# Wildfire Risk Management on a Landscape with Public and Private Ownership: Who Pays?


*Gwenlyn M. Busby, 541-737-6543, gwen.busby@oregonstate.edu

**Heidi J. Albers,** 541-737-1483, hj.albers@oregonstate.edu

**Claire A. Montgomery**, 541-737-5533, claire.montgomery@oregonstate.edu

*Department of Forest Resources, Oregon State University, Corvallis, OR 97331*

* corresponding author



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## *I. Introduction*

In recent years the western U.S. has seen an increase in the both the frequency and severity of wildland fires. Statistics from the past five years on acres and homes burned (Table 1) provide a stark illustration of the impact these fires have had on the landscape. In 2003, for example, over 4,500 homes in the United States were destroyed by wildland fires, nearly all of them during the October fires in southern California, resulting in more than two billion U.S. dollars in damages (NIFC 2007). These fires have continued to burn in spite of the billions of dollars federal agencies spend on fire suppression. A steady increase in the number of individuals living in and around forested areas (Stewart et al. 2005) has added to the complexity and immediacy of the wildfire problem. If wildfire risk is not considered by individuals and communities in fire-prone areas, values at risk of damage and destruction by wildfire will continue increasing and public expenditures will remain ineffective.

**Table 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 |

Source: National Interagency Coordination Center at the National Interagency Fire Center.

Because wildfire responds to changes in the amount and configuration of fuels, a forest can be managed through the use of various hazardous fuel reduction treatments[1] to minimize wildfire risk (van Wagtendonk 1996; Graham et al. 1999; Hirsch and Pengelly 1999; Pollet and Omi 2002; Agee and Skinner 2006). However, because wildfire moves across a landscape and across property boundaries, the risk an individual faces is a function of fuel reduction decisions made by both the individual owner and other landowners. Because both individual and collective actions affect wildfire risk, this problem is well suited to game theory and the analysis of strategic behavior.

[1] We do not distinguish between different types of fuel reduction treatments (e.g. prescribed fire versus mechanical thinning); instead we use a general measure of "fuel reduction effort."

When deciding where to spend fuel reduction effort, public land management agencies must consider values at risk in the wildland urban interface (WUI), where public and private land is intermixed, as well as values at risk on public land outside the WUI. In the WUI, the extent of wildfire damage depends on both the self-protection actions taken by the private owners and those taken by neighboring public forest managers. Within this context, we examine how a public land management agency's investment in fuel reduction both within and outside the WUI influences, and is influenced by, decisions made by a private land owner within the WUI.

The disinterest in self-protection against natural hazards even when it is cost-effective has been observed for other hazards (Kunreuther 2000). Failure to self-protect against wildfire damage may be due to a variety of factors: lack of information regarding the occurrence and severity of wildfires, the probability or potential damage from a wildfire, risk attitude, a disinclination to worry about low probability hazards, or government provision of disaster relief (Kunreuther and Slovic 1978; Lewis and Nickerson 1989; McGee 2006). In an attempt to force private land owners in the WUI to self-protect, some states have begun requiring fuel treatment on private land. Montana, Minnesota, New Mexico and Washington statutory law require landowners to reduce excessive fuel loads to reduce the possibility of wildfires (Yoder et al. 2004). In a similar move, Oregon passed the Oregon Forestland-Urban Interface Fire Protection Act in 1997 and the associated administrative rules in 2002, which will become effective in 2007. However, these laws remain the exception rather than the rule and the extent to which they will be enforced is uncertain. In general, public land management agencies alone fund fuel reduction projects on public, and in some cases on private, forest land in addition to funding all wildfire suppression effort.

The Healthy Forest Restoration Act (2003) requires that at least fifty percent of funding for hazardous fuel reduction projects be used in the WUI. This policy has had a noticeable impact on the distribution of fuel treatments across the western U.S. For example, in FY2006 fuel treatments conducted under the HFRA on USFS land in Montana totaled 42,304 acres in the WUI and 18,263 acres outside the WUI (www.healthyforests.gov/projects/montana.html. Feb. 3, 2007). Because there are far more acres outside the WUI, the difference between the two figures is even more pronounced when treatment in the WUI as a fraction of total acres in the WUI is compared to treatment outside the WUI as a fraction of total acres outside the WUI.

Fuel reduction is a form of hazard mitigation and has public good characteristics: it is non-rival and non-excludable. If an individual expends fuel reduction effort on her property, then wildfire risk is reduced on both the individual's property and on neighboring properties. Furthermore, the individual cannot exclude neighbors from benefiting from, 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 three alternative technologies – total effort, weakest link, and best shot – that relate individual effort to improvements in provision of the good. Because fuel reduction effort both on an individual plot 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), we employ the total effort technology, in which public good provision depends on the sum of the efforts exerted by the individuals.

Despite the characteristics of wildfire risk WUI that make game theory appropriate (i.e., both individual and collective actions affect wildfire risk), only Amacher et al. (2006) use game theory to explore the interaction between a public agency and a private land owner in the context of wildfire. They use a stand level model to analyze the strategic interaction between government and a private land owner, but focus only on the management of private land. In their model the government chooses level of suppression and the private land owner chooses the level of fuel reduction effort. Because public fuels treatment and suppression decisions are typically unrelated in practice, here we focus on the interaction between public and private land owners in their choices about fuel and risk reduction efforts. The public land manager considers values in the WUI and outside the WUI and determines how to allocate fuels treatment effort across the landscape. The private landowner chooses effort only in the WUI. We use this model of strategic interaction between the public land manager and the private land owner in their choice of fuel reduction effort to analyze the impact of federal disaster relief and evaluate the current government policy of focusing fire-risk mitigating activities in the WUI. We find that both federal disaster relief and increases in public land management agency's spending on fuel reduction effort in the WUI increases private land owner's ability to free ride and may result in inefficiently low levels of fuel reduction effort outside the WUI.

The basic model used to analyze the wildfire risk management problem is described in section II. We being Section II with a description of the social planner's fuel reduction decision and then define the public land manager's and private land owner's decisions. In section III the strategic interaction between the players is made explicit and the results of the game theoretic model are described. We examine the impact of federal disaster relief in section IV. In section V we discuss the degree of free riding, efficiency, and policy implications of the model's results. Concluding remarks are offered in section VI.

## *II. Model*

*Landscape.* We model a landscape with two general areas: outside the WUI and the WUI. The area outside the WUI is comprised of public land only and the public landowner, "Public," chooses the amount of fuel reduction effort there. The WUI includes a mix of public and private land and both Public and the private landowner, "Private," choose their own level of fuel reduction effort there. Total effort in the WUI is the sum of Public and Private effort. We assume the forest fuel conditions are the same both in and outside the WUI.

*Fire.* Fuel reduction effort (e) reduces the amount, and alters the arrangement, of forest fuels thereby decreasing the intensity and spread rate of fires. With less intense, smaller fires the probability that values in the area survive a fire increases. For example, a high intensity fire could kill all the standing trees and thereby destroy both timber and environmental service values while a low intensity fire could kill only the low shrubs and debris without damaging timber and environmental service values. The parameter "fire resistance," $\pi$, describes the probability that values survive a fire and is determined by fuel reduction effort, $e$, in that area.[2] For the fire resistance parameter we have $\pi'(e)>0$ and $\pi''(e)<0$ where prime denotes the derivative with respect to effort, $e$. The first and second order derivatives imply that as effort increases fire resistance increases, but at a decreasing rate. The fuel reduction effort, $e$, describes the total effort for a given

[2] The probability of ignition is exogenous of effort and assumed to be equal in and outside the WUI. The focus of our paper is on the value remaining post-fire.

area – WUI or outside the WUI – regardless of who performs that effort. Throughout the paper we assume a constant cost of fuels reduction effort.[3]

*II. A. Social Optimum*

In order to compare the fuel reduction effort that arises in equilibrium from the game between Private and Public to the socially optimal level of effort, first we solve the Social Planner's problem:

$$\max_{e_{g,o},e_{g,w},e_p} \{A_{g,o}\pi(e_{g,o}) + (A_{g,w} + v + A_p)\pi(e_{g,w} + e_p) - c(e_{g,o} + e_{g,w} + e_p)\}$$

Where

$\pi(\cdot)$ = Fire resistance
$e_{g,o}$ = Public effort outside the WUI
$e_{g,w}$ = Public effort in the WUI
$e_p$ = Private effort ouside the WUI
$A_{g,o}$ = Public amenity value outside the WUI
$A_{g,w}$ = Public amenity value in the WUI
$A_p$ = Private amenity value in the WUI
$v$ = Private value in the WUI
$c$ = unit cost of fuel reduction effort

The social planner chooses the level of three types of effort ($e$) that depict the provider and location of that effort. Similarly, the social planner receives amenity values from three sources. The first subscripts on effort, $e$, and amenity value, $A$, indicate whether the parameter is associated with Public ($g$) or Private ($p$) and the second subscript describes whether the parameter represents value/effort in the WUI ($w$) or outside the WUI ($o$). Private effort and amenity value have only one subscript because we assume Private has no amenity values outside the WUI and, therefore, does not spend effort outside the WUI. Amenity value includes resource values such as scenic views, clean air, and other nonmarket ecosystem services. Private value ($v$) represents uninsured private property

[3] For simplicity we assume the cost of fuel reduction effort is equal in the WUI and away from the WUI and equal for Public and Private. However, the cost of fuel reduction effort may be greater in the WUI due to extra precaution that must be taken to protect private property or higher transaction costs associated with planning and implementing projects in areas of mixed ownership. If the cost of fuel reduction effort in the WUI is greater, then the MNB of effort in the WUI decrease for all levels of effort and Public would want to shift effort away from the WUI.

value such as timber or a home in the WUI. The first order conditions for the maximization of the Social Planner's problem are given by:

$$A_{g,o}\frac{\delta\pi}{\delta e_{g,o}} = c$$

$$(A_{g,w} + A_p + v)\frac{\delta\pi}{\delta(e_{g,w} + e_p)} = c$$

The first order conditions state that fuels reduction effort should be spent in each area up to the point where the marginal net benefit (MNB) of effort is equal to the marginal cost (MC) of effort. The social planner is indifferent about which actor performs the effort.

*II.b. Public land manager's decision*

Public's problem is to choose the optimal level of fuel reduction effort to maximize the expected value on WUI and non-WUI land subject to a budget constraint (*B)*:

$$\begin{aligned}
&\max_{e_{g,o},e_{g,w}} \{A_{g,o}\pi(e_{g,o}) + (A_{g,w} + \phi v)\pi(e_{g,w} + e_p)\} \\
&s.t. \\
&c(e_{g,o} + e_{g,w}) = B \\
&e_{g,o}, e_{g,w} \geq 0
\end{aligned}$$

Where $\phi$ is the fraction of the private property value for which Public has liability and $e_p$ is Private's fuel reduction effort, which we assume to be fixed (at zero or some positive level) for now. In 2000, fire burned a total of a third of a million acres in the Bitterroot National Forest (containing both WUI and non-WUI areas) and on private property including 52 homes, 23 other buildings, and 2 sawmills. As a result of the destruction, 113 individuals filed tort claims against the USFS seeking $54 million in damages (Ring 2003), indicating the relevance of public liability for private losses.[4]

Public values in the WUI include amenity values in addition to private property value for which Public is liable. Public values outside the WUI include amenity values such as endangered species habitat, biodiversity, and watershed protection. Amenity values outside the WUI include wildlife

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[4] Wildfire statistics for Oregon and Washington from the Northwest Interagency Coordination Center indicate that most wildfire ignite on public land and spread to private land. For this reason, we focus on Public liability for Private values and do not consider Private liability for Public values.

habitat, scenic views, and recreation sites. Though fire is a natural part of Western landscapes, current fuel loads contribute to conditions that can create uncharacteristic and catastrophic fires. For example, in the summer of 2002, the Hayman Fire destroyed thousands of acres of threatened and endangered species habitat affecting the Mexican spotted Owl, Bald eagle, Preble's Meadow Jumping Mouse, and Canada lynx habitat (Laverty 2003).

The first order condition for the maximization of Public's problem when the private actor performs no effort is:

$$A_{g,o}\frac{\delta\pi}{\delta e_{g,o}} = (A_{g,w} + \phi v)\frac{\delta\pi}{\delta e_{g,w}}$$

This condition states that at the optimal level of fuel reduction effort, the marginal benefit of effort in the WUI is equal to the marginal benefit of effort outside the WUI. For the case where Public's values at risk, which include both public amenity values and private property value for which Public is liable, and the cost of fuel reduction effort in both areas are equal, Public optimally spends an equal amount of effort in the WUI and outside the WUI.

When Public's value in the WUI is greater than value outside the WUI, it is optimal for Public to spend more effort in the WUI. If Public's budget constraint is binding such that the MNB of the last unit of effort in the WUI is greater than the MNB of the first unit of effort outside the WUI, Public optimally spends effort only in the WUI. However, the opposite outcome can also arise. When the MNB of the last unit of effort outside the WUI is greater than the MNB of the first unit of effort in the WUI, Public optimally spends all fuel reduction effort outside the WUI.

To comply with a state regulation or to protect their property from wildfire damage, Private could spend an exogenously determined, positive amount of fuel reduction effort in the WUI $(\overline{e}_p)$. In this case fire resistance in the WUI depends on the sum of Public's and Private's fuel reduction efforts, whereas fire resistance outside the WUI remains a function of Public effort alone. Here Public's problem becomes:

$$\max_{e_{g,o},e_{g,w}} \{A_{g,o}\pi(e_{g,o}) + (A_{g,w} + \phi v)\pi(e_{g,w} + \bar{e}_p)\}$$
$$s.t.$$
$$c(e_{g,o} + e_{g,w}) = B$$
$$e_{g,o}, e_{g,w} \geq 0$$

Where

$\bar{e}_p$ = Exogenously determined private fuel reduction effort in the WUI

The first order condition for the maximization of Public's problem becomes:

$$A_{g,o}\frac{\delta\pi}{\delta e_{g,o}} = (A_{g,w} + \phi v)\frac{\delta\pi}{\delta(e_{g,w} + \bar{e}_p)}$$

This condition states that at the optimal level of fuel reduction effort, the marginal benefit of effort in the WUI is equal to the marginal benefit of effort outside the WUI, taking Private effort as given. Because we assume fire resistance is an increasing, strictly concave function of fuel reduction effort, any positive amount of Private effort in the WUI will reduce the MNB derived from Public effort. Therefore, as Private effort in the WUI increases, the optimal level of Public effort decreases and Public free-rides on Private's public good provision in the WUI. With a budget constraint for Public, this free riding increases the funding available for fuel reduction effort outside the WUI. If Public values at risk in and outside the WUI are equal, then whenever Private has a positive level of effort in the WUI, Public optimally spends more effort outside the WUI than in it.

*II. C. Private land owner's decision*

Up to this point the private land owner's fuel reduction decision has been exogenously determined. In reality, however, private land owner's decisions are made simultaneously with Public's decision and each player's choice influences the other's optimal fuel reduction choice. In order to model the strategic interaction between the two players, first it is necessary to specify the private land owner's fuel reduction decision.

Private's objective is to choose the optimal level of fuel reduction effort to maximize expected value taking Public's choice of effort as given -- this is the flipside of Public's problem. Private's optimization problem is specified as follows:

$$\max_{e_p} \{(A_p + (1-\phi)v)\pi(e_{g,w} + e_p) - e_p c\}$$
$$s.t.$$
$$e_p \geq 0$$

Where

$e_p$ = Private fuel reduction effort
$A_p$ = Private amenity value in the WUI
$(1-\phi)$ = Private's fraction of liability for private property value

Private value “at risk” ($(1-\phi)v$) is the fraction of total private property value uncompensated by Public liability. Value “at risk” will be greater when the Public player has little or no liability for private property value.

The first order condition for the maximization of Private’s problem is:

$$(A_p + (1-\phi)v)\frac{\delta\pi}{\delta(e_{g,w} + e_p)} = c$$

This condition states that at the optimal level of fuel reduction effort, the MNB of total effort in the WUI is equal to the MC of effort, given Public’s choice of effort.

Differences in the Public’s and Private’s WUI values will create a divergence in the desired level of fuel reduction effort in the WUI. If Public’s WUI values $(A_{g,w} + \phi v)$ are greater than Private’s WUI values $(A_p + (1-\phi)v)$, then Public is willing to spend more fuel reduction effort than Private to protect those values at risk. Similarly, when Private values in the WUI are greater, Private is willing to spend more fuel reduction effort than Public.

### *III. Results*

*III.a. Public and Private’s Strategic Interaction*

A strategic interaction between the Public and Private players in the fuel reduction effort decision arises because each landowner’s decision affects the other landowner’s decision. Because fuels reduction effort has public good characteristics, one landowner’s effort creates a disincentive for the other’s effort. We model the strategic interaction between the two “players” as a single stage simultaneous move game with perfect information. In this game players make their strategy choices simultaneously, without knowing the strategy choices that have been chosen by the other player. Although neither player knows what the other will actually choose, perfect information implies that the strategic choices and values at risk available to each player are known by all players. Players must determine both their own best strategic choice and the best strategic choice of the other player.

For each player we identify the "best response" of each player to the strategy choice of the other player. The best response to all possible strategy choices of the other player is termed the response function. The response function for Public gives the optimal fuel reduction effort as a function of Private's effort. Similarly, the response function for Private gives the optimal fuel reduction effort as a function of Public's effort. When each player's strategy choice is a best response to the strategy choice of the other player, we have a Nash equilibrium (NE). Graphically, the NE exists where the two response functions intersect.

To derive the response functions we use a general functional form for fire resistance.[5] Fuel reduction effort in the WUI is considered a public good and individual actors make decisions based on total effort in the WUI. Given the chosen functional form for fire resistance, Public's objective function becomes:

$$\begin{aligned}
&\max_{e_{g,o},e_{g,w}} \{A_{g,o}\ln(e_{g,o}) + (A_{g,w} + \phi v)\ln(e_{g,w} + e_p)\} \\
&s.t. \\
&c(e_{g,o} + e_{g,w}) = B \\
&e_{g,o}, e_{g,w} \geq 0
\end{aligned}$$

And Private's objective function becomes:

$$\begin{aligned}
&\max_{e_p} \{(A_p + (1-\phi)v)\ln(e_{g,w} + e_p) - e_p c\} \\
&s.t. \\
&e_p \geq 0
\end{aligned}$$

[5] We let fire resistance equal the natural log of total effort in the area: $\pi(e) = \ln(e)$, which satisfies $\pi'(e) > 0$ and $\pi''(e) < 0$.

The response functions for each player are derived by solving the player's optimization problem in terms of the other player's decision variable. For our problem, a NE is a set of effort contributions $(e_p^*, e_{g,w}^*)$ such that:

$$e_p^* = \frac{(1-\phi)v + A_p}{c} - e_{g,w}^*$$

$$e_{g,w}^* = \frac{\phi v + A_{g,w}}{(A_{g,o} + A_{g,w} + \phi v)} \frac{B}{c} - \frac{A_{g,o}}{(A_{g,o} + A_{g,w} + \phi v)} e_p^*$$

These equations demonstrate that as Public's contribution of effort increases, Private's contribution decreases, and vice versa. Graphed on a two-dimensional plane with Public effort on the x-axis and Private effort on the y-axis, each player's response function is downward sloping (Figures 1a and 1b).

**Figure1a: Public's Best response function**

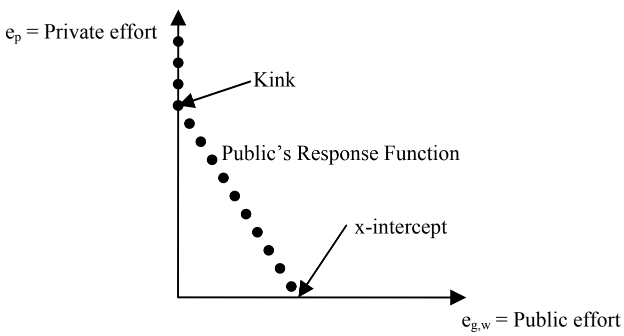
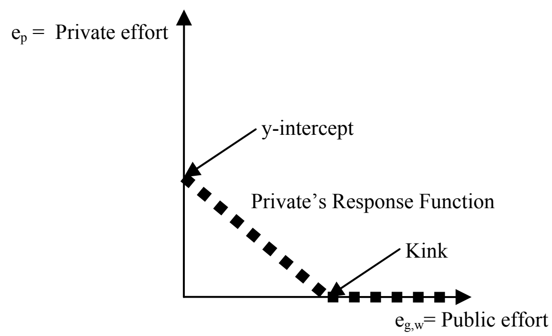



**Figure1b: Private's Best response function**




Because the slope of Public's response function, $-\left(\frac{A_{g,o} + A_{g,w} + \phi v}{A_{g.o}}\right)$, is greater than the slope of Private's response function (-1), Public's response function is always steeper than Private's response function[6]. The individual player's optimal choice of effort is decreasing function of the other player's choice of effort. A kink occurs in the response functions when it becomes optimal for the

[6] This will not hold for cases where Public is not budget constrained, which we will discuss in the next section.

player to choose zero effort. Each player's maximum amount of effort is a best response when the other player chooses zero effort.

Solving the system of equations defined by the response functions, we can determine each player's optimal contribution of effort at a Nash Equilibrium:

$$e_p^{\ *} = \frac{((1-\phi)v + A_p)(A_{g,o} + A_{g,w} + \phi v)}{c(A_{g,w} + \phi v)} - \frac{B}{c}$$

$$e_{g,w}^{*} = \frac{B}{c} - \frac{A_{g,o}}{c}\frac{(A_p + (1-\phi)v)}{(A_{g,w} + \phi v)}$$

Optimal contributions of effort depend on Public's budget ($B$), the assignment of liability($\phi$), and Public and Private values in and outside the WUI. As these parameters vary, interaction between the two players may differ. We consider strategic interaction between Public and Private in two general cases: (1) when Public is budget constrained and (2) when Public is not budget constrained.

*III.b. Public is Budget Constrained*

For the cases where Public is budget constrained there are three possible NE. The first two are extreme free riding outcomes where only one player contributes effort and the third is a shared effort equilibrium. Varian (1994) finds that in a game with two or more agents and the "total effort technology," public good provision is determined by the agent with the highest benefit-cost ratio and all other agents free ride on this agent. Our first two NE constitute a similar, extreme free riding result. However, our problem is distinct in that we have two players with different benefit functions – Public values fire resistance in the WUI and outside the WUI while Private is concerned only with fire resistance in the WUI. Because of this difference, the equilibria that emerge from the game are not limited to the extreme free riding result observed when both players' utility takes a quasilinear form, as described in Varian (1994). In the results described below, first we look at the conditions that lead to each of the three equilibria when public and private WUI values are equal. Next we look at the case where public and private WUI values are not equal.

**Figure 2a:**
**Extreme free riding equilibrium**

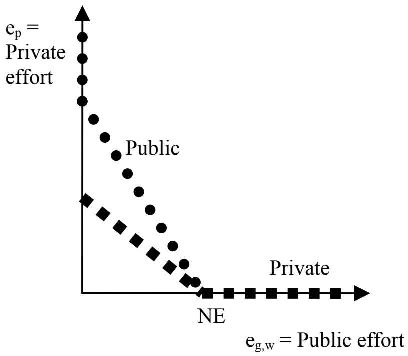



**Figure 2b:**
**Extreme free riding equilibrium**

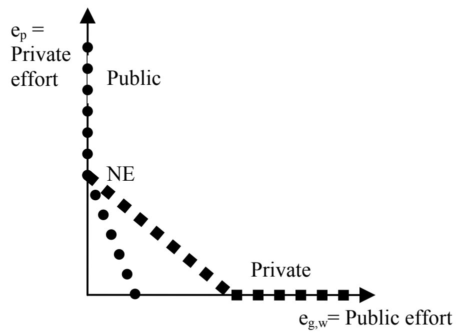
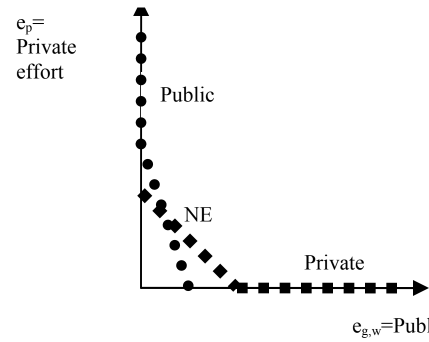



**Figure 2c:**
**Shared effort equilibrium**




### i. *Public and Private WUI Values Are Equal*

When Public and Private WUI values are equal (i.e., $A_{g,w} + \phi v = A_p + (1-\phi)v$) the optimal level of total effort in the WUI is the same for both players. However, Public faces a budget constraint and must decide where to spend limited funds: in or outside the WUI. Of the three possible NE, the equilibrium that emerges will depend on the size of Public's budget. When the x-intercept of Public's response function is at or to the right of the kink in Private's response function, or $B \geq A_{g,o} + A_{g,w} + \phi v$, the extreme free riding equilibrium with only Public contributing effort emerges (Figure 2a). In this case, Public's budget constraint is not binding and funds are large enough to protect values in and outside the WUI.

When the y-intercept of Private's response function is at or above the kink in Public's an extreme free riding equilibrium will emerge with only Private contributing fuel reduction effort in the WUI (Figure 2b). At this equilibrium Public spends the entire budget outside the WUI and free rides on Private effort in the WUI. This equilibrium is most likely to emerge when Public's budget is less than or equal to the amenity value outside the WUI (i.e., $B \leq A_{g,o}$), or when the Public budget is small and Public amenity value outside the WUI is great.

Finally, the shared effort equilibrium will emerge (Figure 2c) when Public's budget is between the two extreme cases described above. This is the case when Public's budget is less than total values in and outside the WUI, but greater than values outside the WUI (i.e., $A_{g,o} \leq B \leq A_{g,o} + A_{g,w} + \phi v$). The greater Public's budget within this range the more effort Public contributes.

*ii.* *Public and Private WUI Values Are Not Equal*

When Public and Private WUI values are not equal (i.e., $A_{g,w} + \phi v \neq A_p + (1-\phi)$) the two players optimal total amounts of fuel reduction in the WUI are different. In this case, the three possible NE are the same as when Public and Private WUI values are equal, but the conditions that produce these outcomes are different. Here the equilibrium that emerges will depend on the size of Public's budget (B), the players' relative values in the WUI and, Public's relative values in the WUI and outside the WUI.

The first equilibrium characterized by extreme free riding, where Public does everything (Figure 2a), will emerge when the x-intercept of Public's response function is to the right of the kink in Private's response function; when $B \geq \dfrac{(A_p + (1-\phi)v)(A_{g,o} + A_{g,w} + \phi v)}{A_{g,w} + \phi v}$. Here Public has a large enough budget to spend the desired amount of effort outside the WUI and spend at least as much effort in the WUI as desired by Private. This condition is most likely to hold when Private's values in the WUI ($A_p + (1-\phi)v$) are low, Public's budget (B) is large, and/or Public's values outside the WUI ($A_{g,o}$) are low.

At other parameter values, a different NE arises in which Private contributes effort in the WUI and Public contributes no effort (Figure 2b). This equilibrium, also characterized by extreme free riding, will emerge when the y-intercept of Private's response function is above the kink in Public's response function, or when parameter values are consistent with the inequality:
$\dfrac{(A_p + (1-\phi)v)A_{g,o}}{(A_{g,w} + \phi v)} \geq B$. At this equilibrium, Public is so severely budget constrained that the player can afford only minimal effort in the WUI. Private, however, desires and can afford a much greater amount of effort. At this much higher level of Private effort, Public effort is zero. This outcome is most likely to occur when Public budgets are small, Private values in the WUI are large relative to

Public values, and Public value outside the WUI is large. At this equilibrium, Public spends effort outside the WUI only.

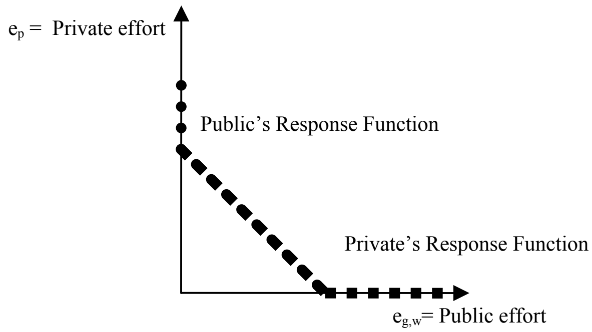
Finally, at other parameter values, a third NE exists where both Public and Private spend effort in the WUI (Figure 2c). This equilibrium emerges when Private's response function intersects the vertical access below the kink in Public's response function; in mathematical terms, these parameter values occur when $B \in \left[ \frac{(A_p + (1-\phi)v)A_{g,o}}{A_{g,w} + \phi v}, \frac{(A_p + (1-\phi)v)(A_{g,o} + A_{g,w} + \phi v)}{A_{g,w} + \phi v} \right]$. Here Public's budget constraint is binding, but is within a range that allows the players to split effort in the WUI. Because the slope of Private's response function is equal to negative one and every unit of Public fuel reduction effort crowds out Private effort, one-for-one.

All three NE are stable. At points to the left of the NE, Public increases effort until the equilibrium is reached. This is because at points to the left of the NE Public is not satisfied with total effort and requires more effort from Private than Private is willing to spend. At points to the right of the NE, Private is not satisfied with total effort and requires more effort from Public than Public is willing to spend. In this case Private increases effort until the equilibrium is reached.

*III.c. Public is Not Budget Constrained*

When Public is not budget constrained, the players' response functions are parallel. Without a budget constraint, Public has sufficient funding for fuel reductions in both areas and no longer has to tradeoff between fuel reduction effort within and outside the WUI. When the Public and Private WUI values are equal ( $A_{g,w} + \phi v = A_p + (1-\phi)v$ ), the two response functions overlap and there are infinitely many NE. Because the players have the same amount of value at risk in the WUI, each player values improvements in WUI fire resistance equally.

**Figure 3: Overlapping Best response functions**




In the case where the Public and Private WUI values are not equal, there are two possible equilibria. Relative values in the WUI will determine which of the extreme free riding equilibria emerges. If Private values are greater than Public values in the WUI, then Private will contribute effort equal to ( $A_p + (1-\phi)v$ )/c and Public will contribute nothing. If the opposite is true, then Public will contribute effort equal to ( $A_{g,w} + \phi v$ )/c in the WUI and Private will contribute nothing. At both equilibria, Public spends the efficient level of effort outside the WUI.

**Figure 4a: Private WUI values greater**

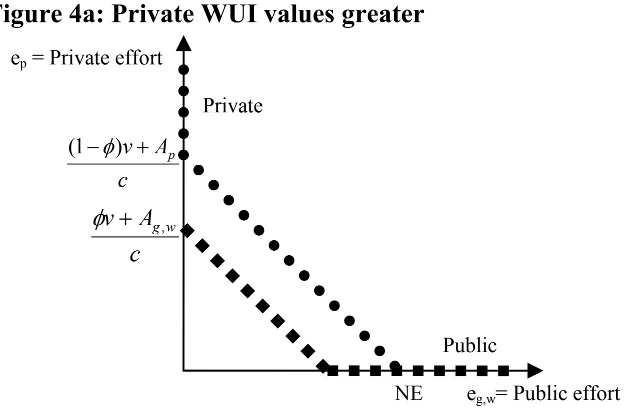
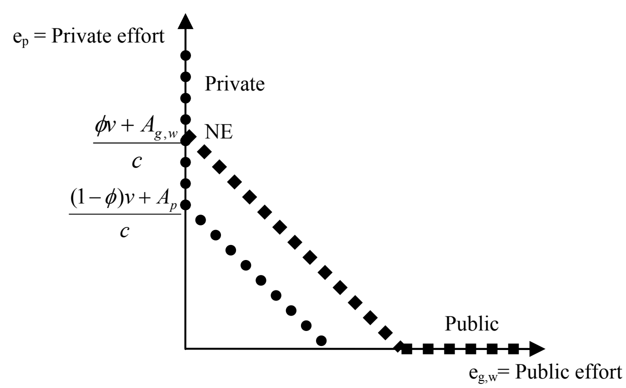



**Figure 4b: Public WUI values greater**




### *IV. Federal Disaster Relief*

After destructive wildfires, the Federal Emergency Management Agency (FEMA) provides aid to individuals affected by the wildfire. Federal disaster relief from FEMA is greatest for individuals in areas that are declared a disaster area by the President, where property damage is not covered or insufficiently covered by insurance,[7] and the individual is a citizen of the U.S.

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[7] An examination of the insurance decision is beyond the scope of the present analysis, but will be addressed in future work.

(http:www.fema.gov/assistance/process/qualify_other_housing.shtm. Aug. 22, 2006). In this section we introduce federal disaster relief into the model and examine the impact on equilibrium fuels reduction effort. With disaster relief, Private's problem becomes:

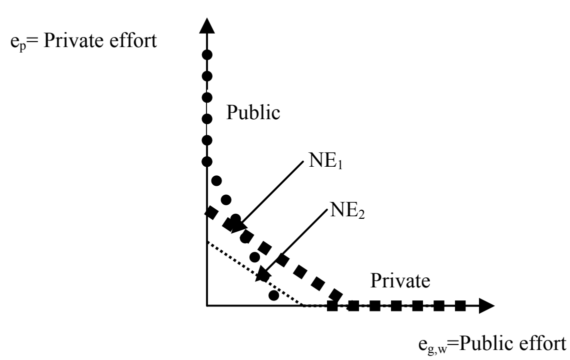
$$\max_{p} \{(A_p + (1-\theta)(1-\phi)v)\pi(e_{g,w} + e_p) - ce_p\}$$
$$s.t.$$
$$e_p \geq 0$$

Where

$$\theta = \text{Fraction of value compensated by federal relief}$$

Disaster relief is essentially federal liability for private property values; it reduces the amount of private property value at risk to Private. The introduction of federal relief causes Private's response function to shift down and to the left in parallel fashion, as illustrated in Figure 6. With less value at risk, the private player has less incentive to contribute fuel reduction effort. Given the new response function, for any level of Public fuel reduction effort in the WUI Private will contribute less effort. At the new equilibrium, Public fuel reduction effort is greater and Private effort is reduced. However, because the slope of Public's response function is steeper, Public's increase in fuel reduction effort will not be enough to off-set the reduction in Private effort and total effort in the WUI will decrease. Furthermore, as public spending in the WUI increases, a smaller portion of the total budget is available for fuel reduction effort outside the WUI.

**Figure 5: Shift in private response function with federal disaster relief**



***V. Discussion***

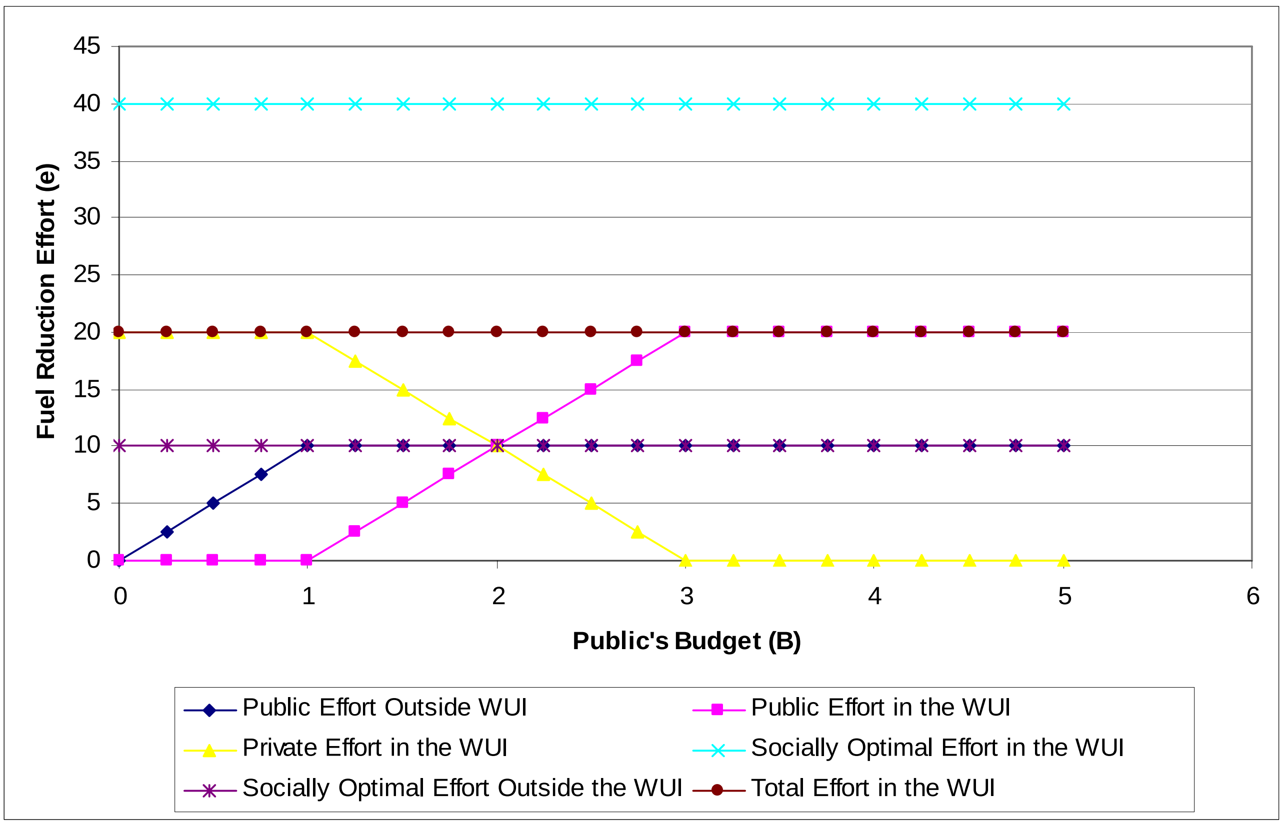
Using the results derived in the previous sections we can compare the equilibrium outcomes to the socially efficient outcomes inside and outside the WUI, evaluate the impact of the Healthy Forest Restoration Act (HFRA) on fuel reduction effort, and identify the policies and characterize the settings that limit Private's ability to free ride. Total effort in the WUI is calculated at the intersection of the response functions. Total effort outside the WUI is calculated by subtracting the cost of Public effort in the WUI from the budget and dividing the remaining budget by the cost of fuel reduction effort. These calculations are described for all cases in Table 2.

*Effort in the WUI.* Because fuel reduction effort is a public good, strategic interaction in the WUI will always lead to a socially suboptimal, or inefficient, level of effort in the WUI due to the free rider problem. The inefficiency results because neither player considers the full value of amenities and private property in the WUI. Public considers only public amenity value and public liability ($A_{g,w} + \phi v$). Similarly, Private considers only private amenity value and private liability ($A_p + (1-\phi)v$). The socially optimal level of effort in the WUI considers all values in the area and is equal to ($A_p + A_{g,w} + v$)/c, as described in Table 2. Federal disaster relief leads to even greater inefficiencies because Private considers an even smaller fraction of property value "at risk."

Even when Public is not budget constrained, effort in the WUI remains suboptimal. In this case, the amount of effort spent in the WUI is equal to either ($A_p + (1-\phi)v$)/c or ($A_{g,w} + \phi v$)/c, whichever is greater (see Figures 4a and 4b). Without the assignment of full liability to one of the players and full consideration of total amenity values fuel reduction in the WUI will remain inefficiently low. This result also holds in the case where Public is not budget constrained and WUI values are equal.

*Effort Outside the WUI.* Public carries full responsibility for the protection of amenity values outside the WUI but decisions about that area are tied, through the budget constraint, to decisions within the WUI. The socially optimal amount of effort outside the WUI is equal to $\frac{A_{g,o}}{c}$, where the MNB of the last unit of effort is equal to its MC. However, the level of effort Public spends outside the WUI depends on the budget, liability, and on relative amenity values in and outside the WUI and on which equilibrium emerges. When Public is budget constrained, limited funds must be divided between the two areas. The players' response functions indicate that increases in Public's budget (*B*) lead to increases in Public effort and decreases in Private effort, or an increase Private's ability to free ride. Figure 7 illustrates how effort by both players changes with Public's budget. Given the parameter values used in Figure 7, the socially optimal levels of effort are 40 in the WUI and 10 outside the WUI. To isolate the effect of Public's budget on fuel reduction effort, we chose the same parameter values for Public values in the WUI and Public values outside the WUI, though this point could be illustrated if these values were not equal.

**Figure 7: How effort changes with Public's budget when Public and Private WUI values are equal.***

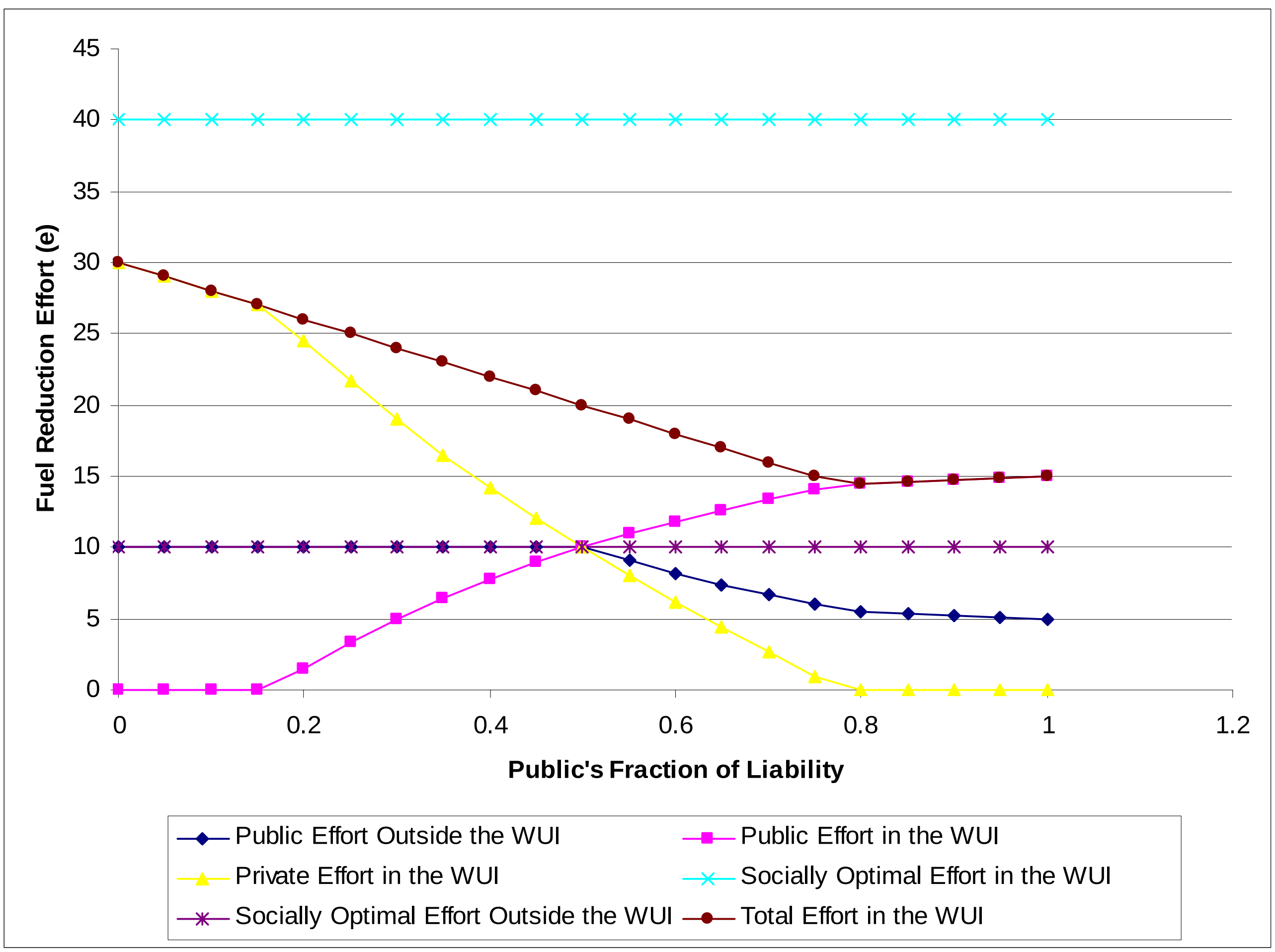



***Equilibrium effort levels depicted are calculated using the following parameter values: $A_{g,o}$ =1; $A_{g,w}$=1; $A_p$=1; φ=0.5; v=2; c=0.1.**

For the parameter values above, when Public's budget (*B*) is between zero and one, the extreme free riding equilibrium where only Private spends effort in the WUI emerges and Public spends the entire budget outside the WUI. When Public's budget is between one and three, Public increases effort in the WUI and Private matches with equivalent reductions in effort. When Public's budget is greater than three, the opposite extreme free riding equilibrium results in which only Public contributes effort in the WUI. It is important to note that whatever Public's budget, total effort in the WUI is half the socially optimal level of effort due to the free-rider problem.

The relationship between effort and Public liability is illustrated in Figure 8. To isolate the effect of Public's fraction of liability on equilibrium fuel reduction effort, we chose the same parameter values for Public values in the WUI and Public values outside the WUI ($A_p = A_{g,w}$). As Public's fraction of liability increases, Public effort in the WUI increases and Private effort in the WUI decreases, as Private's ability to free ride increases. Once liability exceeds 0.5, Public effort in the WUI displaces effort outside the WUI.

**Figure 8: How effort changes with Public's fraction of liability.***

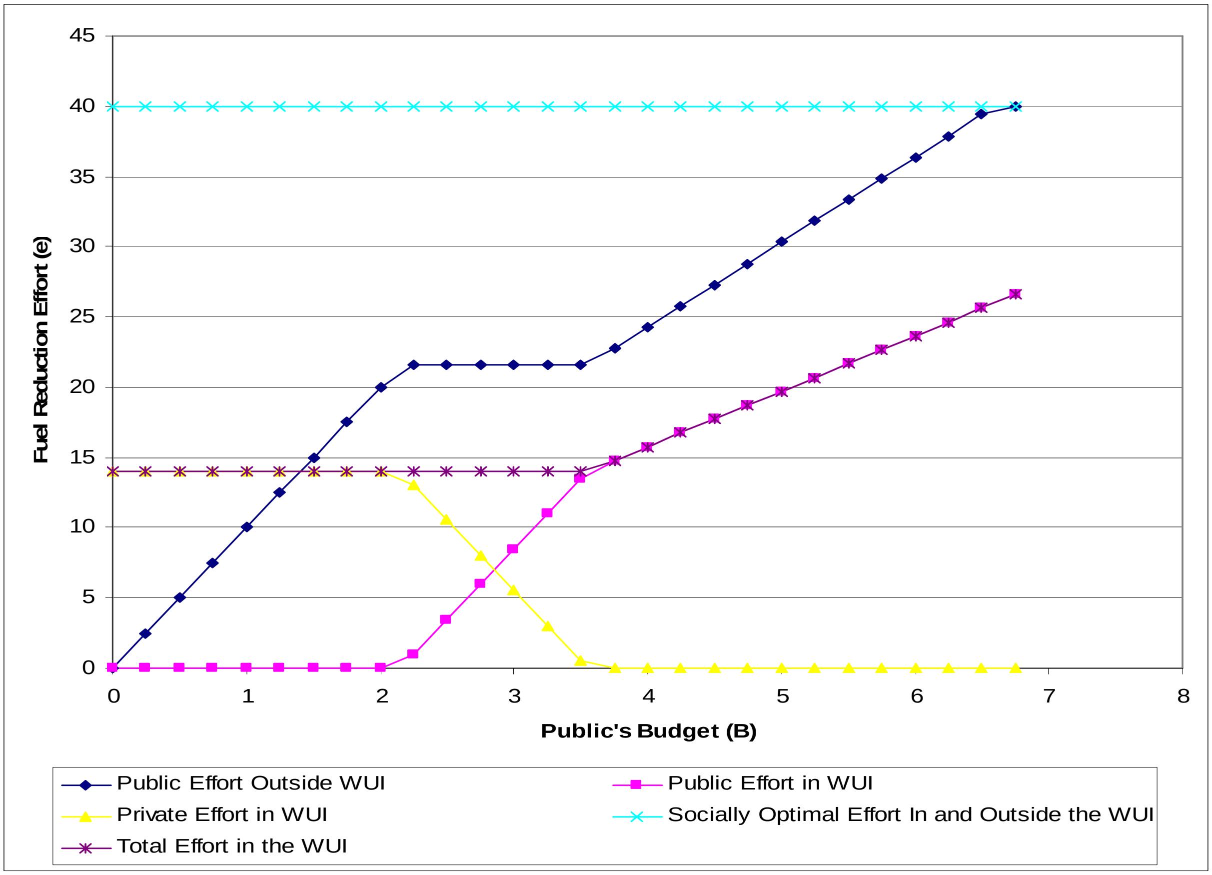



***Equilibrium effort levels depicted are calculated using the following parameter values: $A_{g,o}$ =1; $A_{g,w}$=1; $A_p$=1; B=2; v=2; c=0.1.**

Given the parameter values used in Figure 8, the socially optimal levels of effort are 40 in the WUI and 10 outside the WUI. Equilibrium effort in the WUI is closest to the social optimum when Private has full liability. Equilibrium effort outside the WUI is equal to the social optimum when Public liability within the WUI is less than or equal to 0.5.

The degree of inefficiency in fuel reduction effort outside the WUI is most severe when Public values outside the WUI are high relative to Public values in the WUI and Public liability in the WUI is high. In that case, increases in Public's budget do not necessarily lead to increases in spending outside the WUI nor total effort in the WUI (Figure 9). As Public's budget increases from two to four, Public spends all additional funds in the WUI while Private reduces effort. Public values outside the WUI are neglected as Private's free riding in the WUI increases. Given the parameter values used in Figure 9, the socially optimal levels of effort are 40 in the WUI – which is not attained at any budget level – and 40 outside the WUI – which is not attained until $B$ reaches 6.75.

**Figure 9: How effort changes with Public's budget when WUI values are not equal and values outside the WUI are high.***




***Equilibrium effort levels depicted are calculated using the following parameter values: $A_{g,o}$ =4; $A_{g,w}$=1; $A_p$=1; φ=0.8; v=2; c=0.1.**

Not surprisingly, when Public is not budget constrained, fuel reduction effort outside the WUI is socially optimal for the all cases. However, for the cases where Public is budget constrained and WUI values are equal, the socially optimal level of effort outside the WUI is observed as long as $B > A_{g,o}$. Similarly, for the case where Public is budget constrained and WUI values are not equal, we observe the socially optimal level of effort outside the WUI as long as $B > \frac{(A_p + (1-\phi)v)A_{g,o}}{(A_{g,w} + \phi v)}$. In both cases, sufficiently large budgets ensure that Public is able to fund the efficient level of effort outside the WUI.

*Impact of Policy*. From a societal perspective, budget constraints and regulations for Public actions in the WUI create two issues: potential under protection of resources outside of the WUI for which Public is solely responsible; and an inability to attain the social optimum in the WUI due to the free-riding problem.  HFRA prioritizes the WUI and requires that at least fifty-percent of fuel reduction budgets be spent in the WUI.  This rule creates inefficiencies because it does not allow public land managers to compare the MNB of fuel reduction effort in the WUI to MNB outside the WUI; it simply requires spending in the WUI.  Not only might Public effort be better spent outside the WUI, each additional unit of Public effort in the WUI increases Private's ability to free ride and so does not necessarily result in an increase in the total amount of effort in the WUI.

A policy that focuses fuel reduction effort in the WUI will be most inefficient when Public would otherwise choose to allocate its budget outside the WUI, such as when Public amenity value outside the WUI is high.  This might be the case in areas where there are endangered species, unique ecosystems or high-value watershed services, and the Public budget is small.  In general, when Public budgets are small, all funding increases will optimally be spent outside the WUI (as depicted in Figure 9 for budgets less than two), leaving Private as the sole contributor to fuel reduction effort in the WUI.  This action would not be permitted under HFRA.  When HFRA is imposed on a landscape where both Public and Private are contributing to fuel reduction effort in the WUI, requiring an increase in Public effort moves the actors toward the extreme free riding equilibrium with Private effort falling to zero.

Within the context of the model, limiting Private's ability to free ride and improving Public's ability to spend fuel reduction effort outside the WUI could be achieved through reducing Public liability, increasing the valuation of undervalued (or un-priced) amenities outside the WUI, or reducing/eliminating federal disaster relief.  If the players' amenity values in the WUI are approximately equal, then Private's ability to free ride is driven by Public liability in the WUI and low Public values outside the WUI.  Reducing Public liability in the WUI would reduce Public value thereby reducing Public's optimal effort in the WUI.  Increasing amenity value outside the WUI would increase the incentive to spend fuel reduction effort outside the WUI and reduce Public's optimal effort in the WUI.  Due to the strategic interaction inherent in the game, simply increasing Public's budget will not necessarily increase fuel reduction effort outside the WUI not total effort within the WUI.

Looking outside the model, a strategy to limit Private's ability to free ride and improve Public's ability to effectively protect resource values outside the WUI would be to legally require a fixed amount of effort from Private. This policy option would be similar in spirit to existing statutory law in Montana, Minnesota, New Mexico and Washington that require fuel reduction on private land (Yoder et al. 2004). Such policies might be especially appropriate in areas where public land managers face limited budgets.

### *VI. Concluding remarks*

In this paper, we identify the equilibria that emerge in a game of strategic interaction between a public land manager and a private land owner in their choice of fuel reduction effort. We find that increasing the public land manager's spending on fuel reduction effort in the WUI increases private land owner's ability to free ride and may result in inefficiently low levels of total fuel reduction effort in the WUI, and leave public resources outside the WUI under-protected. The current government policy of focusing fire risk mitigating activities in the WUI increases Private's ability to free ride and diverts funding that might otherwise be used to protect resources outside the WUI. Federal disaster relief reduces Private's incentive for fuel reduction and further enables Private's free riding.

HFRA's emphasis on the WUI, public liability for losses on private land, and federal disaster aid all protect private landowners from losses in the WUI. In that protection, each policy reduces the action taken by the private actors and puts that responsibility on public actors. Such a shift in burden may be desirable from a broader social perspective or from a political perspective but the cost in terms of other projects such as protecting non-WUI resources should be acknowledged. Without removing this safety net, policies that require private risk mitigating activities could reduce the public burden and increase social welfare. This analysis focuses on only one slice in time but the implicit subsidy to private landowners creates both near-term inefficiencies such as unprotected non-WUI resources and long-term inefficiencies such as inducing socially undesirable levels of migration to the WUI. This analysis calls for a recognition of the fact that public and private values in the WUI can be protected by both public and private actors, but outside the WUI Public alone is responsible for the protection of the resource values.

Table 2: Equilibrium Fuel Reduction Effort

| | | Private Effort in the WUI | Public effort in the WUI | Pu |
|---|---|---|---|---|
| WUI values are not equal Public BC | Private Acting Alone (NE 3) | $e_p = \frac{A_p + (1-\phi)v}{c}$ | $e_{g,w} = 0$ | $e_{g,o} = \frac{B}{c}$ [illegible] |
| | Public Acting Alone (NE 2) | $e_p = 0$ | $e_{g,w} = \frac{A_{g,w} + \phi v}{(A_{g,o} + A_{g,w} + \phi v)} \frac{B}{c}$ | $e_{g,o} =$ [illegible] |
| | Public and Private Interacting (NE 1) | Response Function: $e_p = \frac{(1-\phi)v + A_p}{c} - e_{g,w}$ | Response Function: $e_{g,w} = \frac{\phi v + A_{g,w}}{(A_{g,o} + A_{g,w} + \phi v)} \frac{B}{c} - \frac{A_{g,o}}{(A_{g,o} + A_{g,w} + \phi v)} e_p$ | Respon [illegible] $e_{g,o} =$ [illegible] |
| | | $e_p{}^* = \frac{((1-\phi)v + A_p)(A_{g,o} + A_{g,w} + \phi v)}{c(A_{g,w} + \phi v)} - \frac{B}{c}$ | $e^*_{g,w} = \frac{B}{c} - \frac{A_{g,o}}{c} \frac{(A_p + (1-\phi)v)}{(A_{g,w} + \phi v)}$ | $e^*_{g,o} =$ [illegible] |
| WUI Values Not Equal and Public Not BC | Private Acting Alone (NE if Private's WUI Values Greater) | $e_p = \frac{(1-\phi)v + A_p}{c} - e_{g,w}$ | $e_{g,w} = 0$ | $e^*_{g,o} =$ [illegible] |
| | Public Acting Alone (NE if Public's WUI Values Greater) | $e_p = 0$ | $e_{g,w} = \frac{\phi v + A_{g,w}}{c}$ | $e^*_{g,o} =$ [illegible] |
| WUI Values Equal and Public BC | Private Acting Alone (NE 3) | $e_p = \frac{A_p + (1-\phi)v}{c}$ | $e_{g,w} = 0$ | $e^*_{g,o} = \frac{B}{c}$ [illegible] |
| | Public Acting Alone (NE 2) | $e_p = 0$ | $e_{g,w} = \frac{A_{g,w} + \phi v}{(A_{g,o} + A_{g,w} + \phi v)} \frac{B}{c}$ | $e_{g,o} =$ [illegible] |
| | Public and Private Interacting (NE 1) | Response Function: $e_p = \frac{(1-\phi)v + A_p}{c} - e_{g,w}$ | Response Function: $e_{g,w} = \frac{\phi v + A_{g,w}}{(A_{g,o} + A_{g,w} + \phi v)} \frac{B}{c} - \frac{A_{g,o}}{(A_{g,o} + A_{g,w} + \phi v)} e_p$ | |
| | | Intersection: $e_p{}^* = \frac{(A_{g,o} + A_{g,w} + \phi v)}{c} - \frac{B}{c}$ | Intersection: $e^*_{g,w} = \frac{B}{c} - \frac{A_{g,o}}{c}$ | $e^*_{g,o} =$ [illegible] |

| | | | | |
|---|---|---|---|---|
| WUI Values Equal Public Not BC | Private Acting Alone (NE if Private WUI Values Greater) | $e_p = \frac{(1-\phi)v + A_p}{c} - e_{g,w}$ | $e_{g,w} = 0$ | $e^*_{g,o} =$ [illegible] |
| | Public Acting Alone (NE if Public WUI Values Greater) | $e_p = 0$ | $e_{g,w} = \frac{\phi v + A_{g,w}}{c}$ | $e^*_{g,o} =$ [illegible] |
| SOCIAL OPTIMUM | | $e_{g,w} + e_p = \frac{(A_{g,w} + A_p + v)}{c}$ | | $e_{g,o} =$ [illegible] |

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