort $x \in [0,1]$ to minimize expected loss from fire damage. After fuel reduction decisions are made, either a fire occurs or it does not. The payoff to each player is determined by the individual's post-fire values and fuel treatment costs. To summarize, the sequence of events is as described in table 3.1.

TABLE 3.1: Sequence of events in the game

Time = 1	• Players simultaneously choose and implement fuel treatments • Fire occurs or does not occur • Players receive payoffs • Fuel stock grows
Time = 2	• Players simultaneously choose and implement fuel treatments • Fire occurs or does not occur • Players receive payoffs • Fuel stock grows
. . .	. . .
Time = T	• Players simultaneously choose and implement fuel treatments • Fire occurs or does not occur • Players receive payoffs • Fuel stock grows

If there is no fire in time *t*, then fuel stock, s_t, evolves according to the following equation:

$$s_{t+1} = G(s_t, x_t) \tag{3.1}$$

Where s_t is a vector of the pre-treatment individual stocks of forest fuel on each of the *i* units, x_t is the level of fuel treatment on each of the *i* units, and $G(\cdot)$ is growth in forest fuel as a function of post-treatment fuel stock. When there is a fire in time *t*, fuel stock evolves according to the following equation:

$$s_{t+1} = G(D^f(s_t, x_t)) \tag{3.2}$$

Where D^f is a "damage" function giving post-fire fuel stock as a function of post-treatment fuel stock should a fire occur. The amount of fuel consumed by the fire is an increasing function of the post-treatment, pre-fire fuel stock. Fuel stock never goes to zero because even after the most severe surface fire, fuel growth from intact root systems or nearby seed sources, for example, will occur. This might not be the case, however, for catastrophic fire, which has a far more severe impact on vegetation and soils.

In addition to consuming fuel, fire damages private property and public good values on the landscape, causing owners to incur losses.[11] The damage function used to estimate post-fire values is deterministic and increasing in fuel stock. The greater the pre-fire fuel stock, on both the individual and neighboring units, the greater the value loss. Fire suppression is included implicitly in the damage function because suppression will successfully put out the fire more quickly when fuel stocks are low than when they are high.

Because public and private owners have different values at risk, the specification of the equation describing total loss from fire will depend on whether the unit is publicly or privately owned. In practice, private landowners often make fuel management decisions as a coordinated group of individuals in a housing development, as a homeowners' group, or informally as a group of neighbors (Monroe and Nelson, 2004; Brenkert-Smith et al., 2006). When the private actors are acting as a single coordinated player, the fuel stock externalities that exist among private owners are internalized.[12] In the model, the private

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[11] Beneficial fires are not considered, however it is true that in some cases ecosystems might benefit from fire. Structure value, on the other hand, is unlikely to ever benefit from fire. Because the focus here is on fire in the WUI, where public and private land is intermixed, it is reasonable to assume that all fires are undesirable. However, fire does benefit landowners in one way: it acts as free fuel treatment because it reduces the next period's fuel stock.

[12] I do not consider the case where fuel management decisions on private units are made by the owner of each private unit, individually. Comparing the outcome of the game when private actors are coordinating decisions and when private landowners are acting independently, will clearly identify the inefficiency created when the positive spatial externalities of fuel treatment are internalized among private landowners. For this case, I would expect the results to be similar to

landowners act a single coordinated decision-maker. Similarly, fuel treatment decisions on publicly owned units are made by a single public decision-maker.

In the case of fire, total loss due to fire damage in any given time period on privately owned units is given by Equation 3.3 and loss on publicly owned units is given by Equation 3.4:

$$L_t^{PRIV}(v_t(a_t(s_t,x_t),h_t(s_t,x_t))) \tag{3.3}$$

$$L_t^{PUB}(P_t(p_t(s_t,x_t)) \tag{3.4}$$

Where

v_t = total private property value

a_t = vector of amenity value generated on each unit

h_t = vector of structure value on each unit

P_t = total public good value

p_t = vector of each unit's contribution to total public good value

s_t = vector of fuel stock on each unit

x_t = vector of fuel treatment on each unit

If there is no fire, a_t, h_t, and p_t stay the same and the change in values (or the loss) is simply:

$$v_{t+1}(a_{t+1},h_{t+1})-v_t(a_t,h_t)=0 \tag{3.5}$$

$$P_{t+1}(p_{t+1})-P_t(p_t)=0 \tag{3.6}$$

---

the case where public and private owners make uncoordinated decisions, but with even greater inefficiencies.

If there is a fire, post-fire values are calculated with the damage function:

$$a_{it+1} = D^a(s_t, x_t) \cdot a_{it} \tag{3.7}$$

$$h_{it+1} = D^h(s_t, x_t) \cdot h_{it} \tag{3.8}$$

$$p_{it+1} = D^p(s_t, x_t) \cdot p_{it} \tag{3.9}$$

Where $D^{a,h,p}$ gives the proportion of amenity value, structure value, and public good value remaining on each unit *i* after a fire, respectively. When making fuel treatment decisions, each player must consider both the costs and benefits of all fuel management options. The benefit from fuel treatment is in terms of reducing the damage to values at risk in case of a fire. The effect of fuel treatment on unit *j* on unit *i*'s amenity, structure, and public good value is:

$$\frac{\partial a_{it+1}}{\partial x_{jt}} = \frac{\partial\left[D^a(s_t, x_t) \cdot a_{it}\right]}{\partial x_{jt}} = a_{it} \cdot \frac{\partial D^a(s_t, x_t)}{\partial x_{jt}} \tag{3.10}$$

$$\frac{\partial h_{it+1}}{\partial x_{jt}} = \frac{\partial\left[D^h(s_t, x_t) \cdot h_{it}\right]}{\partial x_{jt}} = h_{it} \cdot \frac{\partial D^h(s_t, x_t)}{\partial x_{jt}} \tag{3.11}$$

$$\frac{\partial p_{it+1}}{\partial x_{jt}} = \frac{\partial\left[D^p(s_t, x_t) \cdot p_{it}\right]}{\partial x_{jt}} = p_{it} \cdot \frac{\partial D^p(s_t, x_t)}{\partial x_{jt}} \tag{3.12}$$

The cost of fuel treatment x_{it} is given by the function $C(x_{it})$ and is explicitly considered by both players. I assume fuel reduction cost is positive and the fuel management technologies are the same for all owners. Fuel treatment cost on an individual unit *i* in time *t* is:

$$C(x_{it}) = c_0 + c \cdot (x_{it}) \tag{3.13}$$

Where

c_0 = fixed cost
c = variable unit cost

Each landowner chooses fuel treatment level with the objective of minimizing the discounted sum of expected loss from fire and fuel reduction costs, subject to the fuel stock growth and damage functions.

3.1.3 Myopic Decisions

Landowners who do not consider the future make myopic, or short-sighted, fuel treatment decisions.[13] Comparing the outcome of the game between myopic landowners to the outcome of the game between forward-looking landowners will provide insight into the value of forthcoming information about fire and the degree of strategic behavior over time. If there is a difference between the two outcomes, then either forthcoming information is valuable or landowners are interacting strategically over time, or both.

I model the fuel management decisions of myopic land owners as a series of one-shot games. The public and private landowners' objectives on unit *i* in time *t* for each one-shot game are to choose the fuel treatment patterns that minimize expected costs:

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[13] Myopic landowners are representative of individuals who do not consider future values and could be thought of as individuals with an infinite discount rate (or a discount factor equal to one).

$$\min_{x_{it} for i \in PRIV} \rho \cdot L_t^{PRIV}(v_t(a_t(s_t, x_t), h_t(s_t, x_t))) + \sum_{i \in PRIV} C(x_{it}) \tag{3.14}$$

$$\min_{x_{it} for i \in PUB} \rho \cdot L_t^{PUB}(P_t(p_t(s_t, x_t))) + \sum_{i \in PUB} C(x_{it}) \tag{3.15}$$

The private landowner's objective in the one-shot game is described by Equation 3.14 and the public landowner's objective is descried by Equation 3.15. Player *i*'s optimal strategy $x_{it}^*(s_t)$ is the choice of fuel treatment that minimizes expected costs, given that all other players are making fuel reduction choices to minimize expected costs.

The basic equilibrium concept applied to the one-shot game is the Nash equilibrium (NE). A NE is a set of strategies for each player such that each player's strategy is a best response to the others' and no player has incentive to deviate from their chosen strategy. In the context of the fuel treatment game, a NE is a fuel treatment pattern where each landowner is choosing their best response to what the other players are doing.

3.1.4 Dynamic Decisions

When landowners are forward-looking and consider how decisions in the current time period affect future decisions and outcomes, the game becomes dynamic. Specifically, the game is dynamic because fuel treatment in one period determines the amount of fuel and fire risk in the next period and allows owners to vary the timing of fuel reductions to manage risk. Letting $V_{it}(s_t)$ denote the present value of the aggregate costs on unit *i* when the current fuel stock is s_t, the stochastic dynamic programming problem (or Bellman equation) for privately owned unit is given by Equations 3.16 and by 3.17 for a publicly owned unit:

$$\begin{aligned} V_t^{PRIV}(s_t) &= \min_{x_{it}\ \text{for}\, i\in PRIV} \rho \cdot L_t^{PRIV}(v_t(a_t(s_t,x_t),h_t(s_t,x_t))) \\ &+ \sum_{i\in PRIV} C(x_{it}) + \beta \cdot E[V_{t+1}(a_{t+1},h_{t+1},s_{t+1},x_{t+1})] \\ &\text{for } t = 1,\ldots,T \end{aligned} \tag{3.16}$$

$$\begin{aligned} V_t^{PUB}(s_t) &= \min_{x_{it}\ \text{for}\, i\in PUB} \rho \cdot L_t^{PUB}(P_t(p_t(s_t,x_t))) \\ &+ \sum_{i\in PUB} C(x_{it}) + \beta \cdot E[V_{t+1}(p_{t+1},s_{t+1},x_{t+1})] \\ &\text{for } t = 1,\ldots,T \end{aligned} \tag{3.17}$$

Where $\beta \in [0,1]$ is the discount factor. Equations 3.16 and 3.17 add current and present value of future costs, both of which are functions of values at risk, fuel stock on the individual manager's unit and neighboring units, and the probability of fire. A player's optimal strategy $x_{it}^{*}(s_t)$ is the choice of fuel treatment in time *t* that minimizes expected loss plus cost, given that the other player is making fuel treatment choices to minimize expected loss plus cost.

In repeated, or multi-period, games, the past can matter for two reasons: either the players believe past behavior influences future behavior or past decisions affect the future environment in which the game is played (Fudenberg and Tirole, 1992). I assume that the past matters only through its affect on the environment in which the game is played. Past decisions about fuel removal influence the fuel stock (or "state variable") in future periods. For this reason we focus only on "Markov" strategies or "state space" equilibrium strategies. A

Markov perfect equilibrium (MPE) is a profile of Markov strategies that yields a Nash equilibrium in every time period, or "subgame" (Fudenberg and Triole, 1992). Because the concept of MPE is a refinement of the more general Nash equilibrium (NE) it has several advantages over the NE concept: MPE reduces the number of possible equilibria in dynamic games, thereby improving the predictive power of the model; by allowing only the state variable to affect strategic behavior, the impact of state variables on outcomes is made clear; and, finally, Markov models can be easily simulated (Maskin and Tirole, 2001).

3.1.5 Socially Optimal Fire-Risk Management

Socially optimal fire-risk management is the landscape-level fuel treatment pattern that is best for society, as a whole. The socially optimal fuel treatment pattern is found by solving the "social planner's" problem. The social planner considers all values on the landscape, both public and private, and makes fuel management decisions to protect total value at risk. Equation 3.18 describes the social planner's problem.

$$\begin{aligned} V_t^{SP}(s_t) &= \min_{x_{it} \forall i} \rho \cdot \left(L_t^{PUB}(P_t(p_t(s_t, x_t))) + L_t^{PRIV}(v_t(a_t(s_t, x_t), h_t(s_t, x_t))) \right) \\ &+ \sum_i C(x_{it}) + \beta \cdot E[V_{t+1}(a_{t+1}, h_{t+1}, p_{t+1}, s_{t+1}, x_{t+1})] \\ &\text{for } t = 1, \ldots, T \end{aligned} \tag{3.18}$$

The social planner's optimal decision $x_{it}^*(s_t)$ is the choice of fuel treatment on all public and private units in time *t* that minimizes the sum of public and private expected total costs. If the socially optimal fuel treatment schedule is different from the outcome of the game, then the outcome of the game is sub-optimal and there is opportunity to make society, as a whole, better off.

3.1.6 Policy Analysis

I explore the potential of three policy options to improve the outcome of the game, relative to the social optimum. The three policies include: a fuel stock regulation, a liability rule, and an insurance program. These three policies were chosen because they are in place or are being considered in many parts of the western U.S. as a way to address wildfire risk.

The fuel stock regulation establishes a maximum allowable fuel stock on each public and private unit. To model fuel stock regulation, I add a fuel stock constraint to each landowner's problem. The constraint states that fuel stock on unit i in period t must be less than or equal to the maximum allowable fuel stock $\bar{s}$ on all units and in all time periods.

The liability rule holds a landowner liable for fire damage on neighboring ownerships if a fire ignites and spreads from the landowner's unit. However, because I am not modeling fire behavior or ignition, I assume that all fires ignite on public land. The relevance of this assumption is illustrated by recent claims against the USFS. For example, the 2000 fires in Montana's Bitterroot National Forest burned a third of a million acres and destroyed 52 homes, 23 other buildings, and 2 sawmills, all on private property. As a result of the destruction, 113 individuals files torte claims against the USFS seeking $54 million in damages (Ring 2003). With the liability rule in place, public is liable for a fraction α of private value loss in the case of a fire. When making fuel treatment decisions, the private landowner only considers only the fraction of value $1-\alpha$, which will not be compensated by the public landowner. The complement to this is that the public landowner must now consider the fraction of private value α that must be compensated.

Finally, I examine the impact of private insurance on the outcome of the fuels treatment game. Private insurance compensates the landowner for value lost due to fire damage. I assume fair insurance, where the cost of the policy is equal to its expected value. Because the private landowners are risk neutral, they are indifferent between accepting and rejecting fair insurance. To ensure the insurance is accepted, I assume an insurance requirement.

I examine the "full insurance" case where private landowners fully insure their structure value. Because all value is covered under the insurance policy, the landowner will choose zero fuel treatment. Whether there is a fire or not, the private landowner's loss in every period is the same (the product of the premium per unit value covered and the total private property value, the amount insured). Insurance is fair and the premium per dollar coverage is equal to the probability of fire. Equation 3.19 describes the private landowner's single period decision with full insurance coverage of structure and amenity values:

$$\min_{x_{it} for i \in PRIV} \sum_{i \in PRIV} (C(x_{it}) + \pi \cdot v_{it}) \tag{3.19}$$

where

π = the insurance premium per unit value coverage

v_{it} = private property value on unit *i* in time *t* or the amount insurance pays if fire and 100 percent of value is lost

Equation 3.19 states that if there is a fire, the private landowner's losses are equal to the cost of fuel treatment and the cost of the insurance policy. And if there is not a fire, losses are also equal to the cost of fuel treatment and the cost of the insurance policy.

3.2 Baseline Parameterizations

The base case represents the simplest specifications of the problem and allows me to explore the basic behaviors that arise from the interaction between landowners on a simple landscape. The baseline is not intended to represent a realistic or likely situation, but to provide a foundation for understanding which factors matter in which ways. Subsequent sections will be used to add refinements and complexities, representing realistic situations and policy scenarios, to the base case.

3.2.1 The Game

The fuel management game consists of two landowners, one public and one private, making fuel treatment decisions on a three-by-three grid landscape. The fuel treatment choice is discrete and at the beginning of each of the two ten-year periods the landowners each decide whether or not to treat each of their individual units. When making these decisions, landowners consider both the cost and benefit of fuel treatment. Fuel treatment benefits the landowner because decreasing fuel stocks on the individual and neighboring units reduces the damage to values at risk. But there is a cost to reducing fuel stock with treatment, which must also be considered.

3.2.2 Ownership Patterns

I used ownership maps to identify typical ownership patterns in order to model landowner interaction on landscapes characteristic of the western U.S. Land ownership maps were obtained for the following areas: Beaverhead County, Montana; Deschutes County, Oregon; Harney County, Oregon; Lemhi County, Idaho; Clearwater County, Idaho; Catron County, New Mexico. From ownership patterns observed on these maps, I identified twelve typical public-private ownership patterns. These characteristic patterns are represented on a three-by-three grid landscape (Figure 3.1). A single public manager makes fuel management decisions on all public units and decisions on private units are made by a coordinated group of private individuals.

FIGURE 3.1: Twelve Ownership Patterns

Private Adjoining Public

PUB	PUB	PUB
PUB	PUB	PUB
PRIV	PRIV	PRIV

Public Adjoining Private

PRIV	PRIV	PRIV
PRIV	PRIV	PRIV
PUB	PUB	PUB

Private Corridor

PUB	PUB	PUB
PRIV	PRIV	PRIV
PUB	PUB	PUB

Public Corridor

PRIV	PRIV	PRIV
PUB	PUB	PUB
PRIV	PRIV	PRIV

Isolated Private

PUB	PUB	PUB
PUB	PRIV	PUB
PUB	PUB	PUB

Isolated Public

PRIV	PRIV	PRIV
PRIV	PUB	PRIV
PRIV	PRIV	PRIV

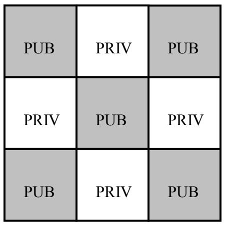
Private Extending into Public

PUB	PUB	PUB
PRIV	PRIV	PUB
PUB	PUB	PUB

Public Extending into Private

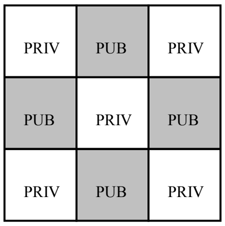
PRIV	PRIV	PRIV
PUB	PUB	PRIV
PRIV	PRIV	PRIV

Checkerboard with Public in Center



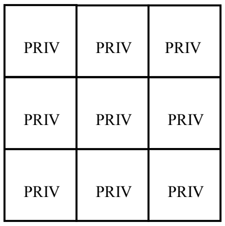
PUB	PRIV	PUB
PRIV	PUB	PRIV
PUB	PRIV	PUB

Checkerboard with Private in Center



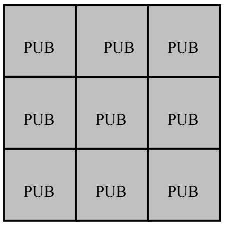
PRIV	PUB	PRIV
PUB	PRIV	PUB
PRIV	PUB	PRIV

All Private



PRIV	PRIV	PRIV
PRIV	PRIV	PRIV
PRIV	PRIV	PRIV

All Public



PUB	PUB	PUB
PUB	PUB	PUB
PUB	PUB	PUB

As depicted in Figure 3.1, ownership units are of equal size and dimension. However, the spatial scale of the landscape itself is not specified and will depend on the spatial externality weighting system and the degree to which fire risk on an individual unit is influenced by nearby land units. When the fuel stock on neighboring units has a significant influence on fire damage on an individual unit, the size of the landscape is relatively small. But for the fuel stock on neighboring units to have close to zero influence on fire damage on an individual unit, the size of the landscape must be relatively large.

3.2.3 Spatial Externality Weighting and Damage Function

Fuel stock measures the quantity of surface fuels–litter and fine woody debris—on the individual unit. The initial fuel condition on each of the nine units in the three-by-three grid landscape is identical. Fuel stock growth is linear and at the end of each ten-year time period fuel stock doubles. If there is a fire, fuel stock decreases as surface fuels are consumed. Post-fire fuel stock is a function of pre-fire fuel stock and, for the baseline results, is calculated in the same way as value loss. I assume that fuel treatment reduces fuel stock to some fixed level, λ_i.[14]

$$G(s_t, x_t) = \mu \cdot (s_t - x_t) \tag{3.20}$$

$$x_t = \lambda \tag{3.21}$$

where

Baseline $\mu = 2$

Baseline $\lambda = 2$

I use a fuel stock weighting system to capture the influence of neighboring units' fuel stock on fire risk. Because values on the landscape respond differently to wildfire and the physical characteristics of a landscape may determine which neighbors' fuel stocks matter, the weighting systems used to determine fire damage may not always be the same. To illustrate how values might respond differently, suppose the survivability of a structure is largely determined by the immediately surrounding area only (Cohen, 1999). If that were the case, then the fuel stock only on unit *i* would determine structure value loss. However, the impact of fire on a unit's habitat value might depend on fuel stock on both the individual unit and all four surrounding units on the grid. In addition, the physical characteristics of the landscape such as slope and the prevailing wind direction

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[14] Because the focus here is on surface fuels and surface fires, this assumption is valid. But for other types of fuels and fires, this might not be the case. For example, a crown fire might actually increase some types of fuels, such as large dead and down woody material.

will also determine how neighboring fuel stocks matter—fuel stock on the up-wind or down-slope unit is significant in determining fire damage on the individual unit.

The equation used to calculate damage to values at risk and fuel consumed by fire is:

$$D_i^k(s_t, x_t) = \eta \cdot w_i \tag{3.22}$$

Where

D_i^k = damage to value, k, at risk on unit i (percent of pre-fire value lost)

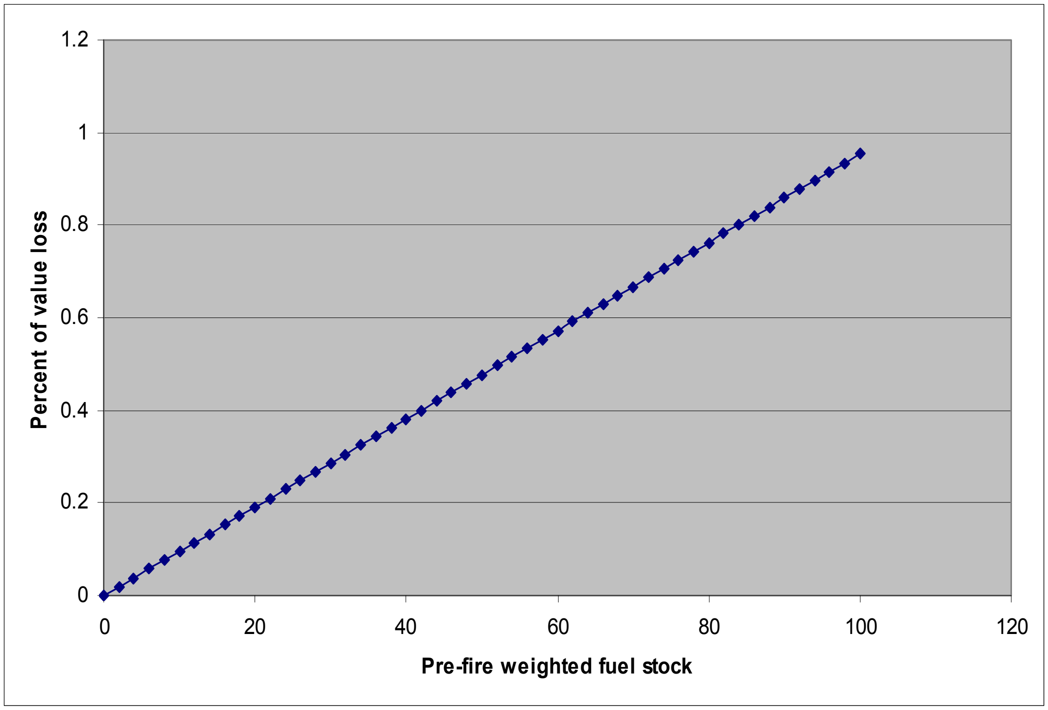
w_i = weighted fuel stock affecting unit i

η = scaling factor

k = a, h, p, f

The damage function is linear and as pre-fire weighted fuel stock increases, the percent of value lost, or fuel consumed, increases at a constant rate. When weighted fuel stock is at its maximum, approximately ninety-five percent of value and fuel stock is lost. The baseline percent loss function is depicted in Figure 3.2 and is the same for a, p, h, and f.

FIGURE 3.2: Percent of Unit *i*'s Value Lost as a Function of Pre-Fire Weighted Fuel Stock on the Individual Unit



The weights assigned to each unit's fuel stock represent *how* fuel stock matters for value loss on an individual unit *i* in the case of a fire. The weighted fuel stock on unit *i*, w_i, represents the combined effect of fuel on unit *i* and all units $j \neq i$ on fire damage on unit *i*. Weighted fuel stock on unit *i* is calculated as:

$$w_i = \sum_{j=1}^{n} \omega_{ij} \cdot (s_{jt} - x_{jt}) \qquad (3.23)$$

Where

ω_{ij} = the impact of fuel stock on unit *j* on fire damage on unit *i*

The weight, ω_{ij}, represents the contribution of post-treatment fuel stock, λ, on unit j to fire damage on unit i. The bigger the weight assigned to unit j, the more important that unit's fuel stock in determining fire damage on unit i. For the baseline results, I assume a simple weighting scheme where the individual unit i and the four surrounding units matter equally for fuel consumed and amenity, structure, and public good value loss on unit i.

In terms of the damage function, the weights are the derivative of the damage function with respect to x_{jt}:

$$\frac{\partial D^k}{\partial x_{jt}} = -\eta\omega_{ij} \tag{3.24}$$

$$k = a, h, p, f$$

The derivative is negative because fuel treatment reduces fire damage and decreases fuel consumption. After weighted fuel stock is calculated, it is used to calculate fire damage. Post-fire values are a function of the pre-fire weighted fuel stock. For the baseline results, the percent of value remaining post-fire and post-fire fuel stock is a linear function of pre-fire weighted fuel stock. In the results section, I also explore the fuel management decision when fire damage is a non-linear function of pre-fire weighted fuel stock. When the equalities described in Equations 3.25, 3.26, and 3.27 hold, the change in total private property value is simply the sum of amenity and structure value (Equation 3.28) and change in total public good value is simply the sum of the changes in each unit's contribution to public good value (Equation 3.29).

$$\frac{\partial v_{t+1}}{\partial a_{t+1}} = 1 \tag{3.25}$$

$$\frac{\partial v_{t+1}}{\partial h_{t+1}} = 1 \tag{3.26}$$

$$\frac{\partial P_{t+1}}{\partial p_{t+1}} = 1 \tag{3.27}$$

$$\frac{\partial v_{t+1}(a_{t+1}, h_{t+1})}{\partial x_{jt}} = \sum_i \frac{\partial v_{t+1}}{\partial a_{t+1}} \cdot \frac{\partial a_{it+1}}{\partial x_{jt}} + \sum_i \frac{\partial v_{t+1}}{\partial h_{t+1}} \cdot \frac{\partial h_{it+1}}{\partial x_{jt}} = \sum_i \frac{\partial a_{it+1}}{\partial x_{jt}} + \sum_i \frac{\partial h_{it+1}}{\partial x_{jt}} \tag{3.28}$$

$$\frac{\partial P_{t+1}(p_{t+1})}{\partial x_{jt}} = \sum_i \frac{\partial P_{t+1}}{\partial p_{t+1}} \cdot \frac{\partial p_{it+1}}{\partial x_{jt}} = \sum_i \frac{\partial p_{it+1}}{\partial x_{jt}} \tag{3.29}$$

The fuel stock weights are calibrated so that they sum to one-hundred, so for the baseline weighting scheme, the weight given to the individual unit *i* and the four surrounding units is twenty. Figure 3.3 depicts this equal weighting system applied to the center unit on the three-by-three unit landscape. To calculate weighted fuel stock on the center unit, I sum the product of the fuel stock on unit *i* and the fuel stock weight for unit *i,* across all *i* units. To illustrate, using the baseline weighting system and the fuel stock ratings given in Figure 3.4, the weighted fuel stock for the center unit is 50 (or 20*3/6+20*3/6+20*3/6+20*3/6+20*3/6). Weighted fuel stock will always be less than 100.

Figure 3.3: Fuel Stock Weighting System

	20	
20	20	20
	20	

Figure 3.4: Fuel Stock Rating out of 6

3	3	3
3	3	3
3	3	3

To calculate the weighted fuel stock for units on the edge of the landscape, assumptions about the fuel conditions outside the three-by-three grid landscape are needed. These assumptions will depend on the underlying ownership pattern. Because each ownership pattern represents public-private ownership patterns characteristic of the western U.S., assumptions made about what lies outside the grid landscape are chosen to perpetuate the relevant ownership pattern. For all public-private ownership patterns except the checkerboard pattern, I assume that units outside the three-by-three grid landscape have identical fuel stocks and make identical fuel management decisions as their adjoining unit, within the three-by-three landscape. Figure 3.5, below, illustrates the assumptions made about the area outside the three-by-three grid.

Figure 3.5: Edge for all ownership patterns except checkerboard

	Same fuel load and management as (1)	Same fuel load and management as (2)	Same fuel load and management as (3)	
Same fuel load and management as (1)	Unit (1)	Unit (2)	Unit (3)	Same fuel load and management as (3)
Same fuel load and management as (4)	Unit (4)	Unit (5)	Unit (6)	Same fuel load and management as (6)
Same fuel load and management as (7)	Unit (7)	Unit (8)	Unit (9)	Same fuel load and management as (9)
	Same fuel load and management as (7)	Same fuel load and management as (8)	Same fuel load and management as (9)	

The checkerboard ownership pattern is unique because simply assuming units outside the edge of the three-by-three grid landscape are identical to adjacent neighbor on the edge of the three-by-three grid landscape would not perpetuate the desired checkerboard pattern outside of the grid. In order to maintain a checkerboard ownership pattern outside the three-by-three grid landscape, a different set of assumptions is needed. I assume that the fuel stock on units outside the three-by-three grid landscape have identical fuel stocks and make identical fuel management decisions as the *neighbor* of their adjoining unit, within the three-by-three landscape. Figure 3.6, below, illustrates the three-by-three grid landscape when modeling decisions on the checkerboard ownership pattern.

Figure 3.6: Edge for checkerboard ownership patterns

	Same fuel stock and management as (4)	Same fuel stock and management as (5)	Same fuel stock and management as (6)	
Same fuel stock and management as (2)	Unit (1)	Unit (2)	Unit (3)	Same fuel stock and management as (2)
Same fuel stock and management as (5)	Unit (4)	Unit (5)	Unit (6)	Same fuel stock and management as (5)
Same fuel stock and management as (8)	Unit (7)	Unit (8)	Unit (9)	Same fuel stock and management as (8)
	Same fuel stock and management as (4)	Same fuel stock and management as (5)	Same fuel stock and management as (6)	

3.2.4 Values on the Landscape

To generate the baseline results, I assume that both public and private landowners have the same per unit value. Further, I assume that public good values are generated only on publicly owned units and private structure values exist on private units. For the baseline, private amenity value is set to zero.[15] Each landowner's per-unit value is 400 and total value on the landscape is 3600 (400*9) for all ownership patterns. The per-unit fixed cost of fuel treatment is 1, or 0.25 percent of per-unit value, and the variable cost of fuel treatment is 0.5. The baseline results are described in the next chapter.

3.2.5 Summary

The model described in this chapter provides the analytical framework I use to study the fire risk management problem over a wide range of settings and policy scenarios. Although the model is a simplified, theoretical representation of reality, it contains sufficient complexity to provide insight into numerous real-world fire risk management issues. To summarize, the defining characteristics of the model are described below, in Table 3.4.

TABLE 3.2: Defining characteristics of the model

Time	Two discrete time periods.
Landscape	Three-by-three grid landscape with nine units of equal size.
Decision-makers	Fuel treatment decisions on publicly owned units are made by a single public decision-maker and decisions on privately owned units are made by a coordinated group of private landowners.
Risk Preferences	Public and private landowners are risk neutral and make decisions based on expected values.
Fuel Treatment	The fuel treatment decision is a binary choice variable and treatment reduces fuel stock to a fixed level.
Fire	The probability of fire is constant and when a fire occurs it burns the entire landscape.
Suppression	The fire suppression decision is exogenous.

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[15] While the location of private structure values will always be on private units, the location of private amenity value does not necessarily need to be on privately owned units. For example, a private landowner might benefit from scenic views, hiking trails, and rivers on nearby public lands. This case is not addressed in the baseline, but will be explored in the results chapter.

4. RESULTS

This chapter begins with a description of the baseline results and then explores a number of variations in the model and the impact of those variations on the public and private landowners' fuel treatment decisions and outcomes. After a description of the baseline results, I examine the case where private landowners get amenity value from public land. Second, I look the cases where there are increasing and decreasing returns to fuel treatment. Third, I impose two alternative fuel stock weighting schemes, each representing distinct characteristics of the physical landscape. And finally, I use the model to evaluate the impact of three fire risk management policies—a fuel stock regulation, a public liability rule, and a private insurance program—on fuel treatment decisions.

4.1 Baseline Results

The baseline is meant to reflect a simple landscape and set the context for exploring the more complex interactions introduced in the model's extensions. Each landowner has an equal amount of value on their individual unit only and fire damage is a linear function of the pre-fire weighted fuel stock. In this setting, neither landowner's fuel treatment decision depends on the other's decision, so the inefficiencies that emerge from the game are a result of the ownership pattern and spatial externalities, not strategic interaction.

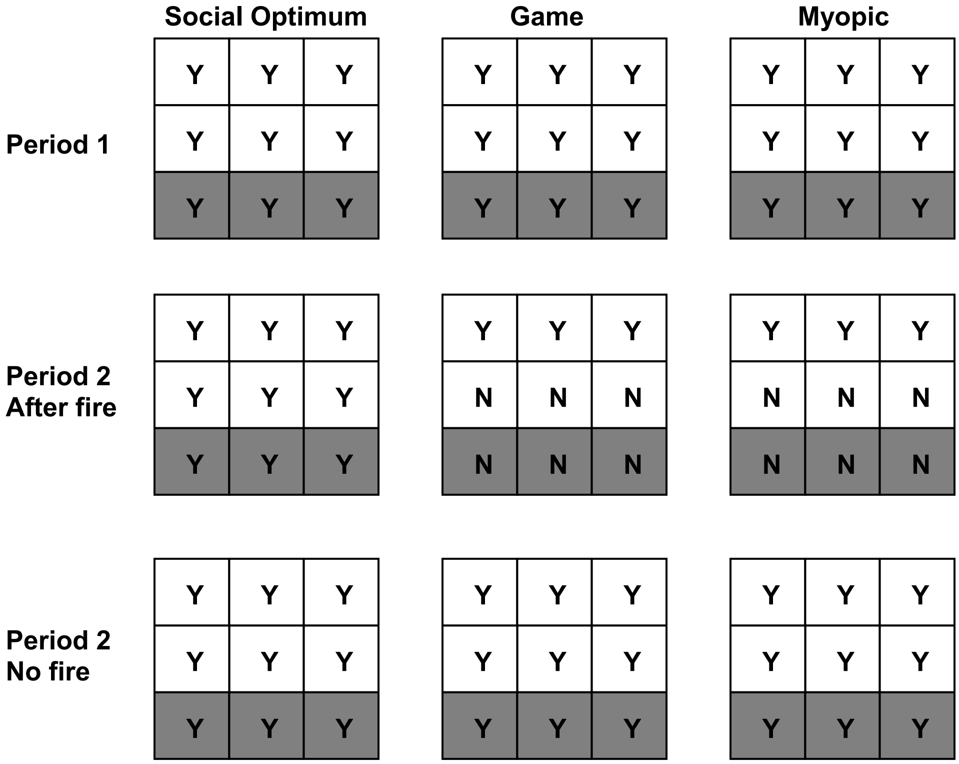
The chosen fire and fuel parameters are characteristic of eastern Cascade forests dominated by Ponderosa pine and are listed in Table 4.1. The fuel stock growth rate, post-treatment fuel stock, and probability of fire on the landscape are reasonable estimates for eastern Cascade forests (Agee and Lolley, 2006; Everett et al., 2000). Fuel treatment cost estimates range from \$25 to \$446 per acre (Calkin and Gerbert, 2006). For the baseline, cost estimates were chosen so that the landowners would choose some positive level of fuel treatment. The fixed and variable cost parameter estimates are 0.25 and 0.125 percent of per unit value, respectively. A summary of the baseline parameter values are described in Table 4.1, except for the fuel stock weights matrix which was described in chapter 3, section 3.2.3.

TABLE 4.1: Baseline Parameters

Probability of fire	ρ	0.05
Post-treatment fuel stock	λ	2
Fuel stock growth rate	μ	2
Fixed fuel treatment cost	c_0	1
Variable fuel treatment cost	c	0.5
Discount rate	β	0
Maximum percent value loss	η	0.95

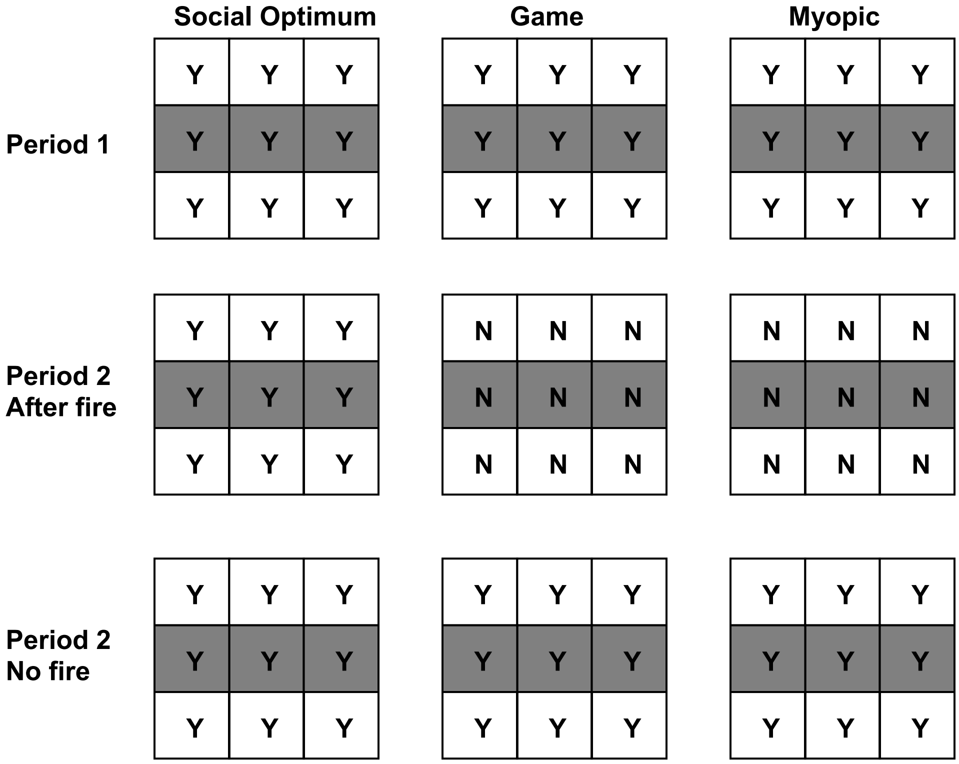
The fuel treatment decisions for the twelve ownership patterns are described in Figures 4.1 to 4.6. Shaded units on the grid landscape represent public ownership and un-shaded units represent private ownership. Units marked with a “Y” are treated in the given period and those marked with an “N” are not treated. Results in the “Game” column describe the outcome of the game between two forward-looking landowners and results in the “Myopic” column describe the outcome of the game between two myopic landowners. The outcomes of the game for the six ownership patterns in parentheses are identical to those above, except that the owners are reversed.

FIGURE 4.1: Private Adjoining Public (Public Adjoining Private) – Baseline Results



	Social Optimum	Game	Myopic
Period 1	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y
Period 2 After fire	Y Y Y Y Y Y Y Y Y	Y Y Y N N N N N N	Y Y Y N N N N N N
Period 2 No fire	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y

FIGURE 4.2: Private Corridor (Public Corridor) – Baseline Results



	Social Optimum	Game	Myopic
Period 1	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y
Period 2 After fire	Y Y Y Y Y Y Y Y Y	N N N N N N N N N	N N N N N N N N N
Period 2 No fire	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y

FIGURE 4.3: Isolated Private (Isolated Public) – Baseline Results

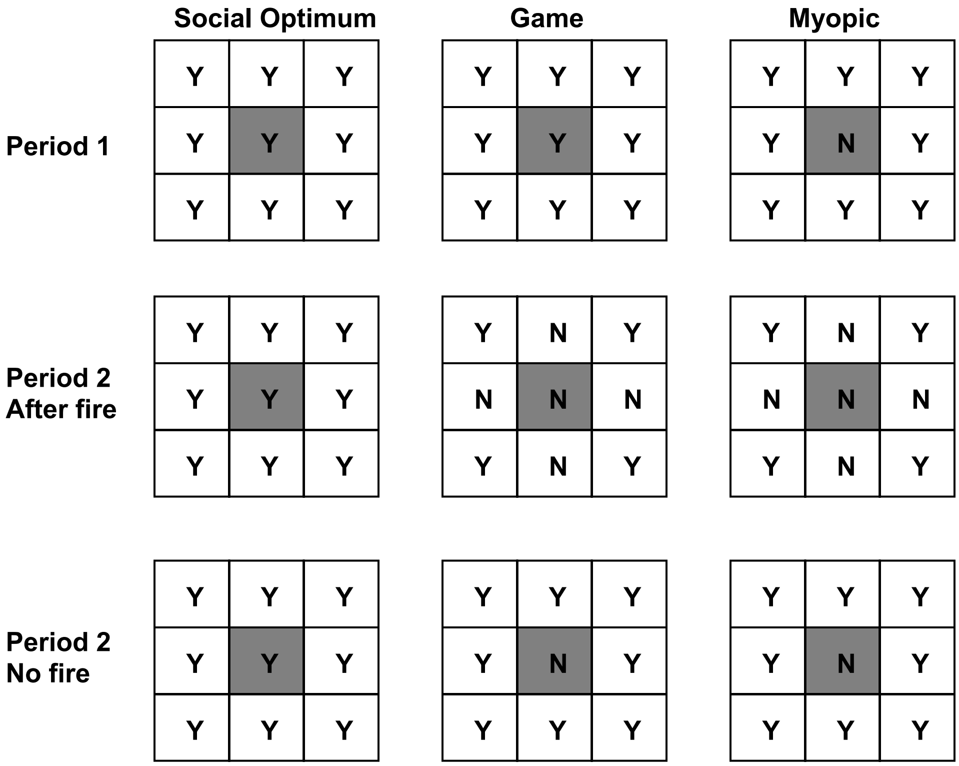


FIGURE 4.4: Private Extending into Public (Public Extending into Private) – Baseline Results

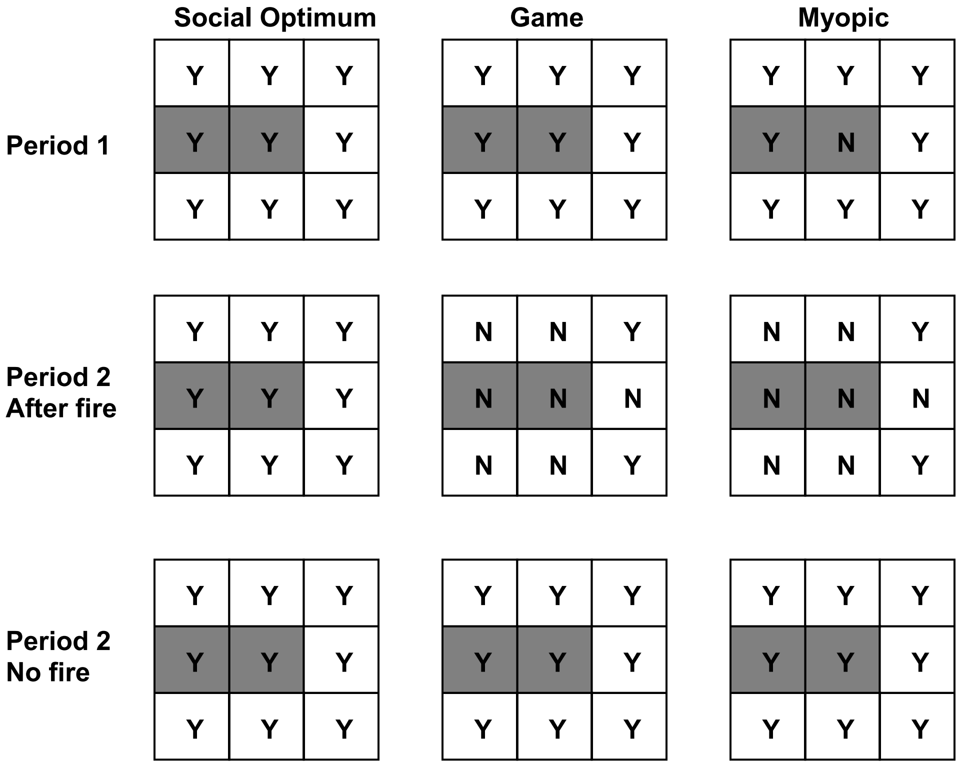
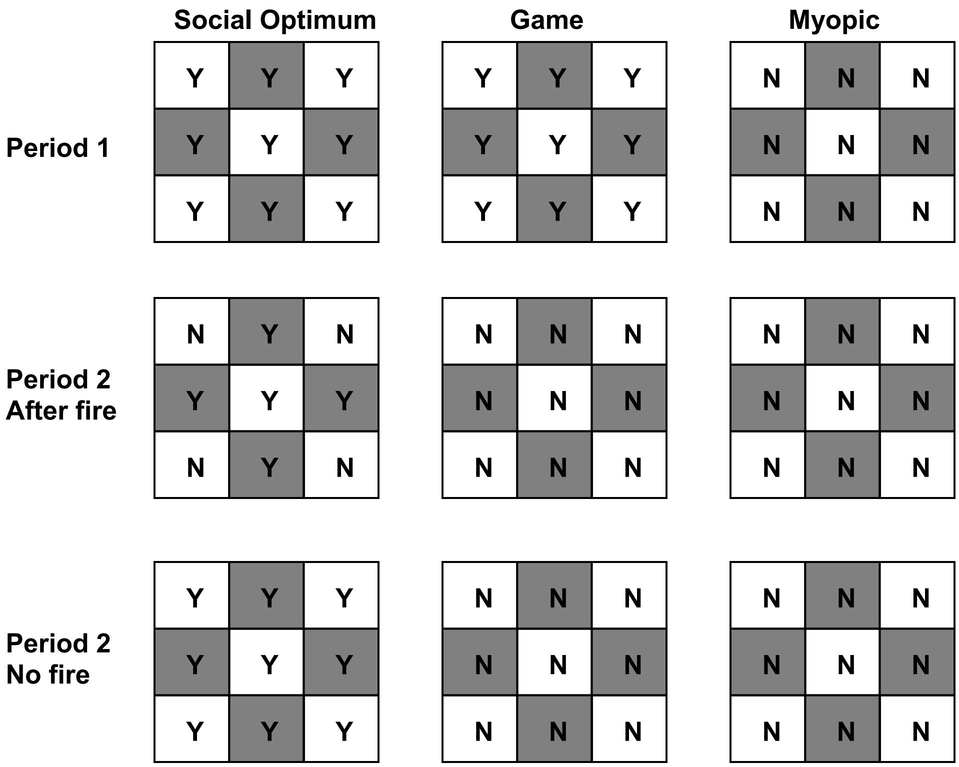
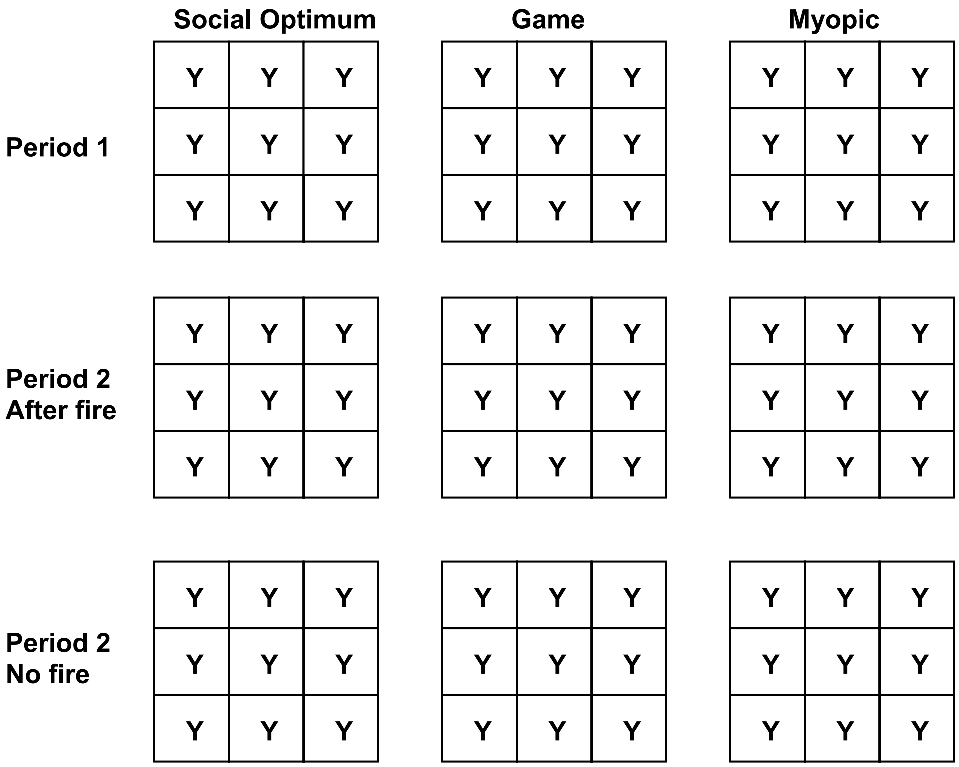


FIGURE 4.5: Checkerboard Public in Center (Checkerboard Private in Center) – Baseline Results



	Social Optimum	Game	Myopic
Period 1	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y	N N N N N N N N N
Period 2 After fire	N Y N Y Y Y N Y N	N N N N N N N N N	N N N N N N N N N
Period 2 No fire	Y Y Y Y Y Y Y Y Y	N N N N N N N N N	N N N N N N N N N

FIGURE 4.6: All Public (All Private) – Baseline Results



	Social Optimum	Game	Myopic
Period 1	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y
Period 2 After fire	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y
Period 2 No fire	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y	Y Y Y Y Y Y Y Y Y

There are four basic conclusions that can be drawn from the baseline results. First, the outcome from the game between forward-looking landowners is not socially optimal. Second, the fuel treatment decisions made by the public and private landowners depend on ownership pattern. Third, the inefficiencies from the baseline game are caused by fragmented ownerships and the failure of landowners to coordinate their decisions. And finally, in the first period, myopic landowners tend to treat fewer units than forward-looking landowners.

For all ownership patterns with a mix of public and private ownerships, the fuel treatment pattern that results from the game is not the same as the socially optimal treatment pattern.[16] There is always less fuel treatment on the landscape from the outcome of the game compared to the social optimum. This result indicates that on a landscape with mixed ownership, even when landowners have perfect information about fire risk, fuel management decisions are suboptimal. A measure of the difference between the socially optimum and the outcome of the game is described in Table 4.2. The departure from the social optimum is calculated as the difference between total expected loss from the game and the social optimum, as a percent of total expected loss from the socially optimal treatment pattern. The greatest departure from the socially optimal treatment pattern occurs on the landscapes with the most fragmented ownership pattern. The most significant departure from the social optimum occurs when the

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[16] The socially optimal fuel treatment pattern is the same for all ownership patterns except the checkerboard pattern. This difference is due to differing assumptions about management decisions outside the nine-by-nine grid landscape; distinct fuel stock weighting systems described in chapter 3 (Figures 3.4 and 3.5) capture this difference.

ownership pattern is checkerboard and the slightest departure occurs with the private adjoining public ownership pattern.

TABLE 4.2: Departure from Social Optimum – Baseline

Ownership Pattern	Game	Myopic
Private adjoining public	0.04%	0.04%
Private corridor	0.06%	0.06%
Isolated private	3.11%	11.67%
Private extending into public	0.26%	2.08%
Checkerboard with public in center	26.07%	72.08%

The departure from the social optimum is different for each ownership pattern because the amount of fuel treatment on the landscape varies with ownership pattern. Specifically, when the ownership pattern is less fragmented and there are more same-owner adjacencies there is more fuel treatment on the landscape. Comparing the outcome of the game with the private corridor ownership pattern (Figure 4.2) to the outcome from the game with the isolated ownership pattern (Figure 4.3) illustrates this point. When the private owner has three adjacent units, as in the private corridor ownership pattern, all three units are treated in the second period, if no fire in the first period. But when the private owner has only one isolated unit, as in the isolated private ownership pattern, it is not treated in the second period, if no fire in the first period. In both cases, the center unit's value is the same, fuel treatment cost is the same, and fuel treatment decisions on the surrounding units are the same. But the treatment decision on the center unit is different because when there are three adjacent private units, treating the center unit provides protection for the values on that unit *and* the two neighboring units on either side. The positive externality from reducing forest fuels on the center unit provides additional protection to the two neighboring private units and increases the total benefit of treating that unit. But for the isolated private unit, the positive externalities from treating the center unit benefit the public owner. Because the benefit from fuel treatment increases with same-owner adjacencies, the amount of treatment on the landscape will be greater when ownerships are less fragmented.

In the baseline, there is no strategic interaction between the public and private landowners. Given the current period's fuel stock, the individual landowner's best fuel treatment decision does not depend on the other landowner's treatment decision. In other words, each land owner has a dominant strategy and there is a unique NE. This is because the damage function is linear, the marginal benefit of additional fuel treatment is constant, and the marginal cost of fuel treatment depends on the individual unit's fuel stock only. The calculus of the fuel treatment decision does not depend on fuel treatment decisions on neighboring units. Therefore, the inefficiency that results from the game is not a result of strategic interaction, but a result of a coordination failure among landowners and their failure to internalize the external benefits of fuel treatment.

The myopic landowner treats fewer units than the forward-looking landowner in the first period when the ownership pattern is isolated private (public), private (public) extending in the public (private), and checkerboard (Figures 4.3, 4.4, and 4.5). This is because the myopic landowner does not consider the second period benefits of fuel treatment in period one. Fuel treatment in the first period reduces the second period's beginning fuel stock, which reduces expected fire damage and the cost of fuel treatment in period two. Table 4.3 shows that when landowners are myopic, the departure from the social optimum is greater for the three most fragmented ownership patterns than when landowners are forward-looking.

4.2 Private Amenity Value on Public Land

Next I look at the case where private amenity value is generated on each publicly owned land unit. When this is the case, the private landowner's fuel treatment decision is motivated by a desire to protect structure value on private units as well as off-site private amenity values on publicly owned units. For example, in a survey of Florida and Minnesota residents regarding defensible space for fire protection, individuals reported the value of wildlife habitat and recreation opportunities on public land surrounding their homes as a motivation for risk-reducing actions (Monroe and Nelson, 2004). In the model, although the private landowner has value on both ownerships, only the public landowner can carry out fuel treatments on publicly owned units. This setting creates the potential for a divergence in the public and private landowners' desired level of fuel treatment on public units.

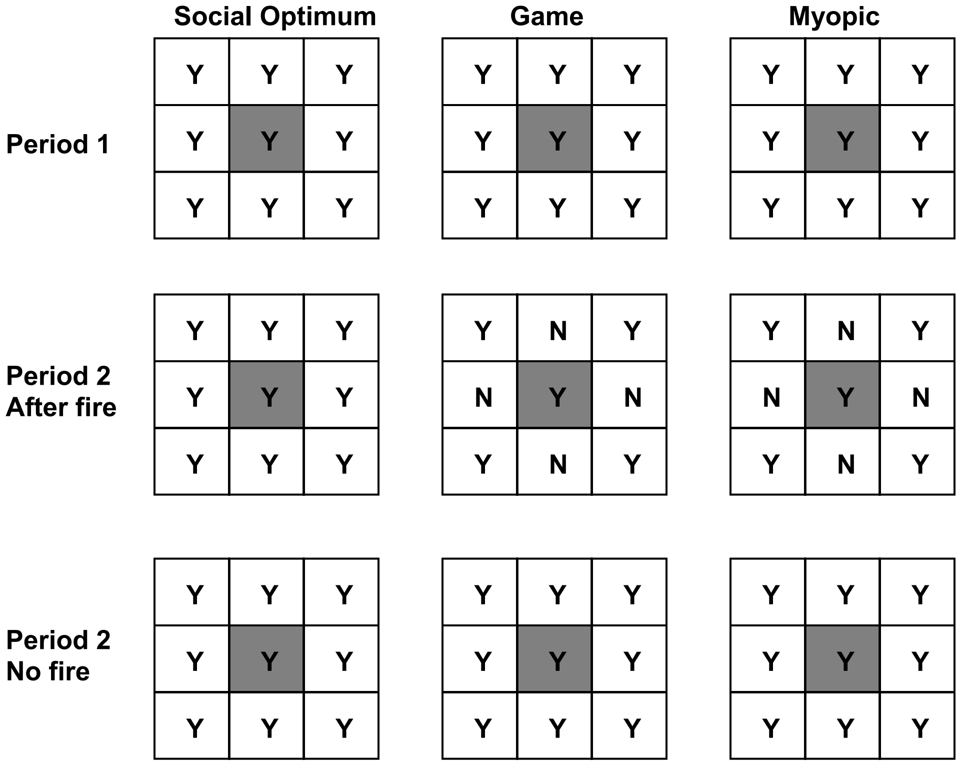
The results discussed in this section emerge from a setting where, for all ownership patterns, the public landowner's per unit value is 400 on all publicly owned units. The private landowner's structure value is 400 on every private unit and amenity value is 400 on all publicly owned units. Total private value is 3600 for all ownership patterns and total public good value depends on the total number of public units on the landscape. Because the publicly owned units have twice the value of privately owned units, the socially optimal treatment pattern targets treatment on the high-value publicly owned units and varies with ownership pattern. Compared to the baseline results, for every ownership pattern, the private landowner does more fuel treatment. In some cases, the increase in fuel treatment on private units improves the outcome relative to the social optimum, but in other cases, the private landowner's inability to treat high-value public worsens the outcome relative to the social optimum.

The private landowner carries out more fuel treatment than in the baseline for every ownership pattern because total private value on the landscape is greater than in the baseline. Even though the additional private value is generated on publicly owned units only, because of the positive spatial externalities created by fuel treatment, protective action on private units can effectively reduce fire risk on publicly owned units. However, fuel treatment on privately owned units reduces the expected loss of private values on public units only when treatment occurs within the spatially relevant range, as determined by the fuel stock weighting scheme. Therefore, the ownership pattern influences the private landowner's ability to protect private values on publicly owned units.

For every ownership pattern, the socially optimal treatment pattern is to treat every unit in both periods, which is more fuel treatment than results from the game. When the private landowner has value on both public and privately owned units, the outcome is closer to the social optimum for the isolated private, private extending into public, and both checkerboard ownership patterns, compared to the baseline. For most ownership patterns, the level of under-protection is now even greater because of the private landowner's inability to directly protect values on publicly owned units.

However, for five ownership patterns, the outcome of the game is actually closer to the socially optimal treatment pattern compared to the baseline. These five ownership patterns include isolated private, private extending into public, public extending into private, and the two checkerboard patterns. A more fragmented private ownership increases the number of public-private adjacencies and ability of the private landowner to effectively protect private amenity values on publicly owned units. To illustrate, the outcome of the game with private values on publicly owned land units on the checkerboard landscape is illustrated in Figure 4.7. Here, unlike the baseline, the private landowner treats the center unit in all three time periods.

FIGURE 4.7: Isolated Private – Private Amenity Value on Public Land



The departure from the social optimum for the case where there are private values on public land and the baseline are described in Table 4.3. Given the baseline fuel stock weighting system, fuel treatment on private units that are not adjacent to public units provides no protection for private values on public land. When private ownership is less fragmented, there are fewer public-private adjacencies and the private landowner’s ability to protect values on publicly owned units is diminished.

TABLE 4.3: Departure from Social Optimum – Private Value on Public Land

Ownership Pattern	Baseline	Private Value on Public Land
Private adjoining public	0.04%	0.10%
Public adjoining private	0.04%	0.12%
Private corridor	0.06%	0.20%
Public corridor	0.06%	0.09%
Isolated private	3.11%	0.12%
Isolated public	3.11%	3.42%
Private extending into public	0.26%	0.16%
Public extending into private	0.26%	0.06%
Checkerboard with public in center	26.07%	10.58%
Checkerboard with private in center	26.07%	13.54%

4.3 Returns to Fuel Treatment

Fuel treatment benefits the landowner by reducing fuel stock on the individual unit thereby reducing expected fire damage to values at risk. In the baseline, the relationship between weighted fuel stock and fire damage is linear and the marginal benefit of fuel treatment is constant at all levels of weighted fuel stock. In this section I explore two nonlinear relationships between weighted fuel stock and fire damage. First I look at the case where as weighted fuel stock decreases, fire damage decreases at an increasing rate. This represents a setting where each additional unit of fuel treatment reduces fire damage more than the last. Second, I look at the case where as weighted fuel stock decreases, fire damage decreases at a decreasing rate.[17] This represents a setting where initial fuel treatment reduces fire damage more than subsequent fuel treatment.

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[17] When there are decreasing returns to fuel treatment it is possible to have multiple NE. Because no single NE is more likely than the others, when there are multiple equiliria period I select the one with the least amount of fuel treatment.

4.3.1 Increasing returns to fuel treatment

When there are increasing returns to fuel treatment, as weighted fuel stock decreases with additional treatment, fire damage decreases at an increasing rate. This means that the more fuel treatment on unit adjacent to the individual unit, the greater the marginal benefit from treatment on the individual unit. In this type of setting, the last unit of treatment provides the greatest amount of additional protection. This might be the case on landscapes where even a small amount of fuel results in significant wildfire damage, such as when severe drought conditions exist or fire suppression is absent or ineffective. When this is the case, landowners who treat a single unit will have incentive to continue reducing fuels until the fuel stock is driven to zero.

The form of the damage function for increasing returns to fuel treatment is described by Equation 4.1. Fire damage is a function of pre-fire weighted fuel stock and a constant. The constant term , κ , determines the curvature of the damage function and is set equal to 1000 for the results presented here.

$$D_i^{a,h,g,f} = \frac{w_i}{(w_i^2 + \kappa)^{1/2}} \tag{4.1}$$

Where

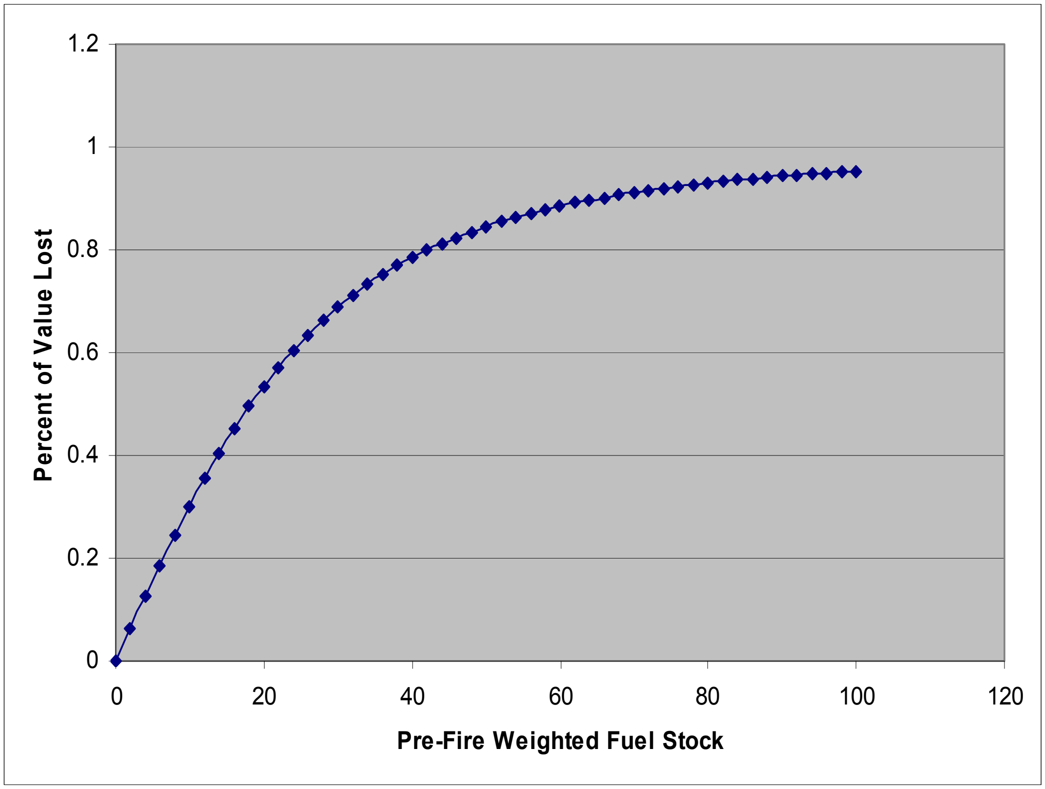
D_i = damage to value at risk on unit *i* (percent of pre-fire value lost)

w_i = pre-fire weighted fuel stock on unit *i*

κ = constant

The function used to generate the results for the case where there are increasing returns to fuel treatment is illustrated in Figure 4.8.

FIGURE 4.8: Percent of Value on Unit *i* Lost as a Function of Pre-Fire Weighted Fuel Stock on the Individual Unit – Increasing Returns to Fuel Treatment



Comparing the outcome of the game with the baseline parameters to the outcome of the game when there are increasing returns to fuel treatment provides insight into how the relationship between fuel stock and fire damage influences the interaction between landowners and the outcome of the game. The major difference between the baseline and the case where there are increasing returns to fuel treatment is that the nonlinear damage function makes the game between the public and private landowners strategic.

Compared to the baseline, when there are increasing returns to fuel treatment, the socially optimal treatment pattern has less fuel treatment in the second period, after fire. This is because for all levels of pre-fire weighted fuel stock, fire damage is greater. If there is a fire in period one, then there is less value at risk and less fuel on the ground in the second period. Therefore, when there are increasing returns to fuel treatment, after a fire, there is less incentive for fuel treatment in period two.

When there are increasing returns to fuel treatment, the players no longer have a dominant strategy that depends only on fuel stock. Instead, the optimal fuel treatment decision depends on the other landowner's treatment decision and will be all or nothing: either treat every single unit or do nothing. If the marginal benefit of the first unit of treatment exceed its marginal cost, then the same will be true for each additional unit treated. Because the marginal benefit of additional fuel treatment increases as weighted fuel stock decreases, the more the public landowner does, the greater the private landowner's optimal level of treatment and vice versa. Similarly, the less fuel treatment the public land owner does, the lower the private landowner's optimal level of treatment and vice versa. It is the shape of the damage function and the relationship between fuel stock and fire damage that leads to these all or nothing outcomes.

TABLE 4.4: Departure from Social Optimum – Increasing Returns to Fuel Treatment

Ownership Pattern	**Baseline**	**Game with Increasing Returns**
Private adjoining public	0.04%	0.0%
Private corridor	0.06%	0.0%
Isolated private	3.11%	3.85%
Private extending into public	0.26%	0.0%
Checkerboard with public in center	26.07%	10.23%

4.3.2 Decreasing returns to fuel treatment

When there are decreasing returns to fuel treatment, as weighted fuel stock decreases, fire damage decreases at a decreasing rate. In this type of setting, it is important to do at least some amount of fuel treatment, but reducing fuel stock to very low levels provides only a small amount of additional fire protection. This might be the case on landscapes where suppression is very effective or fire is only damaging when fuel stock is at very high levels.

The form of the damage function for decreasing returns to fuel treatment is described by Equation 4.2. Fire damage is a function of pre-fire weighted fuel stock and two constants, κ and η.

$$D_i^{a,g,h,f} = \eta - \frac{(100 - w_i)}{((100 - w_i)^2 + \kappa)^{1/2}} \tag{4.2}$$

Where

D_i = damage to value at risk on unit *i* (percent of pre-fire value lost)

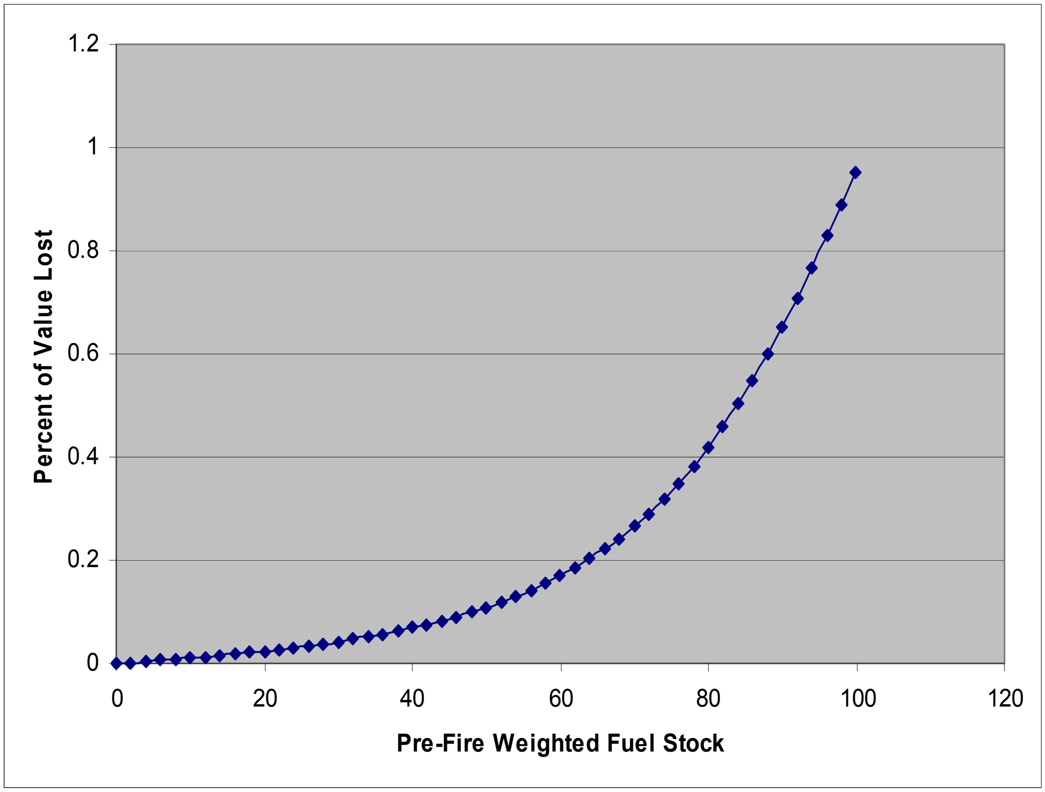
w_i = pre-fire weighted fuel stock on unit *i*

κ = constant

η = scaling factor

The function used to generate the results is illustrated in Figure 4.9.

FIGURE 4.9: Percent of Unit *i*'s Value Lost as a Function of Pre-Fire Weighted Fuel Stock on the Individual Unit – Decreasing Returns to Fuel Treatment



Comparing the outcome of the game with the baseline parameters to the outcome of the game when there are decreasing returns to fuel treatment again provides additional insight into how the relationship between fuel stock and fire damage influences landowners' interaction. There are two major differences between the baseline and the setting with decreasing returns to fuel treatment. First, with decreasing returns to fuel treatment, both landowners choose less fuel treatment for all ownership patterns except the checkerboard pattern. And, second, similar to the case with increasing returns to fuel treatment, the game between the public and private landowners becomes strategic.

When there are decreasing returns to fuel treatment, the socially optimal fuel treatment pattern is to treat all public and private units in the first period, all units except the center unit in the second period, if no fire in the first period, and all units except the two to the right and left of the center unit in the second period, after fire. Fewer units are treated under the socially optimal fuel treatment pattern than in the baseline social optimum because for all levels of weighted fuel stock, damage is less; and with each additional unit treated, the marginal benefit of fuel treatment decreases.

When there are decreasing returns to fuel treatment, the players no longer have a dominant strategy that depends only on fuel conditions. Each landowner's optimal fuel treatment choice depends on the other's choice. Because the marginal benefit of additional fuel treatment decreases as weighted fuel stock decreases, the more fuel treatment on publicly owned units, the lower the private landowner's optimal level of treatment and vice versa. Similarly, the less fuel treatment there is on publicly owned units, the greater the private landowner's optimal level of treatment and vice versa. This interaction reduces the amount of fuel treatment on the landscape and, compared to the baseline, the outcome of the game with decreasing returns to fuel treatment is further from the social optimum for all ownership patterns (Table 4.5).

TABLE 4.5: Departure from Social Optimum – Decreasing Returns to Fuel Treatment

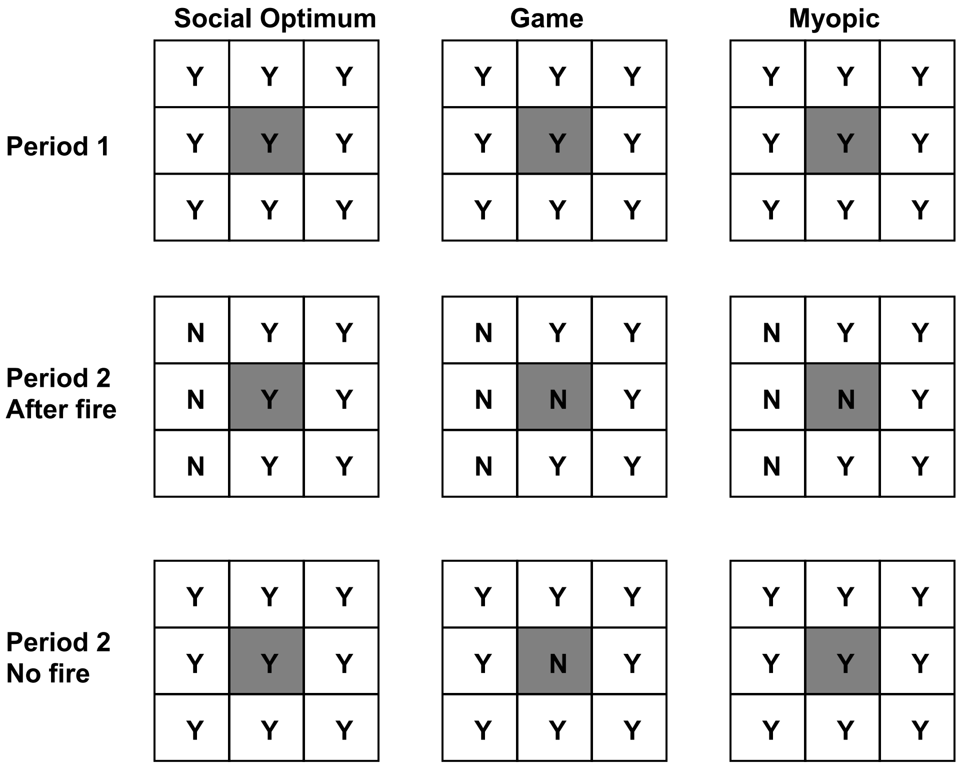
Ownership Pattern	**Baseline**	**Game with Decreasing Returns**	**Myopic**
Private adjoining public	0.04%	0.18%	11.54%
Private corridor	0.06%	1.20%	13.84%
Isolated private	3.11%	3.98%	11.65%
Private extending into public	0.26%	3.90%	11.83%
Checkerboard with public in center	26.07%	83.84%	87.32%

4.4 Fuel Stock Weighting Scheme

The weighting scheme used to generate the baseline results gives equal weight to the individual unit and the four adjacent units on the grid landscape. I consider three alternative weighting schemes to approximate the effect of unit *j*’s fuel stock on value loss on unit *i* in case of a fire. The first two weighting systems give equal weight to the individual unit and a single neighboring unit. The first system gives weight to the individual unit *i* and the neighboring unit to the right and the second system gives weight to the individual unit *i* and the neighboring unit above. The first and second weighting systems represent scenarios where the fuel stock on the up-wind or down-slope unit is significant to loss on the individual unit. Depending on the underlying ownership pattern, the first and second weighting systems will lead to different outcomes. The third weighting system gives weight to the fuel stock on the individual unit *i* only.

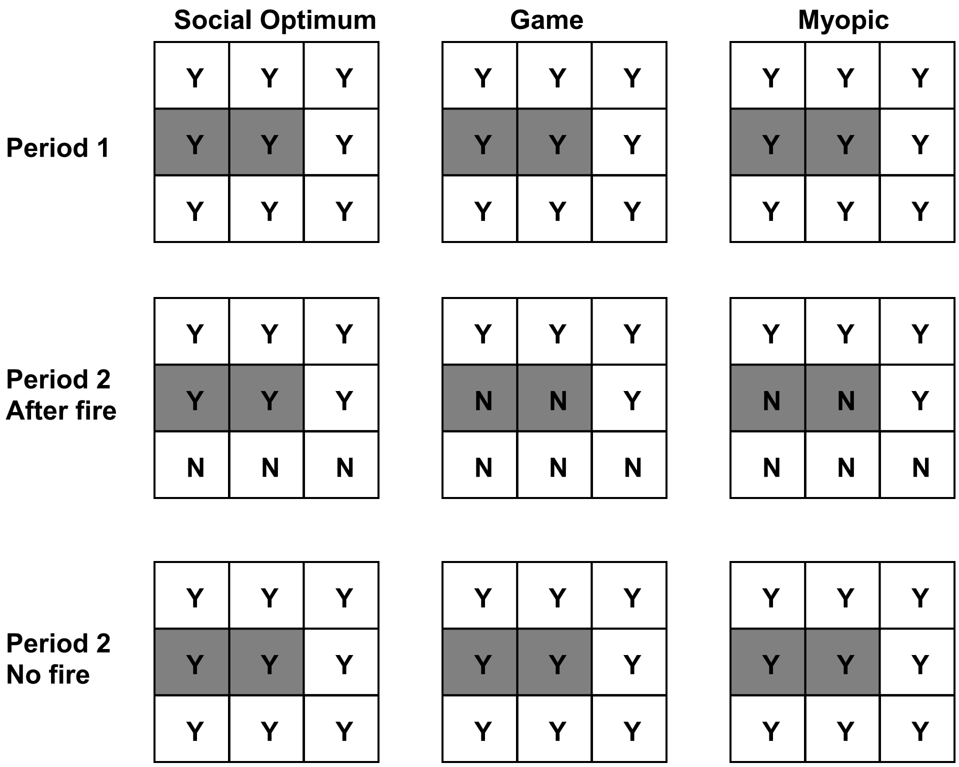
For the first weighting scheme, where the fuel stock on the individual unit and the unit to the right matter equally, there is a tendency to treat units on the right-side of the landscape, as illustrated by the results for the isolated private ownership pattern (Figure 4.10). Similarly, for the weighting scheme where the fuel stock on the individual unit and the unit to the above matter equally, there is a tendency to treat units on the upper portion of the landscape, as shown by the results for the private extending into public ownership pattern (Figure 4.11).

FIGURE 4.10: Isolated Private – Fuel Stock Weighting Scheme where the Individual Unit and Unit to the Right Equally Determine Fire Damage



	Social Optimum			Game			Myopic		
Period 1	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Y	Y	Y	Y	Y	Y	Y	Y	Y
Period 2 After fire	N	Y	Y	N	Y	Y	N	Y	Y
	N	Y	Y	N	N	Y	N	N	Y
	N	Y	Y	N	Y	Y	N	Y	Y
Period 2 No fire	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Y	Y	Y	Y	N	Y	Y	Y	Y
	Y	Y	Y	Y	Y	Y	Y	Y	Y

FIGURE 4.11: Private Extending into Public – Weighting Scheme Where the Individual Unit and Unit Above Equally Determine Fire Damage



	Social Optimum			Game			Myopic		
Period 1	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Y	Y	Y	Y	Y	Y	Y	Y	Y
Period 2 After fire	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Y	Y	Y	N	N	Y	N	N	Y
	N	N	N	N	N	N	N	N	N
Period 2 No fire	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Y	Y	Y	Y	Y	Y	Y	Y	Y

For the weighting scheme where only the fuel stock on the individual unit matters, there are no cross-owner externalities associated with fuel treatment and the model becomes aspatial. When there are no externalities and constant returns to fuel treatment, forward-looking landowners make optimal fuel management choices. However, when landowners are myopic, suboptimal fuel treatment patterns may result.

4.5 Policy Analysis

The model provides a mechanism to evaluate alternative fire risk management policies. In this section I compare the fuel treatment decisions made by public and private landowners in the baseline to the fuel treatment decisions in the presence of a fuel stock regulation, a liability rule, and a private insurance program. The fundamental intent of policy is to improve outcomes and, in the context of the fuel treatment decision, bring the outcome of the game between public and private landowners closer to the social optimum. The extent to which this goal is achieved will depend on the specification of the policy and setting into which the policy is introduced.

4.5.1 Fuel stock regulation

First, I apply a fuel stock regulation to the baseline. The regulation is designed to achieve the socially optimal treatment pattern, which is to treat all units in both periods, whether or not there is a fire in the first period. If policy-makers know the optimal treatment pattern, it can be achieved by setting the maximum allowable fuel stock equal to two, which is the post-treatment fuel stock. In order to meet this requirement, landowners need to treat all units in both periods, whether or not there is fire in period one. Because this regulation leaves landowners with no flexibility in meeting the standard, it is effective. However, the optimal fuel treatment pattern and appropriate regulation design is not always as simple.

To explore the impact of regulation in a more complex setting, I increase the cost of fuel treatment so that, in the absence of regulation, forward-looking landowners choose zero treatment in both periods and I increase the maximum allowable fuel stock under the regulation. The maximum allowable fuel stock is equal to 4, the fixed cost of fuel treatment is 7, and variable cost is 3.5. In order to meet this regulation, each unit only needs to be treated once in the two-period time horizon, if there is no fire in period one. If there is a fire in the first period, a sufficient amount of forest fuels are consumed by fire so that no treatment is necessary in order to comply with the regulation. In this way, the regulation affords landowners some flexibility in meeting the standard.

Because landowners have a certain degree of flexibility in meeting the standard, they are able to consider the tradeoffs between treatment in periods one and two when making the fuel treatment decision. Treatment in the first period protects values in both time periods. If the landowner puts off fuel treatment until the second period and there is a fire, fuel treatment is unnecessary. But if the landowner waits and there is no fire, fuel treatment in period two is more costly because the fuel stock has grown and a greater quantity needs to be removed.

The departure from the social optimum for the outcome of the game with regulation is compared the departure from the social optimum for the baseline outcome in Table 4.6. To meet the fuel stock regulation, forward-looking landowners choose to treat all units in the first period, which is also the socially optimal treatment pattern. On the checkerboard landscape, the socially optimal treatment pattern is to treat only five of the nine units in period one. Comparing the socially optimal treatment pattern on the checkerboard landscape to the outcome of the regulated game reveals that with regulation there is too much treatment in the first period. The inability to achieve the optimal treatment pattern on the checkerboard landscape indicates that more complex treatment patterns may be more difficult to achieve through regulation.

TABLE 4.6: Departure from Social Optimum – Regulation

Ownership Pattern	**Baseline***	**Game with Regulation**
Private adjoining public	0.25%	0%
Private corridor	0.41%	0%
Isolated private	0.41%	0%
Private extending into public	0.55%	0%
Checkerboard with public in center	6.59%	5.89%

*The departure from the social optimum for the baseline is calculated here using the higher fixed and variable costs.

4.5.2 Liability rule

The liability rule holds the public landowner liable for a fraction of private value lost due to fire damage. This liability rule is representative of a setting where the public landowner is deemed responsible for protecting private values and, if private values are damaged by wildfire, compensating the private landowner for fifty-percent of lost value. In this section, I compare the outcome of the game with the liability rule to the social optimum from the baseline, which is to treat all units in both periods, whether or not there is a fire in the first period.

The liability rule increases the public landowner's incentive to reduce forest fuels. For a majority of the ownership patterns, compared to the baseline treatment pattern, the public landowner increases fuel treatment and the private landowner decreases fuel treatment. For the private adjoining public pattern, the public owner increases the number of units treated and the private owner treats the same number of units, compared to the baseline. And for the isolated private ownership pattern, the public owner treats the same number of units and the private owner treats fewer units. For all cases except the private adjoining public pattern, there is a net decrease in fuel treatment on the landscape and the outcome from the game with liability is worse than the outcome of the game without liability (Table 4.7). For the private adjoining public ownership pattern, there is a net increase in treatment on the landscape and the outcome of the game with liability is closer to the social optimum than the baseline.

TABLE 4.7: Departure from Social Optimum – Liability

	Baseline	Game with Liability
Private adjoining public	0.04%	0.02%
Private corridor	0.06%	8.60%
Isolated private	3.11%	8.46%
Private extending into public	0.26%	5.95%
Checkerboard with public in center	26.07%	41.43%

4.5.3 Private insurance requirement

The private insurance program requires that all private landowners fully insure their structure value. I assume that insurance is fair (i.e., the premium per dollar of coverage is equal to the probability of fire). Because the private landowners are risk neutral, they are indifferent to purchasing fair insurance or not. In order to ensure private owners purchase the insurance, a requirement is necessary. However, there is value in examining the use of insurance to mitigate fire risk because it is commonly applied the wildfire problem and other natural hazards (Ehrlich and Becker 1972; Brunette and Couture 2006; Lankoande 2006). As a protective measure, insurance is also of interest because, unlike fuel treatment, it does not generate positive externalities.

When private land owners are required to fully insure the value of their property, there is no incentive for fuel treatment. A private landowner who is fully insured chooses zero treatment for all ownership patterns. At the same time, the public landowner chooses the same fuel treatment pattern for all ownership patterns as in the baseline. The result is a net loss in the number of units treated for each ownership pattern, compared to the baseline. When fewer units are treated, weighted fuel stock is higher and expected fire damage to values is also higher.

The departure from the social optimum for the outcome of the game with private insurance is compared the departure from the social optimum for the baseline outcome in Table 4.8. Overall, the outcomes are significantly worse than the baseline results, without private insurance. The public landowner's expected loss is greater because values on publicly owned units are no longer protected by fuel treatment on privately owned units. The fully insured private landowner's expected loss is greater because, in the baseline, fuel treatments reduced the amount of fire damage and offered a lower cost form of protection.

TABLE 4.8: Departure from the social optimum – Private Insurance

	Baseline	Game with Private Insurance
Private adjoining public	0.04%	55.08%
Private corridor	0.06%	61.47%
Isolated private	3.11%	25.02%
Private extending into public	0.26%	43.35%
Checkerboard with public in center	26.07%	105.45%

5. SENSITIVITY ANALYSIS

The sensitivity analysis tests the robustness of the model's results to changes in parameter values. I test the sensitivity of the results to variations in fire and fuels parameters in section 5.1 and economic parameters in section 5.2. Rather than describe the sensitivity of the results for each of the twelve ownership patterns, I focus the analysis on a less fragmented ownership pattern and a more fragmented ownership pattern, private adjoining public and checkerboard with public in the center, respectively. If the model's results are not sensitive to changes in fire, fuels, and economic parameter values, then a certain degree of confidence can be placed in the results.

5.1 Fire and Fuels Parameters

5.1.1 Probability of fire

When the probability of fire is increased sufficiently, landowners will treat all units in both time periods in order to protect against the likely hazard. For the less fragmented landscapes, such as private adjoining public, when the probability of fire increases to 11 percent or higher, every unit is treated. For the more fragmented landscapes, the increase in probability of fire necessary to see all units treated in both periods is higher. On the checkerboard landscape, for example, once the probability of fire increases to twenty-five percent, every unit is treated in both periods.

When the probability of fire is decreased sufficiently, landowners will treat zero units in both time periods because of the unlikely nature of the hazard. On a less fragmented landscape, such as private adjoining public, when the probability of fire in each time period is at or below 0.6 percent there is zero treatment on the landscape. On the most fragmented checkerboard landscape there is zero fuel treatment on all units in both periods when the probability of fire is at or below 4 percent, which is only 1 percent below the base case probability.

5.1.2 Fuel stock growth

The baseline fuel stock growth rate is set equal to 200 percent (i.e., fuel stock doubles) in every ten-year period. If there is a fire in the first period, a portion of the fuel stock is consumed and the post-fire fuel stock grows, doubling in size. When the fuel stock's growth rate is higher than in the baseline, the beginning fuel stock in period two is greater than in the baseline. This change increases the incentive to do fuel treatment in the first period and in the second period. In the first period, forward-looking landowners know that fuel treatment in period one reduces the amount of fuel able to grow and reduces the second period's beginning fuel stock. Incentive for fuel treatment in the second period comes from the fact that, in the absence of additional treatment in the first period, the second period's beginning fuel stock is higher. On the public adjoining private ownership pattern, when the fuel stock growth rate increases to 350 percent (i.e., fuel stock increases three-and-a-half times), all units are treated in both periods.

When the fuel stock growth rate is less than in the baseline for all period one fuel treatment decisions, the second period's beginning fuel stock is also less than in the baseline. Here there is less incentive for fuel treatment in both periods one and two. On a less fragmented ownership pattern, such as public adjoining private, when the fuel stock growth rate decreases to 118 percent, there is no fuel treatment in the second period. However, even if fuel stock growth rate is 100 (i.e., fuel stock remains constant) all public and private land units are still treated in the first time period. On the more fragmented checkerboard landscape, when fuel stock decreases to 147 percent, there is no zero fuel treatment in both periods one and two.

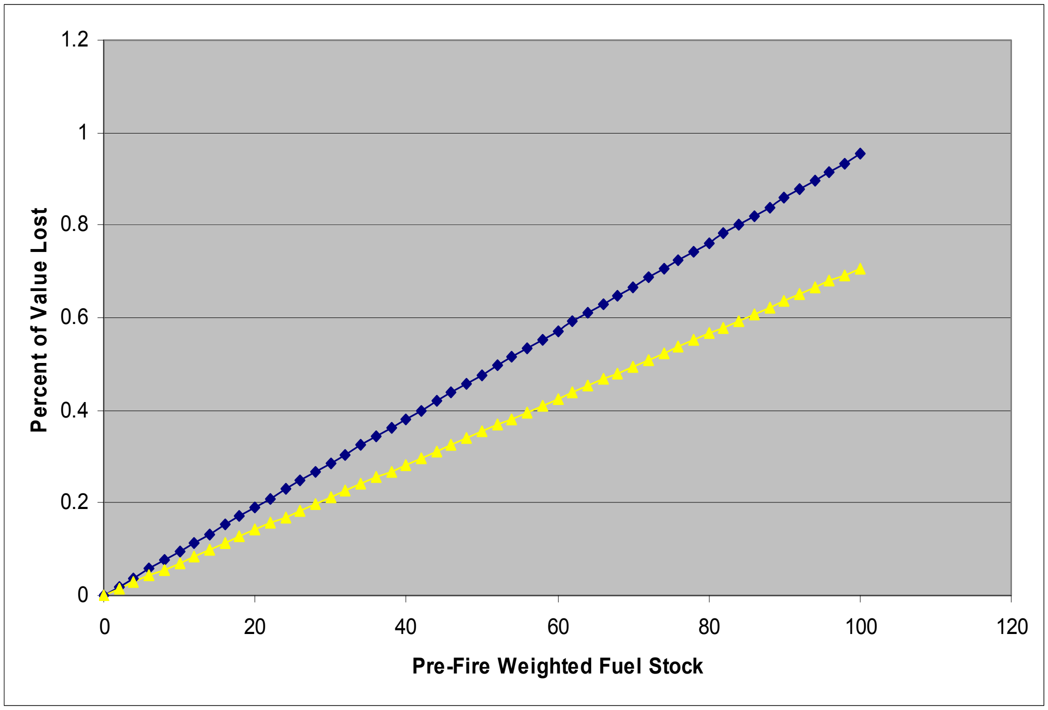
5.1.3 Damage function

The damage function used in the baseline is linear. In the baseline, when pre-fire weighted fuel stock on a unit is at a minimum of 2, the percent of value loss is 0.7 and when pre-fire weighted fuel stock on a unit is at a maximum of 100, the percent of value loss is 95.35. To test the sensitivity of the results to the damage function's specification, I reduce the slope of the linear damage function such that when pre-fire fuel stock is at a maximum, the percent of pre-fire value lost from fire damage is 70.71 (Figure 5.1). This change might represent a setting where suppression is less effective.

A less steep damage function may represent more effective fire suppression or reduced sensitivity to fire. When this is the case, there is less incentive to engage in fuel treatment because at every level of fuel stock, damage to values at risk is less. However, it is also true that there is more value remaining after a fire. If there is a fire in period one, the amount of fuel treatment in the second period might be greater than in the base case. This post-fire second period decision will depend on whether the benefits from protecting higher post-fire values outweigh the reduced risk.

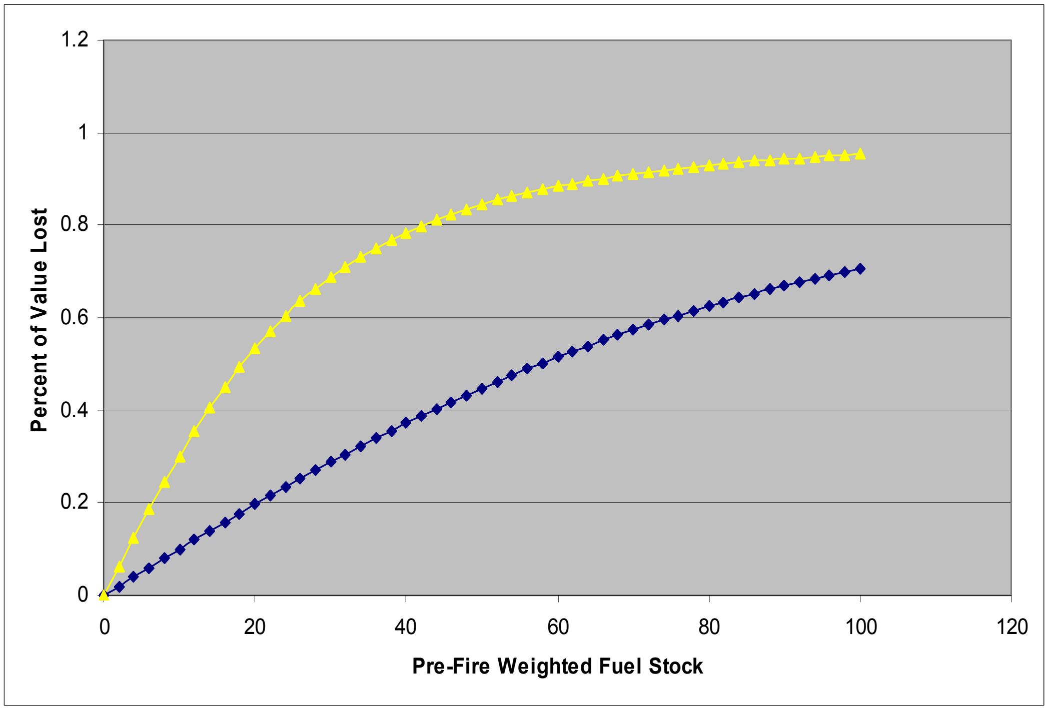
On the private adjoining public ownership pattern, when the damage function is less steep and all else is held constant, treatment in period two, after fire, increases compared to the baseline. For this ownership pattern, fuel treatment in periods one and two, when there is no fire in period one, is the same. On the more fragmented checkerboard ownership pattern, compared to the baseline, there is the same amount of fuel treatment in period two (zero units treated) and less fuel treatment in the first period.

FIGURE 5.1: Constant Returns to Fuel Treatment – Sensitivity Analysis



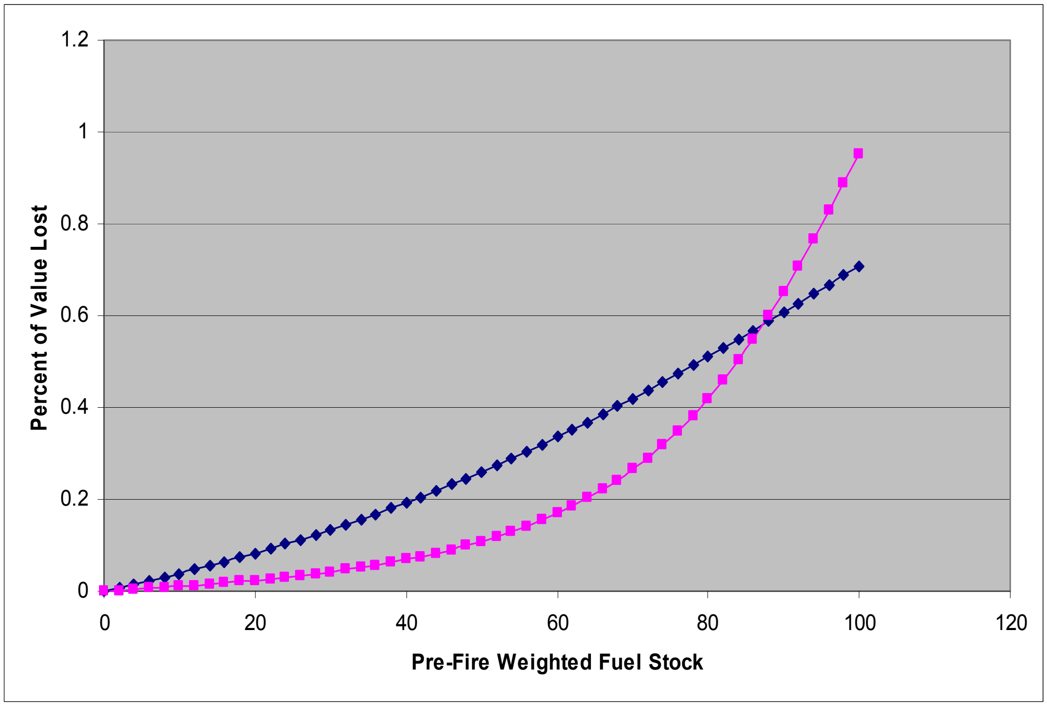
When there are increasing returns to fuel treatment, I test the sensitivity of the results by reducing the curvature of the damage function. Just as in the case of a linear damage function, when pre-fire weighted fuel stock is at its maximum, the percent of pre-fire value lost from fire damage is 70.71. This less steep damage function is illustrated in Figure 5.2. Again, I would expect to see less fuel treatment in both periods, except in period two, after fire, when there might be more fuel treatment compared to the baseline (again because a larger portion of forest fuels and public and private values survive a fire). The results show that both the public and private landowners choose less fuel treatment in the second period: private after a fire in period one and public when there is not a fire in period one. For the checkerboard ownership pattern, both landowners choose zero treatment in both periods, whereas in the baseline all units were treated in the first period.

FIGURE 5.2: Increasing Returns to Fuel Treatment – Sensitivity Analysis



When there are decreasing returns to fuel treatment, I test the sensitivity of the results by shifting the damage function in a similar manner. This is an interesting comparison because, as shown in Figure 5.3, the two damage functions intersect. To the left of the intersection of the two curves the baseline percent loss is lower, but to the right of the intersection, the baseline percent loss is higher. Therefore, the amount of fuel treatment, compared to the baseline, will depend on the level of pre-fire weighted fuel stock and whether it is above or below the intersection of the two damage functions. If pre-fire weighted fuel stock is below the intersection, there is more fuel treatment with the less steep damage function. But if the pre-fire weighted fuel stock is above the intersection, there is less fuel treatment with the less steep damage function.

FIGURE 5.3: Decreasing Returns to Fuel Treatment – Sensitivity Analysis



5.1.4 Initial fuel conditions

For all the results described in chapter 4, beginning fuel stock on all units, both public and private, is identical and equal to 3. To test the sensitivity of the results to this assumption, I decrease fuel stock on public units to 1 and leave fuel stock on private units unchanged. In general, whether there are constant, increasing, or decreasing returns to fuel treatment, the results change very little.

With a diminished beginning fuel stock, when there is no fire in period one, the public landowner either chooses the same amount or less fuel treatment. Similarly, in the second period, when there is no fire in period one, the public landowner either chooses the same amount or less fuel treatment. The public landowner, however, tends to increase fuel treatment in the second period, after fire. This increase is due to the fact post-fire values are greater as a result of lower levels of pre-fire fuels. On a landscape with a lower beginning fuel stock on public land units, the private landowner chooses either the same amount or less fuel treatment in both periods.

The observed change in each landowner's loss is consistent with the direction of change in fuel stock. When initial fuel stock decreases (increases), expected loss remains the same or decreases (increases). When both make the same treatment choices as in the baseline and initial fuel stock is less (greater) than in the base case, both landowners' expected loss is less (greater). This is because with less (more) fuel on the landscape, when there is a fire, damage to values at risk reduces (increases).

5.3 Economic Parameters

5.3.1 Fuel treatment cost

I test the sensitivity of the results to variations in both the fixed and the variable costs. As expected, the number of units treated decreases as cost increases and increases as cost deceases. On a landscape with the less fragmented private adjoining public ownership pattern, holding variable cost constant, fixed cost must increase to 11 to drive public and private treatment to zero in both periods. Holding fixed cost constant, variable cost must increase to 9 to drive public and private treatment to zero in both periods. To get both landowners to treat all units in both periods, fixed cost must decrease to 0.5 or variable cost must decrease to 0.3, each change made while holding the other constant.

On a landscape with a more fragmented ownership, such as the checkerboard pattern, landowners are more sensitive to upward movements in fuel treatment costs. Increasing fixed cost to 3 drives public and private fuel treatment to zero in both periods. Given the checkerboard ownership pattern and holding fixed cost constant, increasing variable cost to 1 drives public and private fuel treatment to zero in both periods. To induce both landowners to treat all units in both periods cannot be achieved through a reduction in fixed or variable cost alone. But when fixed cost is reduced to 0.3 and variable cost is 0 or if variable cost is reduced to 0.3 and fixed cost is zero, then both landowners treat all units in both periods.

5.3.2 Discount rate

The baseline discount rate is set equal to zero, meaning that expected losses in both time periods are valued equally. Increasing the discount rate means that expected losses in future time periods are valued less than an equivalent loss in the present time period. In the model, a positive discount rate would have an ambiguous effect on the timing of fuel treatment. Increasing fuel treatment in the first time period would reduce losses, but would also increase cost. Delaying fuel treatment would postpone treatment costs, but would also increase losses in the present time period. It is, however, certain that increasing the discount rate does not change fuel treatment decisions made in the second time period because it is the final period and both the costs and benefits of fuel treatment occur in period two and decrease proportionally in response to the higher discount rate. The relative differences between treatment options in period two is constant, thereby leaving period two decisions unchanged.

5.3 Summary

The basic results of the model are robust to variations in fire, fuels, and economic parameters, which indicates that I can be confident in the model's results. Over a range of parameter values chosen for the probability of fire, fuel stock growth, the damage function, initial fuel conditions, fuel treatment costs, and the discount rate, fuel treatment decisions and outcomes vary in a consistent and measured way. Therefore, the sensitivity analysis provides a validation of the model.

6. DISCUSSION AND CONCLUSIONS

This final chapter includes a discussion of the results from the model and summarizes the main conclusions about the fire risk management on a landscape with public and private ownership. I begin with a discussion of how ownership pattern affects landowners' fuel treatment decisions and outcomes. In the second section, I describe the settings that produce strategic behavior between landowners. Next I compare outcomes from the game when landowners are myopic to outcomes when landowners are forward-looking. An evaluation of the fuel stock regulation, liability rule, and insurance program effectiveness is included in the fourth section. In the final section, I summarize the main findings and offer concluding remarks.

6.1 Effect of Ownership Pattern on Outcomes

In general, ownership fragmentation leads to higher expected losses and worse outcomes, as measured by deviation from the socially optimal outcome. However, the negative influence of fragmentation on outcomes depends largely on the direction and the degree of spatial interdependence. When there is less spatial interdependence, the difference between the socially optimal fuel treatment pattern and the outcome on the game between forward-looking landowners decreases. Additionally, if the direction and range of spatial relevance is consistent with the underlying ownership pattern, then there will be little difference between the outcome of the game and the social optimum. This is illustrated for the private adjoining public and private corridor ownership patterns and the weighting scheme where fuel stock on the individual unit and the unit to the right determine fire damage. Because the spatially relevant fuel stocks for each public (private) land unit were other public (private) units, the spatial externalities are effectively internalized.

There is, however, one case where greater ownership fragmentation leads to better outcomes: when there are significant private values on public land, or vice versa. When this is the case, the fragmentation allows owners to effectively protect off-site values through treatment on their individual units. This result was described in chapter 4, section 4.2 for where there were private values on public land.

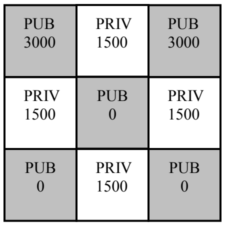
6.2 Strategic Behavior

The nature of the strategic behavior observed between landowners will depend on the shape of the damage function. The additional protection from increases in fuel treatment on the individual and adjacent units will depend on whether returns to fuel treatment are increasing, decreasing, or constant. When there are decreasing returns to fuel treatment, landowners will try to spend as little as possible on fuel treatment and free ride on their neighbor’s effort. In this case, a reduction in one landowner’s fuel treatment increases the marginal benefit of treatment on neighboring units, making their neighbor more likely to increase fuel treatment. But when there are increasing returns to fuel treatment, landowners will carry out additional fuel treatment in order to induce their neighbor to increase fuel treatment and thereby provide them with additional protection. When this is the case, an increase in one landowner's fuel treatment effort increases the marginal benefit of treatment on neighboring units, making these neighbors more likely to increase fuel treatment.

When there are decreasing returns to fuel treatment, an increase in one landowner's fuel treatment causes a reduction in the neighboring landowner's fuel treatment and is evidence of free riding. Free riding allows a landowner to benefit from the fire risk reduction provided by the neighboring landowner without paying for it. An illustration of the free riding result can be seen simply by looking at the best responses for each landowner: as one landowner's fuel treatment increases, the response of the neighboring landowner is to decrease fuel treatment. In general, the owner with less value on the landscape is able to reduce fuel treatment and free ride on the increased fuel treatment by the owner with more value on the landscape. This is because the owner with less value is certain that reducing their own fuel treatment will cause the high-value land owner to increase treatment in order to protect their greater value at risk.

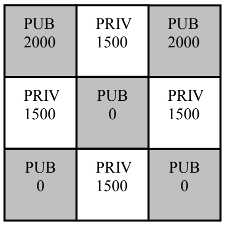
When there are increasing returns to fuel treatment, I find the opposite type of strategic behavior—land owners increase the number of units treated or change the location of fuel treatment to induce additional treatment by their neighbors. Two examples of this type of strategic behavior are on the checkerboard ownership when per unit values are as described in Figures 6.1 and 6.2.

FIGURE 6.1: Public and Private Values on a Checkerboard Landscape with Increasing Returns to Fuel Treatment



PUB 3000	PRIV 1500	PUB 3000
PRIV 1500	PUB 0	PRIV 1500
PUB 0	PRIV 1500	PUB 0

FIGURE 6.2: Public and Private Values on a Checkerboard Landscape with Increasing Returns to Fuel Treatment

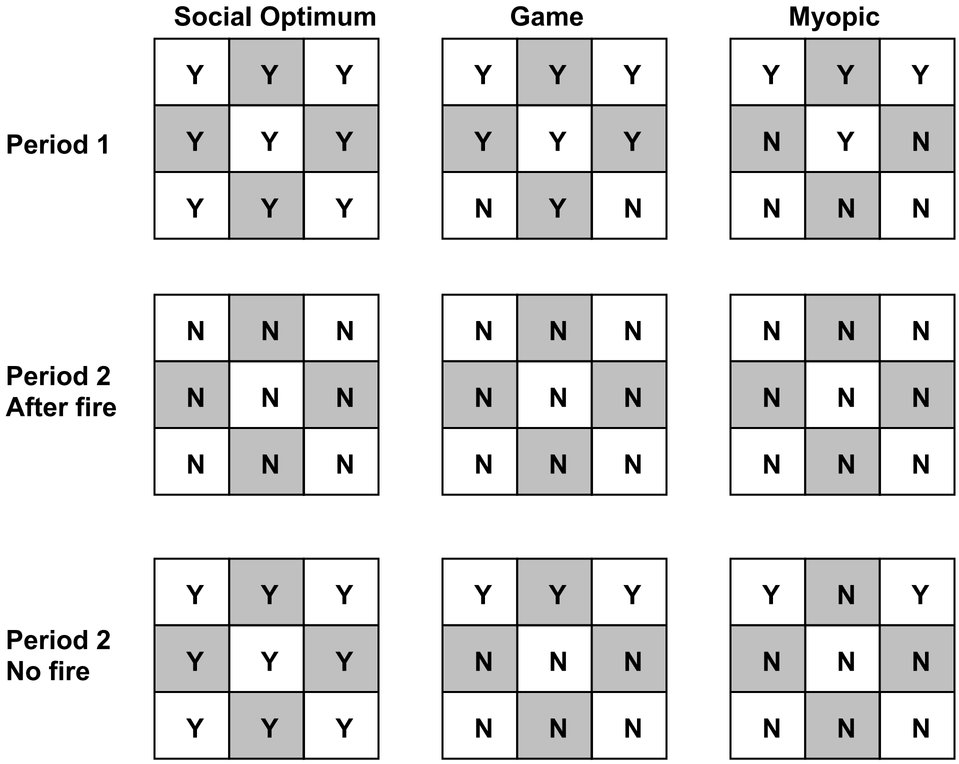


PUB 2000	PRIV 1500	PUB 2000
PRIV 1500	PUB 0	PRIV 1500
PUB 0	PRIV 1500	PUB 0

The results from the strategic interaction given the values in Figure 6.1 are described in Table 6.1. In the first period, the public landowner treats the top two corner units and the center unit. The public landowner chooses to treat the center unit even though it has zero public value and, given the spatial weighting pattern, it does not protect public values on the top two corner units. However, by treating the center unit in the first period the public landowner induces the private landowner to treat one unit in period two, if there is no fire in period one. The private landowner's best response to all possible fuel treatment choices reveals that if the public landowner had not treated the center unit, private would not have carried out any fuel treatment in period two. This example illustrates strategic behavior in terms of quantity, or the number of units treated.

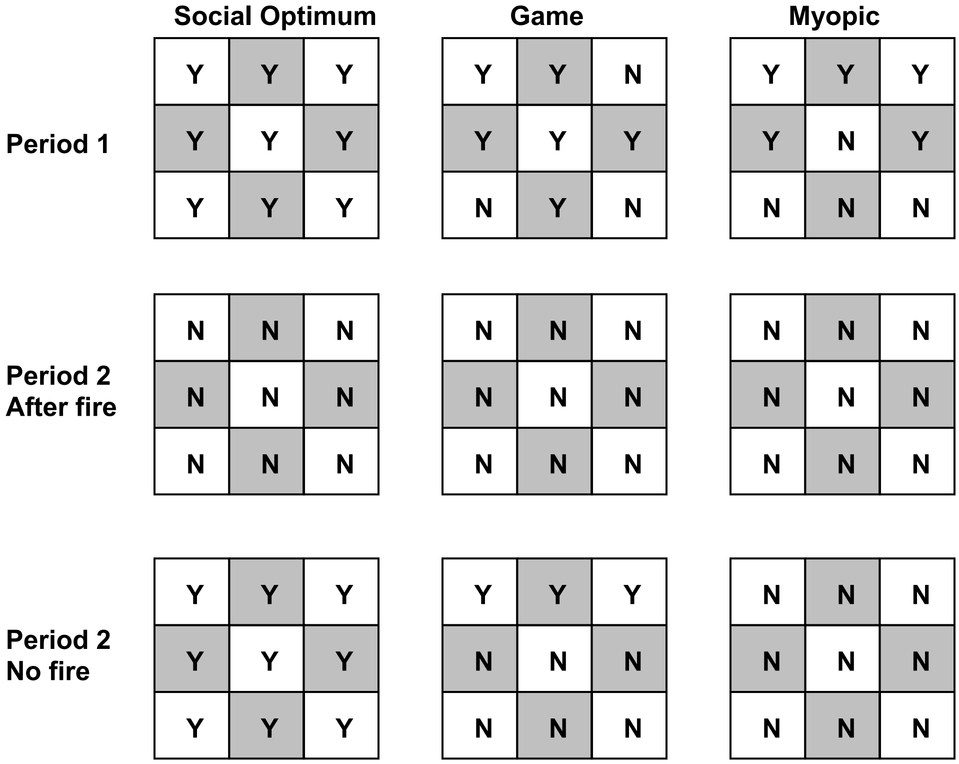
An example of spatially strategic behavior, where the benefits of fuel treatment placement outweigh the benefits of simply treating the unit with value, results when the pattern of values is as described in Figure 6.2. Given these values, the outcome of the game is described in Table 6.3. Here the public landowner forgoes fuel treatment on one of the high-value units, in the top right corner, in order to treat the center unit, which has zero public value and does not directly protect public values at risk. However, treating the center unit induces additional fuel treatment on privately owned units in periods one and two. If the public landowner had treated the top two corner units in period one, then both the public and the private landowner would have chosen zero fuel treatment in period two, if no fire in period one. By treating the top left and center units in period one, the period two outcome has more fuel treatment on both public and private units.

FIGURE 6.3: Checkerboard Public in Center – Increasing Returns



	Social Optimum			Game			Myopic		
Period 1	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Y	Y	Y	Y	Y	Y	N	Y	N
	Y	Y	Y	N	Y	N	N	N	N
Period 2 After fire	N	N	N	N	N	N	N	N	N
	N	N	N	N	N	N	N	N	N
	N	N	N	N	N	N	N	N	N
Period 2 No fire	Y	Y	Y	Y	Y	Y	Y	N	Y
	Y	Y	Y	N	N	N	N	N	N
	Y	Y	Y	N	N	N	N	N	N

FIGURE 6.4: Checkerboard Public in Center – Increasing Returns



	Social Optimum			Game			Myopic		
Period 1	Y	Y	Y	Y	Y	N	Y	Y	Y
	Y	Y	Y	Y	Y	Y	Y	N	Y
	Y	Y	Y	N	Y	N	N	N	N
Period 2 After fire	N	N	N	N	N	N	N	N	N
	N	N	N	N	N	N	N	N	N
	N	N	N	N	N	N	N	N	N
Period 2 No fire	Y	Y	Y	Y	Y	Y	N	N	N
	Y	Y	Y	N	N	N	N	N	N
	Y	Y	Y	N	N	N	N	N	N

Interviews and observational data on private fuel treatment decisions in the WUI reveal that landowners view the benefits of fuel treatment as greatest when forest fuels are reduced on their individual property and nearby ownerships. For example, a WUI resident in Larimer County, Colorado believed that the benefit of fuel treatment on his property would be even greater if his neighbors down the canyon, in an area which he believed to be a source of risk, also removed forest fuels (Brenkert-Smith et al., 2006). Additionally, there is some unwillingness among landowners to reduce forest fuels unless their entire neighborhood has done so as well (Monroe and Nelson, 2004).

There is no evidence in this literature to support the notion that landowners will forego fuel treatment if adjacent properties have already done so, which would suggest free riding. While this could imply that landowners believe the relationship between fuel stock and fire damage is characterized by increasing returns, it could also mean that current fuel stock levels are very high and that they are still on the steep portion of the decreasing returns to treatment damage curve. However, if landowners do in fact believe that the relationship between fuel stock and fire damage is characterized by increasing returns, this suggests another policy option—undertake fuel treatment on publicly owned units to induce private landowners to reduce forest fuel on their property as well.

6.3 Myopic Landowners

Myopic landowners tend to do less fuel treatment than forward-looking landowners in the first period, especially when the ownership pattern is fragmented. This is because the myopic managers do not consider the full benefits of fuel treatment in the first period. Fuel treatment in the first period provides immediate protection for values at risk, which the myopic landowner considers, but also benefits the landowner in the second period by: (1) reducing the beginning fuel stock and thereby the potential fire damage and (2) reducing the cost of fuel treatment. The myopic landowner's failure to consider these second period benefits leads to too little treatment in the first period.

Myopic landowners most often choose less fuel treatment compared to their forward-looking counterparts when the ownership pattern is isolated private/public, private/public extending into public/private, and checkerboard. With less fuel treatment in the first period, fuel stock in the second period is greater and, in some cases, this leads to more fuel treatment in the second period. However, fuel treatment in the second period is not a perfect substitute for treatment in the first period because fuel stock grows over time and there is a chance of fire in period one. Hence, the departure from the social optimum is much greater when landowners are myopic.

When returns to fuel treatment are increasing or decreasing, the decisions made by the myopic and forward-looking landowners will largely depend on the initial fuel stock and position along the damage function. When returns to fuel treatment are increasing, the myopic public landowner makes the same fuel treatment decisions as the forward-looking public landowner. But when returns to fuel treatment are decreasing, the myopic public landowner chooses less fuel treatment than the forward-looking private landowner for every ownership pattern except checkerboard, where both choose zero treatment.

When landowners are myopic, the three fire risk management policies studied here are generally less effective. This is especially significant in the case of the fuel stock regulation (Table 6.1). When landowners are forward-looking, the fuel stock regulation achieves the social optimum for every ownership pattern except checkerboard. However, in the presence of the regulation, myopic landowners wait until the second period to treat fuels and the socially optimal treatment pattern is not achieved on any ownership pattern. When landowners are myopic, in order to achieve the socially optimal treatment pattern through regulation would require a temporal component to the regulation. This result highlights the fact that achieving desired outcomes requires that regulators consider how landowners' time preferences affect their fuel treatment decisions.

TABLE 6.1: Departure from Social Optimum – Fuel Stock Regulation

Ownership Pattern	**Baseline**	**Game with Regulation**	**Myopic with Regulation**
Private adjoining public	0.25%	0%	18.96%
Private corridor	0.41%	0%	18.96%
Isolated private	0.41%	0%	18.96%
Private extending into public	0.55%	0%	18.93%
Checkerboard with public in center	6.59%	5.89%	25.90%

6.4 Policy Effectiveness

Of the three policy applications, the fuel stock regulation appears to be the most effective at achieving the socially optimal fuel treatment pattern and the insurance program appears to be the least effective and most costly. Both private insurance and public liability reduce the private landowners' incentive to self-protect. This is costly because fuel treatment on privately owned units is a very effective way to minimize wildfire damage to private values at risk on those units. By removing incentives for fuel treatment on privately owned units, the insurance program and public liability actually increase private landowners' expected losses from fire. In addition, because the public landowner is no longer able to benefit from the positive spatial externalities from fuel treatment on privately owned units, the public landowner's expected loss also increases. The liability rule is preferred to the insurance program because it increases the public landowner's value at risk, creating additional incentive for fuel treatment on publicly owned units, and partially offsetting reductions in fuel treatment on privately owned units. With the private insurance program, however, decreases in private fuel treatment are not accompanied by increases in public fuel treatment.[18]

The tables comparing the difference between the expected loss from the game with policy and the social optimum, as a percent of expected loss from the social optimum (Tables 4.6, 4.7, and 4.8), indicate that outcomes without policy intervention are relatively close to the social optimum. This suggests that less fragmented landscapes might be best left alone, without policy intervention. The best policy on less fragmented landscapes might simply be to educate landowners about wildfire risk on the landscape and then to let them make their own well-informed fuel management decisions, without interference. In particular,

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[18] The introduction of risk-adjusted insurance, which rewards landowners for self-protective actions with reduced premiums, would provide private landowners with incentive to reduce forest fuels but is not discussed here.

educating myopic landowners on landscapes with fragmented ownerships about the long-term benefits of fuel treatment might be especially beneficial. Including the cost of policy design and enforcement would further strengthen the case against policy intervention on less fragmented landscapes where the departure from the social optimum is relatively small.

Although the results indicate that a fuel stock regulation can effectively improve outcomes, crafting a regulation that achieves the socially optimal treatment requires a great deal of information on the part of the regulator. The design of an effective fuel stock regulation requires information about the socially optimal treatment pattern itself, current fuel stock, fuel stock growth rate, and how landowners make decisions, for example. The costs associated with the development and enforcement of the regulation must also be considered when evaluating this policy option.

6.4 Concluding remarks

The primary objective of this dissertation is to examine how spatial configuration and location affect fire risk management decisions on a landscape with mixed ownership and to explore policies intended to promote efficient outcomes. In order to explore these issues, I develop a dynamic model of forest fuel management decisions on a three-by-three grid landscape with spatially interdependent public and privately owner land units. Results from the model indicate that ownership pattern and location have a substantial influence on individual fire risk management decisions and outcomes and that, in some cases, policy may be able to improve the observed outcomes. The four major conclusions that can be drawn from the research are:

1. Ownership fragmentation increases the inefficiency of fire risk management except when off-site values exist.
2. Myopic landowners under-protect in early time periods, which increases the inefficiency of fire risk management.
3. The exact nature of strategic interaction among landowners depends on whether there are constant, increasing, or decreasing returns to fuel treatment.
4. Of the policies examined, the fuel stock regulation appears to have the greatest potential to improve the efficiency of fire risk management.

Landscapes where ownership is highly fragmented have few same-owner adjacencies and, because reducing forest fuel generates positive spatial externalities, landowners are unable to capture the full benefit of fuel treatment on a single unit. For this reason, ownership fragmentation generally leads to inefficient outcomes. However, when an individual landowner has value on neighboring property, highly fragmented landscapes increase the ability of the individual landowner to protect those off-site values, thereby improving outcomes.

Cross-ownership externalities are the sole source of inefficiency when there are constant returns to fuel treatment. However, in the presence of increasing or decreasing returns to fuel treatment, landowners behave strategically. When there are decreasing returns to fuel treatment, landowners spend as little as possible on fuel treatment as they attempt to free ride on their neighbor’s effort. In contrast, when there are increasing returns to fuel treatment, the opposite strategic behavior emerges and landowners increase the number of units treated or change the location of fuel treatment to induce additional treatment by their neighbors.

Results from the model indicate that when landowners are myopic and do not consider how decisions in the current period affect choices and outcomes in future periods, they tend to do less fuel treatment than forward-looking landowners in the first period. Reducing fuel treatment in early time periods results in outcomes that are further from the social optimum than when landowners are forward-looking. Additionally, fire risk management policies that seek to achieve fuel treatment in early periods will be less effective when landowners are myopic.

An examination of three policies—fuel stock regulation, liability, and private insurance—designed to achieve the socially optimally fuel treatment pattern reveals that the fuel stock regulation produced the best outcomes. The public liability rule and private insurance program reduce the incentive for fuel treatment on privately owned units, which results in higher fuel stocks and increased expected losses from fire damage. Therefore, a fuel stock regulation offers the greatest potential for improving outcomes on a fire-prone landscape.

This game theoretic model uses a set of simplifying assumptions which limits the application of the results to some extent. However, the advantage of a stylized theoretical model is that it provides basic insights that are not site-specific and can be applied across a range of settings. Another advantage of the modeling framework used here is that it can serve as a platform for numerous extensions such as: increasing the number of landowners, addressing non-market values, incorporating fire behavior, including the suppression decision, and applying the model to a real-world landscape. These lines of research offer additional opportunities to gain a better understanding of wildfire and improve the ability of policy-makers to effectively address wildfire management on a landscape where an increasing number of individuals living in the wildland urban interface are at risk.

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APPENDICIES

APPENDIX A Fuel Treatment Pattern – Private Value on Public Land

A.1 Private adjoining public

	Public Decision			**Private Decision**		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY
Period 2 After Fire	YYY NNN	YYY YYY	YYY NNN	YYY	YYY	YYY
Period 2 No Fire	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY

Social Exp Loss = 220.09, Public Exp Loss = 96.16, Private Exp Loss = 124.15

A.2 Public adjoining private

	Public Decision			**Private Decision**		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY	YYY	YYY	YYY YYY	YYY YYY	YYY YYY
Period 2 After Fire	NNN	YYY	NNN	YYY YYY	YYY YYY	YYY YYY
Period 2 No Fire	YYY	YYY	YYY	YYY YYY	YYY YYY	YYY YYY

Social Exp Loss = 182.52, Public Exp Loss = 48.19, Private Exp Loss = 134.55

A.3 Private corridor

	Public Decision			**Private Decision**		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY
Period 2 After Fire	NNN NNN	YYY YYY	NNN NNN	YYY	YYY	YYY
Period 2 No Fire	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY

Social Exp Loss = 220.09, Public Exp Loss = 96.15, Private Exp Loss = 124.39

A.4 Public corridor

	Public Decision			**Private Decision**		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY	YYY	YYY	YYY YYY	YYY YYY	YYY YYY
Period 2 After Fire	NNN	YYY	NNN	YYY YYY	YYY YYY	YYY YYY
Period 2 No Fire	YYY	YYY	YYY	YYY YYY	YYY YYY	YYY YYY

Social Exp Loss = 182.52, Public Exp Loss = 48.14, Private Exp Loss = 134.55

A.5 Isolated Private

	Public Decision			**Private Decision**		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY	Y	Y	Y
Period 2 After Fire	YNY N N YNY	YYY Y Y YYY	YNY N N YNY	Y	Y	Y
Period 2 No Fire	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY	Y	Y	Y

Social Exp Loss = 245.62, Public Exp Loss = 128.62, Private Exp Loss = 117.29

A.6 Isolated Public

	Public Decision			**Private Decision**		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	N	Y	Y	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY
Period 2 After Fire	N	Y	N	YNY N N YNY	YYY Y Y YYY	YYY Y Y YYY
Period 2 No Fire	N	Y	N	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY

Social Exp Loss = 157.33, Public Exp Loss = 15.34, Private Exp Loss = 147.37
Myopic: Public Exp Loss = 15.72, Private Exp Loss = 156.53

A.7 Private extending into public

	Public Decision			Private Decision		
	Myopic	Social Optimum	Game	Myopic	Social Optimum	Game
Period 1	YYY Y YYY	YYY Y YYY	YYY Y YYY	YY	YY	YY
Period 2 After Fire	NNY N NNY	YYY Y YYY	NNY N NNY	YY	YY	YY
Period 2 No Fire	YYY Y YYY	YYY Y YYY	YYY Y YYY	YY	YY	YY

Social Exp Loss = 233.00, Public Exp Loss = 112.53, Private Exp Loss = 120.84

A.8 Public extending into private

	Public Decision			Private Decision		
	Myopic	Social Optimum	Game	Myopic	Social Optimum	Game
Period 1	YN	YY	YY	YYY Y YYY	YYY Y YYY	YYY Y YYY
Period 2 After Fire	NN	YY	NN	YYY Y YYY	YYY Y YYY	YYY Y YYY
Period 2 No Fire	YY	YY	YY	YYY Y YYY	YYY Y YYY	YYY Y YYY

Social Exp Loss = 169.94, Public Exp Loss = 32.10, Private Exp Loss = 137.94
Myopic: Public Exp Lost = 32.82, Private Exp Loss = 141.12

A.9 Checkerboard with public in center

	Public Decision			Private Decision		
	Myopic	Social Optimum	Game	Myopic	Social Optimum	Game
Period 1	N N N N N	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y	Y Y Y Y	Y Y Y Y
Period 2 After Fire	N N N N N	N N Y N N	N N N N N	N N N N	Y Y Y Y	Y Y Y Y
Period 2 No Fire	N N N N N	Y Y Y Y Y	N N N N N	Y Y Y Y	Y Y Y Y	Y Y Y Y

Social Exp Loss = 207.76, Public Exp Loss = 76.68, Private Exp Loss = 153.07
Myopic: Public Exp Loss = 78.06, Private Exp Loss = 190.66

A.10 Checkerboard with private in center

	Public Decision			**Private Decision**		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	N N N N	Y Y Y Y	Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y
Period 2 After Fire	N N N N	Y Y Y Y	N N N N	N N N N N	Y Y Y Y Y	N N Y N N
Period 2 No Fire	N N N N	Y Y Y Y	N N N N	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y

Social Exp Loss = 195.17, Public Exp Loss = 61.47, Private Exp Loss = 160.13
Myopic: Public Exp Loss = 61.50, Private Exp Loss = 203.20

APPENDIX B Fuel Treatment Pattern – Decreasing Returns to Fuel Treatment

B.1 Private adjoining public (public adjoining private)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	NNN NNN	YYY YYY	YYY YYY	NNN	YYY	YYY
Period 2 After Fire	YYY NNN	YYY NYN	YYY NNN	YNY	YYY	YNY
Period 2 No Fire	YYY YYY	YYY YNY	YYY NYN	YYY	YYY	YYY

Social Exp Loss = 49.13, Public Exp Loss = 31.99, Private Exp Loss = 17.23
Myopic: Public Exp Loss = 36.44, Private Exp Loss = 18.36

B.2 Private corridor (public corridor)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	NNN NNN	YYY YYY	YYY YYY	NNN	YYY	YYY
Period 2 After Fire	YNY NNY	YYY YYY	YYY NNN	NYN	NYN	NNN
Period 2 No Fire	YYY YYY	YYY YYY	YYY NYN	YNY	YNY	NYN

Social Exp Loss = 49.13, Public Exp Loss = 34.00, Private Exp Loss = 15.72
Myopic: Public Exp Loss = 37.84, Private Exp Loss = 18.09

B.3 Isolated private (isolated public)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	NNN N N NNY	YYY Y Y YYY	YYY Y Y YYY	N	Y	Y
Period 2 After Fire	YNY N N YNY	YYY N N YYY	YNY N N YNY	Y	Y	N
Period 2 No Fire	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY	N	N	N

Social Exp Loss = 49.19, Public Exp Loss = 47.40, Private Exp Loss = 3.75
Myopic: Public Exp Loss = 50.59, Private Exp Loss = 4.33

B.4 Private extending into public (public extending into private)

	Public Decision			**Private Decision**		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	NNY N NNN	YYY Y YYY	YYY Y YYY	NN	YY	YN
Period 2 After Fire	YNY N NNY	NNY Y YYY	YNY Y YNY	NY	YY	YN
Period 2 No Fire	YYY Y YYY	YNY Y YYY	NYY Y YYY	YN	YY	YN

Social Exp Loss = 49.20, Public Exp Loss = 40.90, Private Exp Loss = 10.22
Myopic: Public Exp Loss = 43.80, Private Exp Loss = 11.22

B.5 Checkerboard with public in center (checkerboard with private in center)

	Public Decision			**Private Decision**		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	N N N N N	Y Y Y Y Y	N N N N N	N N N N	Y Y Y Y	N N N N
Period 2 After Fire	N N N N N	N N Y N N	N N N N N	N N N N	Y Y Y Y	Y Y Y Y
Period 2 No Fire	N N N N N	N N Y N N	N N N N N	Y Y Y Y	Y Y Y Y	Y Y Y Y

Social Exp Loss = 46.22, Public Exp Loss = 20.07, Private Exp Loss = 64.90
Myopic: Public Exp Loss =20.44, Private Exp Loss = 66.14

B.6 All public (all private)

	Public Decision		
	Myopic	**Social Optimum**	**Game**
Period 1	NNN NYN NNN	YYY YYY YYY	YYY YYY YYY
Period 2 After Fire	YYY YNY NNN	YYY NYN YYY	YYY NYN YYY
Period 2 No Fire	YYY YNY YYY	YYY YNY YYY	YYY YNY YYY

Social Exp Loss = 49.19, Public Exp Loss = 49.29
Myopic: Public Exp Loss = 49.97

APPENDIX C Fuel Treatment Patterns – Increasing Returns to Treatment

C.1 Private adjoining public (public adjoining private)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY
Period 2 After Fire	NNN NNN	NNN NNN	NNN NNN	NNN	NNN	NNN
Period 2 No Fire	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY

Social Exp Loss = 286.16, Public Exp Loss = 190.67, Private Exp Loss = 95.49

C.2 Private adjoining public (public adjoining private)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY
Period 2 After Fire	NNN NNN	NNN NNN	NNN NNN	NNN	NNN	NNN
Period 2 No Fire	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY

Social Exp Loss = 286.16, Public Exp Loss = 190.67, Private Exp Loss = 95.49

C.3 Private adjoining public (public adjoining private)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY	N	Y	N
Period 2 After Fire	NNN N N NNN	NNN N N NNN	NNN N N NNN	N	N	N
Period 2 No Fire	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY	N	Y	N

Social Exp Loss = 286.16, Public Exp Loss = 266.18, Private Exp Loss = 30.99

C.4 Private extending into public (public extending into private)

	Public Decision			Private Decision		
	Myopic	Social Optimum	Game	Myopic	Social Optimum	Game
Period 1	YYY Y YYY	YYY Y YYY	YYY Y YYY	YN	YY	YY
Period 2 After Fire	NNN N NNN	NNN N NNN	NNN N NNN	NN	NN	NN
Period 2 No Fire	YYY Y YYY	YYY Y YYY	YYY Y YYY	YY	YY	YY

Social Exp Loss = 286.16, Public Exp Loss = 222.81, Private Exp Loss = 63.66
Myopic: Public Exp Loss = 224.81, Private Exp Loss = 64.38

C.5 Checkerboard with public in center (checkerboard with private in center)

	Public Decision			Private Decision		
	Myopic	Social Optimum	Game	Myopic	Social Optimum	Game
Period 1	N N N N N	Y Y Y Y Y	N N N N N	N N N N	Y Y Y Y	N N N N
Period 2 After Fire	N N N N N	N N N N N	N N N N N	N N N N	N N N N	N N N N
Period 2 No Fire	N N N N N	Y Y Y Y Y	N N N N N	N N N N	Y Y Y Y	N N N N

Social Exp Loss = 286.47, Public Exp Loss = 175.43, Private Exp Loss = 140.35

C.6 All public (all private)

	Public Decision		
	Myopic	Social Optimum	Game
Period 1	YYY YYY YYY	YYY YYY YYY	YYY YYY YYY
Period 2 After Fire	NNN NNN NNN	NNN NNN NNN	NNN NNN NNN
Period 2 No Fire	YYY YYY YYY	YYY YYY YYY	YYY YYY YYY

Social Exp Loss = 144.42, Public Exp Loss = 144.42

APPENDIX D Fuel Treatment Patterns – Fuel Stock on the Individual Unit and the Unit to the Right Matter Equally

D.1 Private adjoining public (public adjoining private)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY
Period 2 After Fire	NYY NYY	NYY NYY	NYY NYY	NYY	NYY	NYY
Period 2 No Fire	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY

Social Exp Loss = 144.33, Public Exp Loss = 96.12, Private Exp Loss = 48.21

D.2 Private corridor (public corridor)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY
Period 2 After Fire	NYY NYY	NYY NYY	NYY NYY	NYY	NYY	NYY
Period 2 No Fire	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY

Social Exp Loss = 144.33, Public Exp Loss = 96.12, Private Exp Loss = 48.21

D.3 Isolated private (isolated public)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY	Y	Y	Y
Period 2 After Fire	NYY N Y NYY	NYY N Y NYY	NYY N Y NYY	N	Y	N
Period 2 No Fire	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY	Y	Y	Y

Social Exp Loss = 144.63, Public Exp Loss = 128.59, Private Exp Loss = 16.05

D.4 Private extending into public (public extending into private)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**

Period 1	YYY
	  Y
	YYY
		YYY
		  Y
		YYY
			YYY
			  Y
			YYY
				YY	YY	YY

Period 2 After Fire	NYY
	  Y
	NYY
		NYY
		  Y
		NYY
			NYY
			  Y
			NYY
				NY	NY	NY

Period 2 No Fire	YYY
	  Y
	YYY
		YYY
		  Y
		YYY
			YYY
			  Y
			YYY
				YY	YY	YY

Social Exp Loss = 144.42, Public Exp Loss = 112.49, Private Exp Loss = 32.13

D.5 Checkerboard with public in center (checkerboard with private in center)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y	Y Y Y Y	Y Y Y Y
Period 2 After Fire	N N N N N	N Y Y N Y	N N N N N	N N N N	Y N Y Y	N N N N
Period 2 No Fire	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y	Y Y Y Y	Y Y Y Y

Social Exp Loss = 144.63, Public Exp Loss = 80.45, Private Exp Loss = 64.36

D.6 All public (all private)

	Public Decision		
	Myopic	**Social Optimum**	**Game**
Period 1	YYY YYY YYY	YYY YYY YYY	YYY YYY YYY
Period 2 After Fire	NYY NYY NYY	NYY NYY NYY	NYY NYY NYY
Period 2 No Fire	YYY YYY YYY	YYY YYY YYY	YYY YYY YYY

Social Exp Loss = 144.63, Public Exp Loss = 144.63

APPENDIX E Fuel Treatment Patterns – Fuel Stock on the Individual Unit and the Unit Above Matter Equally

E.1 Private adjoining public (public adjoining private)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY
Period 2 After Fire	YYY NNN	YYY NNN	YYY NNN	NNN	YYY	NNN
Period 2 No Fire	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY

Social Exp Loss = 144.33, Public Exp Loss = 96.09, Private Exp Loss = 48.27

E.2 Private corridor (public corridor)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY
Period 2 After Fire	YYY NNN	YYY NNN	YYY NNN	NNN	YYY	NNN
Period 2 No Fire	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY

Social Exp Loss = 144.33, Public Exp Loss = 96.21, Private Exp Loss = 48.15

E.3 Isolated private (isolated public)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY	Y	Y	Y
Period 2 After Fire	YYY Y Y NNN	YYY Y Y NNN	YYY Y Y NNN	N	Y	N
Period 2 No Fire	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY	Y	Y	Y

Social Exp Loss = 144.63, Public Exp Loss = 128.59, Private Exp Loss = 16.05

E.4 Private extending into public (public extending into private)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY Y YYY	YYY Y YYY	YYY Y YYY	YY	YY	YY
Period 2 After Fire	YYY Y NNN	YYY Y NNN	YYY Y NNN	NN	YY	NN
Period 2 No Fire	YYY Y YYY	YYY Y YYY	YYY Y YYY	YY	YY	YY

Social Exp Loss = 144.63, Public Exp Loss = 112.55, Private Exp Loss = 32.10

E.5 Checkerboard with public in center (checkerboard with private in center)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y	Y Y Y Y	Y Y Y Y
Period 2 After Fire	N N N N N	Y Y Y N N	N N N N N	N N N N	Y Y Y N	N N N N
Period 2 No Fire	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y	Y Y Y Y	Y Y Y Y

Social Exp Loss = 144.63, Public Exp Loss = 80.45, Private Exp Loss = 64.36

E.6 All public (all private)

	Public Decision		
	Myopic	**Social Optimum**	**Game**
Period 1	YYY YYY YYY	YYY YYY YYY	YYY YYY YYY
Period 2 After Fire	YYY YYY NNN	YYY YYY NNN	YYY YYY NNN
Period 2 No Fire	YYY YYY YYY	YYY YYY YYY	YYY YYY YYY

Social Exp Loss = 144.63, Public Exp Loss = 144.63

APPENDIX F Fuel Treatment Patterns – Regulation

F.1 Private adjoining public (public adjoining private)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	NNN NNN	YYY YYY	YYY YYY	NNN	YYY	YYY
Period 2 After Fire	NNN NNN	NNN NNN	NNN NNN	NNN	NNN	NNN
Period 2 No Fire	YYY YYY	NNN NNN	NNN NNN	YYY	NNN	NNN

Social Exp Loss = 249.12, Public Exp Loss = 165.93, Private Exp Loss = 83.19
Without Regulation: Public Exp Loss = 166.39, Private Exp Loss = 83.74
Myopic: Public Exp Loss = 197.44, Private Exp Loss = 98.91
Myopic without Regulation: Public Exp Loss = 165.27, Private Exp Loss = 82.96

F.2 Private corridor (public corridor)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	NNN NNN	YYY YYY	YYY YYY	NNN	YYY	YYY
Period 2 After Fire	NNN NNN	NNN NNN	NNN NNN	NNN	NNN	NNN
Period 2 No Fire	YYY YYY	NNN NNN	NNN NNN	YYY	NNN	NNN

Social Exp Loss = 249.12 Public Exp Loss = 165.93, Private Exp Loss = 83.19
Without Regulation: Public Exp Loss = 166.80, Private Exp Loss = 83.73
Myopic: Public Exp Loss = 197.44, Private Exp Loss = 98.91
Myopic without Regulation: Public Exp Loss = 165.27, Private Exp Loss = 82.96

F.3 Isolated private (isolated public)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	NNN N N NNN	YYY Y Y YYY	YYY Y Y YYY	N	Y	Y
Period 2 After Fire	NNN N N NNN	NNN N N NNN	NNN N N NNN	N	N	N
Period 2 No Fire	YYY Y Y YYY	NNN N N NNN	NNN N N NNN	Y	N	N

Social Exp Loss = 249.50, Public Exp Loss = 221.84, Private Exp Loss = 27.73
Without Regulation: Public Exp Loss = 222.60, Private Exp Loss = 27.94
Myopic: Public Exp Loss = 263.75, Private Exp Loss = 32.97
Myopic Without Regulation: Public Exp Loss = 221.24, Private Exp Loss = 27.65

F.4 Private extending into public (public extending into private)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	NNN N NNN	YYY Y YYY	YYY Y YYY	NN	YY	YY
Period 2 After Fire	NNN N NNN	NNN N NNN	NNN N NNN	NN	NN	NN
Period 2 No Fire	YYY Y YYY	NNN N NNN	NNN N NNN	YY	NN	NN

Social Exp Loss = 249.50, Public Exp Loss = 194.10, Private Exp Loss = 55.46
Without Regulation: Public Exp Loss = 195.03, Private Exp Loss = 55.84
Myopic: Public Exp Loss = 230.78, Private Exp Loss = 65.94
Myopic Without Regulation: Public Exp Loss = 193.57, Private Exp Loss = 55.31

F.5 Checkerboard with public in center (checkerboard with private in center)

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	N N N N N	N N Y N N	Y Y Y Y Y	N N N N	Y Y Y Y	Y Y Y Y
Period 2 After Fire	N N N N N	N N N N N	N N N N N	N N N N	N N N N	N N N N
Period 2 No Fire	Y Y Y Y Y	N N N N N	N N N N N	Y Y Y Y	N N N N	N N N N

Social Exp Loss = 235.68, Public Exp Loss = 138.65, Private Exp Loss = 110.92
Without Regulation: Public Exp Loss = 139.56, Private Exp Loss = 111.65
Myopic: Public Exp Loss = 164.85, Private Exp Loss = 131.88
Myopic Without Regulation: Public Exp Loss = 138.27, Private Exp Loss = 110.62

F.6 All public (all private)

	Public Decision		
	Myopic	**Social Optimum**	**Game**
Period 1	NNN NNN NNN	YYY YYY YYY	YYY YYY YYY
Period 2 After Fire	NNN NNN NNN	NNN NNN NNN	NNN NNN NNN
Period 2 No Fire	YYY YYY YYY	NNN NNN NNN	NNN NNN NNN

Social Exp Loss = 249.50, Public Exp Loss = 263.06
Without Regulation: Public Exp Loss = 249.56
Myopic: Public Exp Loss = 321.99
Myopic Without Regulation: Public Exp Loss = 219.38

APPENDIX G Fuel Treatment Patterns – Liability

G.1 Private adjoining public

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY YYY	YYY YYY	YYY YYY	NNN	YYY	YYY
Period 2 After Fire	YYY YYY	YYY YYY	YYY YYY	NNN	YYY	NNN
Period 2 No Fire	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	YYY

Social Exp Loss = 144.42, Public Exp Loss = 115.24, Private Exp Loss = 29.21
Myopic: Public Exp Loss = 121.15, Private Exp Loss = 31.38

G.2 Private corridor

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY YYY	YYY YYY	YYY YYY	NNN	YYY	YYY
Period 2 After Fire	YYY YYY	YYY YYY	YYY YYY	NNN	YYY	NNN
Period 2 No Fire	YYY YYY	YYY YYY	YYY YYY	YYY	YYY	NNN

Social Exp Loss = 144.42, Public Exp Loss = 121.92, Private Exp Loss = 28.92
Myopic: Public Exp Loss = 122.12, Private Exp Loss = 30.40

G.3 Isolated private

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY	N	Y	N
Period 2 After Fire	YNY N N YNY	YYY Y Y YYY	YNY N N YNY	N	Y	N
Period 2 No Fire	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY	N	Y	N

Social Exp Loss = 144.42, Public Exp Loss = 148.77, Private Exp Loss = 7.87

G.4 Private extending into public

	Public Decision			Private Decision		
	Myopic	Social Optimum	Game	Myopic	Social Optimum	Game
Period 1	YYY Y YYY	YYY Y YYY	YYY Y YYY	NN	YY	YY
Period 2 After Fire	YNY N YNY	YYY Y YYY	YYY Y YYY	NN	YY	NN
Period 2 No Fire	YYY Y YYY	YYY Y YYY	YYY Y YYY	YN	YY	NN

Social Exp Loss = 144.42, Public Exp Loss = 134.35, Private Exp Loss = 18.67
Myopic: Public Exp Loss = 139.88, Private Exp Loss = 19.52

G.5 Checkerboard with public in center

	Public Decision			Private Decision		
	Myopic	Social Optimum	Game	Myopic	Social Optimum	Game
Period 1	N N Y N N	Y Y Y Y Y	Y Y Y Y Y	N N N N	Y Y Y Y	N N N N
Period 2 After Fire	N N N N N	N N Y N N	N N N N N	N N N N	Y Y Y Y	N N N N
Period 2 No Fire	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	N N N N	Y Y Y Y	N N N N

Social Exp Loss = 144.63, Public Exp Loss = 172.93, Private Exp Loss = 31.32
Myopic: Public Exp Loss = 175.13, Private Exp Loss = 33.77

APPENDIX H Fuel Treatment Patterns – Insurance

H.1 Private adjoining public

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY YYY	YYY YYY	YYY YYY	NNN	YYY	NNN
Period 2 After Fire	YYY NNN	YYY YYY	YYY NNN	NNN	YYY	NNN
Period 2 No Fire	YYY YYY	YYY YYY	YYY YYY	NNN	YYY	NNN

Social Exp Loss = 144.42, Public Exp Loss = 105.30, Private Exp Loss = 118.67

H.2 Private corridor

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY YYY	YYY YYY	YYY YYY	NNN	YYY	NNN
Period 2 After Fire	NNN NNN	YYY YYY	NNN NNN	NNN	YYY	NNN
Period 2 No Fire	YYY YYY	YYY YYY	YYY YYY	NNN	YYY	NNN

Social Exp Loss = 144.42, Public Exp Loss = 114.43, Private Exp Loss = 118.76

H.3 Isolated private

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY	N	Y	N
Period 2 After Fire	YNY N N YNY	YYY Y Y YYY	YNY N N YNY	N	Y	N
Period 2 No Fire	YYY Y Y YYY	YYY Y Y YYY	YYY Y Y YYY	N	Y	N

Social Exp Loss = 144.42, Public Exp Loss = 140.90, Private Exp Loss = 39.65

H.4 Private extending into public

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	YYY Y YYY	YYY Y YYY	YYY Y YYY	NN	YY	NN
Period 2 After Fire	NNY N NNY	YYY Y YYY	NNY N NNY	NN	YY	NN
Period 2 No Fire	YYY Y YYY	YYY Y YYY	YYY Y YYY	NN	YY	NN

Social Exp Loss = 144.42, Public Exp Loss = 127.82, Private Exp Loss = 79.21

H.5 Checkerboard with public in center

	Public Decision			Private Decision		
	Myopic	**Social Optimum**	**Game**	**Myopic**	**Social Optimum**	**Game**
Period 1	N N N N N	Y Y Y Y Y	Y Y Y Y Y	N N N N	Y Y Y Y	N N N N
Period 2 After Fire	N N N N N	Y Y Y Y Y	N N N N N	N N N N	Y Y Y Y	N N N N
Period 2 No Fire	N N N N N	Y Y Y Y Y	N N N N N	N N N N	Y Y Y Y	N N N N

Social Exp Loss = 144.42, Public Exp Loss = 138.11, Private Exp Loss = 158.60
Myopic: Public Exp Loss = 138.27, Private Exp Loss = 156.19

H.6 All private

	Private Decision		
	Myopic	**Social Optimum**	**Game**
Period 1	NNN NNN NNN	YYY YYY YYY	NNN NNN NNN
Period 2 After Fire	NNN NNN NNN	YYY YYY YYY	NNN NNN NNN
Period 2 No Fire	NNN NNN NNN	YYY YYY YYY	NNN NNN NNN

Social Exp Loss = 144.42, Public Exp Loss = 278.48