Environmental Management (2010) 45:296–310
DOI 10.1007/s00267-009-9381-x

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

**Gwenlyn Busby · Heidi J. Albers**

Received: 17 June 2008 / Accepted: 2 September 2009 / Published online: 21 January 2010
© Springer Science+Business Media, LLC 2010

**Abstract** Wildfire, like many natural hazards, affects large landscapes with many landowners and the risk individual owners face depends on both individual and collective protective actions. In this study, we develop a spatially explicit game theoretic model to examine the strategic interaction between landowners' hazard mitigation decisions on a landscape with public and private ownership. We find that in areas where ownership is mixed, the private landowner performs too little fuel treatment as they "free ride"—capture benefits without incurring the costs—on public protection, while areas with public land only are under-protected. Our central result is that this pattern of fuel treatment comes at a cost to society because public resources focus in areas with mixed ownership, where local residents capture the benefits, and are not available for publicly managed land areas that create benefits for society at large. We also find that policies that encourage public expenditures in areas with mixed ownership, such as the Healthy Forest Restoration Act of 2003 and public liability for private values, subsidize the residents who choose to locate in the high-risk areas at the cost of lost natural resource benefits for others.

**Keywords** Fire · Game theory · Spatially explicit game · Natural hazard · Hazard mitigation · Public goods

## Introduction

In recent years, numerous catastrophic wildfires have struck the western U.S. causing large losses in terms of forest benefits, private dwellings, and suppression costs (Table 1). The steady increase in the number of people living in and around fire-prone forests means that a growing number of people and structures are at risk in those areas (Stewart and others 2005). These areas, where houses meet or intermingle with undeveloped wildland vegetation, are referred to as the wildland–urban interface (WUI). In 2003, for example, 4,508 homes in the United States were destroyed by wildland fires, resulting in more than 2 billion U.S. dollars in damages (NIFC 2009) despite the billions of dollars federal agencies spend every year on fire suppression. To prevent fire damage, public land managers use limited budgets to reduce the "fuels" that have built up in forests, such as dried grasses, bushes, and woody debris, to reduce the severity of fires. Public land managers are responsible for forests within and outside of the WUI and face difficult choices about where to place their preventive fuel treatment efforts. The Healthy Forest Restoration Act (HFRA 2003) partially regulates that decision and determines the distribution of fuel treatments in a landscape by requiring that at least 50% of funding for fuel treatment projects be used in the WUI. In FY2006, fuel treatment treatments conducted under the HFRA on USFS land in Montana totaled 42,304 acres of the 3,285,231 acres within the WUI (about 1.3%) and only 18,263 acres of the 9,484,150 forest acres outside the WUI (about 0.2%) (Healthy Forests 2007; US Forest Service 2004).

Private landowners can also undertake such damage prevention activities but tend to self-protect too little in the face of many natural hazards (Kunreuther 2000; Kunreuther and Slovic 1978; Lewis and Nickerson 1989; McGee

---

G. Busby (✉)
Department of Forestry, Virginia Tech, 310 Cheatham Hall, 0324, Blacksburg, VA 24061, USA
e-mail: gbusby@vt.edu

H. J. Albers
Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR, USA

**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 |
| 2007 | $1.844 | 9,321,326 | 5,401 |

*Source*: National Interagency Fire Center (2009)

2005). In an attempt to force private landowners in the WUI to self-protect and to reduce the burden on public land managers, Oregon, Montana, Minnesota, New Mexico, and Washington now require fuel treatments on private land to reduce the possibility and severity of wildfires (Yoder and others 2003). Despite these new laws, public land management agencies bear the vast majority of fuel treatment costs in addition to funding all WUI and non-WUI wildfire suppression effort.

One reason that private landowners may under-provide fuel treatment is that fuel treatments have important public good characteristics, similar to many other types of hazard mitigation (Reddy 2000). Because wildfire moves across a landscape and across property boundaries, the fire risk an individual landowner faces is a function of fuel treatment decisions made by both that individual owner and all other landowners (Hann and Strohm 2003; Finney 2001; Gill and Bradstock 1998). If an individual reduces the fuel load on his or her property, 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 his or her effort. In the fuel treatment public good case, the production function fits with the "total effort" technology (Varian 2004; Hirshleifer 1983) because fuel treatment effort both on an individual ownership unit and on the surrounding landscape affects wildfire risk. In an additional complication, public land management agencies must consider values at risk in the WUI, where public and private land intermix, as well as values at risk on public land outside the WUI. Using a game theory structure, we examine how a public land manager's investment in fuel treatment both within and outside the WUI influences, and is influenced by, decisions made by a private landowner within the WUI and how close the outcome of the interactions between landowners comes to the socially preferred amount and distribution of fuel treatment across the landscape. We also use the model to evaluate the current government policy of focusing fire-risk mitigating activities in the WUI and of public liability for private damages.

Game theory has been applied to a range of natural resource problems (see Albers and others 2008 and Buckley and Haddad 2006, for example), but, despite the characteristics of fire-risk management that make game theory appropriate (i.e., both individual and collective actions affect wildfire risk), only Amacher and others (2006) and Crowley and others (2009) use a game theory structure to analyze the strategic interaction inherent in fire risk management. Both studies examine the interaction between government and private landowners in their choice of suppression level and fuel treatment effort level, respectively, on a landscape with private land only. In this paper we explore the strategic interaction between the public land manager and the private landowner in their choice of fuel treatment effort on a heterogeneous landscape, with both public and private land.

As is typical with public goods, we find that private landowners in the WUI perform too little fuel treatment as they "free ride"—capture benefits without incurring the costs—on public fuel treatment in the WUI. Our central result is that this pattern of fuel treatment comes at a cost to society because public resources focus in the WUI where local residents capture the benefits while public resources are not available for the non-WUI forests that create benefits for society at large. The policies that encourage public expenditures in the WUI subsidize the residents who choose to locate in the high-risk WUI at the cost of lost natural resource benefits for others. To capture that loss to society, the next section describes the social planner's fuel treatment decision in addition to defining the public land manager's and private landowner's decisions. The strategic interaction between the landowners and the results of the spatially explicity game theoretic model are described in the third section and the game outcomes are compared to the socially preferred landscape of fuel treatments. We discuss the policy implications of the model's results and offer concluding remarks in the fourth section.

## Model

We model a landscape with two general areas: the WUI and the area outside the WUI. The area outside the WUI is comprised of public land only and the public land manager, "Public," chooses the amount of fuel treatment effort there. The WUI includes a mix of public and private land and both Public and the private landowner, "Private," independently choose their level of fuel treatment effort there. Total effort in the WUI is the sum of Public and Private effort. We assume the forest fuel conditions and fuel treatment costs are the same both in and outside the WUI. Because most wildfires ignite on public land, we assume that ignition occurs on public land and we follow the fire literature's standard assumption that ignition itself is not a function of fuel levels (Schmidt and others 2002; Deeming and others 1977). Because our emphasis lies in the strategic interaction of WUI public and private landowners and the impact of that behavior on non-WUI policy, we focus on a one-period model with a period reflecting a length of time long enough to permit fuel treatment activities (see Konoshima and others 2008 for multi-period fuel treatment decisions without a game context).

To focus on the public policy across the two regions, we operate at a scale in which a fire burns through the entire area but the amount of fuels treatment in that area determines the level of loss associated with fire. Fuel treatment effort ($e$) reduces the amount of forest fuels, thereby decreasing the intensity and spread rate of fires (e.g., Agee and Skinner 2005 and Graham and others 1999). 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 consume debris without damaging timber and environmental service values. The parameter "fire resilience," $\pi$, describes the probability that values survive a fire and is determined by total fuel treatment effort, $e$, in that area, such that $\pi'(e) > 0$ and $\pi''(e) < 0$. The first and second order derivatives imply that as effort increases, fire resilience increases, but at a decreasing rate. Because we are interested in risk-mitigating behavior, all fires modeled here threaten values at risk and the possibility of beneficial fires is not considered. Reflecting the public good characteristics of fuel treatment within a region, as described above, the fuel treatment effort, $e$, describes the total effort for a given area—WUI or outside the WUI—regardless of who performs that effort.

## Social Optimum

In order to compare the fuel treatment 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. Here, the Social Planner is the sole decision-maker and faces no budget constraint in providing the appropriate level and location of fuel treatment:

$$\max_{e^{\mathrm{g}}_{\mathrm{o}},e^{\mathrm{g}}_{\mathrm{w}},e^{\mathrm{p}}} \{\mathrm{PG}^{\mathrm{g}}_{\mathrm{o}}\pi(e^{\mathrm{g}}_{\mathrm{o}}) + (\mathrm{PG}^{\mathrm{g}}_{\mathrm{w}} + v + A)\pi(e^{\mathrm{g}}_{\mathrm{w}} + e^{\mathrm{p}}_{\mathrm{w}}) - c(e^{\mathrm{g}}_{\mathrm{o}} + e^{\mathrm{g}}_{\mathrm{w}} + e^{\mathrm{p}}_{\mathrm{w}})\} \tag{1}$$

where $\pi(\cdot)$ fire resilience; $e^{\mathrm{g}}_{\mathrm{o}}$ public effort outside the WUI; $e^{\mathrm{g}}_{\mathrm{w}}$ public effort in the WUI; $e^{\mathrm{p}}_{\mathrm{w}}$ private effort in the WUI; $\mathrm{PG}^{\mathrm{g}}_{\mathrm{o}}$ public good value outside the WUI; $\mathrm{PG}^{\mathrm{g}}_{\mathrm{w}}$ public good value in the WUI; $A$ private amenity value in the WUI; $v$ private structure value in the WUI and $c$ unit cost of fuel reduction effort.

The social planner maximizes this equation to find the optimal level of fuel treatment effort ($e$) inside and outside the WUI. When making fuels management decisions, the social planner considers all values at risk: public good value (PG), private amenity value ($A$), and private structure value ($v$). Private property value is the sum of private amenity value and structure value. The superscript on effort and public good value indicate whether the parameter is associated with the Public (g) or Private (p) landowner and the subscript describes whether the parameter represents value or effort in the WUI (w) or outside the WUI (o).

Public good values may include biodiversity, ecosystem function, carbon sequestration and similar values that are not location dependent. Private amenity value includes scenic views and proximity to recreation, for example, which are location dependent and are capitalized into private property values. Though fire is a natural part of many Western landscapes, current fuel loads, which are typically very high, contribute to conditions that can create uncharacteristically intense and potentially catastrophic fires. Wildfire damage to amenity values on public land within but also outside of the WUI can be costly and in some cases permanent. For example, in the summer of 2002, the Hayman Fire destroyed thousands of acres of threatened and endangered species habitat in Colorado affecting the Mexican spotted Owl, Bald eagle, Preble's Meadow Jumping Mouse, and Canada lynx habitat (Laverty 2003). Scarcity of threatened and endangered species habitat made this loss particularly significant.

The first order conditions, derived from the Social Planner's maximization problem, are given by:

$$\mathrm{PG}^{\mathrm{g}}_{\mathrm{o}}\frac{\partial\pi}{\partial e^{\mathrm{g}}_{\mathrm{o}}} = c \tag{2}$$

$$(\mathrm{PG}^{\mathrm{g}}_{\mathrm{w}} + v + A)\frac{\partial\pi}{\partial(e^{\mathrm{g}}_{\mathrm{w}} + e^{\mathrm{p}}_{\mathrm{w}})} = c \tag{3}$$

Equations 2 and 3 state that fuel treatment effort in each area should be spent up to the point where the benefit of the last unit of fuel treatment effort is equal to the cost of the last unit of effort. Assuming a constant cost of fuel treatment effort across areas (a discussion of cases where costs are not equal across areas is included in the fourth section) and setting the left-hand side of (2) and (3) equal to each other gives a classic result from economic optimization: at the optimal level of fuel treatment effort, the marginal net benefit of effort in the WUI is equal to the marginal net benefit of effort outside the WUI. That is, when the marginal benefit of effort is equal to the marginal cost of effort, net benefits are maximized and the outcome is socially optimal. Because fuel treatment effort costs are equal for both the public land manager and the private landowner, the social planner is indifferent about which landowner performs the effort.

### Public Land Manager's Decision

Our public land manager, "Public," differs from a social planner in three ways. First, because public land managers view themselves as seriously budget constrained (Stephens and Ruth 2005), our Public faces a budget constraint, which, in comparison to the social optimum determined by our unconstrained social planner, allows us to see the impact of underfunding public land management agencies. Second, while the social planner makes all decisions about effort, the public landowner interacts through a game with the decisions of other managers. Comparing the outcome of the game to the outcome of the social optimum identifies the social losses associated with free-riding and coordination failures between land managers. Third, unlike the Social Planner, our public land manager does not consider amenity values that accrue to the private landowner nor the full amount of private property value. Public's problem is to choose the optimal level of fuel treatment effort to maximize their expected value on WUI and non-WUI land subject to a budget constraint ($B^{\mathrm{g}}$):

$$\max_{e_{\mathrm{o}}^{\mathrm{g}},e_{\mathrm{w}}^{\mathrm{g}}}\{\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}\pi(e_{\mathrm{o}}^{\mathrm{g}}) + (\phi(v+A) + \mathrm{PG}_{\mathrm{w}}^{\mathrm{g}})\pi(e_{\mathrm{w}}^{\mathrm{g}} + e_{\mathrm{w}}^{\mathrm{p}})\} \tag{4}$$

s.t.

$$c(e_{\mathrm{o}}^{\mathrm{g}} + e_{\mathrm{w}}^{\mathrm{g}}) = B^{\mathrm{g}}$$

$$e_{\mathrm{o}}^{\mathrm{g}}, e_{\mathrm{w}}^{\mathrm{g}} \geq 0$$

where $e_{\mathrm{w}}^{\mathrm{g}}$ public fuel reduction effort in the WUI; $e_{\mathrm{o}}^{\mathrm{g}}$ public fuel reduction effort outside the WUI; $e_{\mathrm{w}}^{\mathrm{p}}$ private fuel reduction effort in the WUI; $\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}}$ public good value in the WUI; $\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}$ public good value outside the WUI; $A$ private amenity value in the WUI; $v$ private structure value in the WUI; $\phi$ public's fraction of liability for private property value and $B^{\mathrm{g}}$ public budget. Where $\phi \in [0, 1]$ is the fraction of private property value ($v + A$) for which Public is liable. Also included in Public's problem is Private's fuel treatment effort in the WUI ($e_{\mathrm{w}}^{\mathrm{p}}$), which makes the problem strategic in the sense that the fuel treatment choice of the public decision-maker depends on the other's actions. We include public liability for private losses for several reasons. First, liability here can be interpreted as "responsibility"; many public managers are tasked with protecting society and this functional form is one simple way to represent how much public decisions reflect private values. Second, public agencies fund recovery efforts following wildland fires including contributions through FEMA, which can be modeled as incorporating some portion of the private value into public decisions as above. Third, public land managers face liability issues, as evidenced by recent claims against the USFS and state forest managers throughout the western U.S. Lawsuits were filed against public forestland managers to recover between \$54 and \$236 million in damages to private property following the 2000 fires in Montana's Bitterroot Valley, the 2002 Hayman Fire in Colorado, and the 2003 Cedar Fire in southern California (Ring 2003; AP 2008; *Cary v. United States* 2007; Figueroa 2005). While public land managers were found to be responsible for damages in the 2000 fire only, the threat of litigation remains a real concern. We do not address the case where private amenity value loss cannot be compensated. However, this issue is explored in Talberth and others (2006) and the authors find that the presence of private amenity values whose losses cannot be adequately compensated creates additional incentive for private fuel treatment effort.

We do not consider the impact of private landowner liability for wildfires originating on private land because, although many states impose liability laws on private landowners for wildfires that spread beyond that land, these rules typically pertain to fires caused by forest operations, including prescribed burns, and do not generally apply to fires caused by "non-operational" activities such as lightning (ODF 2007; Yoder and others 2003). In fact, increasingly in the U.S., private landowners who follow regulations about burning face more lenient liability rules for prescribed burns that escape and cause damage elsewhere because governments recognize the public good nature of the fuel treatments through prescribed burns (Yoder and others 2003; Yoder 2008). For these reasons, and because the majority of naturally occurring fires ignite on public land, we focus here on public's liability or responsibility to consider the private landowners' values in their decisions.

The equality constraint in Eq. 4 implies that the public land manager exhausts its budget on fuel treatment effort in the two areas, which is in keeping with public managers' complaints about small budgets for these activities. Solving the budget constraint for public effort outside the WUI and substituting this into objective function simplifies the problem and leads to the first order condition for the maximization of Public's problem:

$$(\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}} + \phi(v+A))\frac{\partial\pi}{\partial(e_{\mathrm{w}}^{\mathrm{g}} + e_{\mathrm{w}}^{\mathrm{p}})} - \mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}\frac{\partial\pi}{\partial(B/c - e_{\mathrm{w}}^{\mathrm{g}})} = 0 \tag{5}$$

Equation 5 states that fuel treatment effort in the WUI should be spent up to the point where the marginal benefit of effort in the WUI is equal to the marginal benefit of effort outside the WUI. Because fire resilience is an increasing, strictly concave function of total—Private and Public—fuel treatment effort, any positive amount of Private effort in the WUI will reduce the marginal net benefit derived from each unit of Public effort in the WUI. Again, because the benefits of fuel treatment to Public and Private is a function of total effort, the public land manager and the private landowner make decisions that are strategic in nature as they include the decision of the other in their own decision—making a game theoretic structure appropriate for solving this problem.

Equation 5 implicitly defines the optimal level of public effort in the WUI. Because fire resilience is a function of total effort (first term of Eq. 5), increasing the levels of private effort in the WUI decreases the optimal level of public effort in the WUI because Public is able to free ride on Private's public good provision in the WUI—they need not provide as much fuel treatment because Private provides some effort. Given Public's budget constraint, their free riding increases the funding available for fuel treatment effort outside the WUI. This especially important case illustrates a mechanism through which public budgets can be redirected for fire protection outside the WUI, where, if the public land manager does not spend fuel treatment effort, no one will.

## Private Landowner's Decision

The private landowner's fuel management decision is made simultaneously with the public land manager's decision and each individual's choice of effort influences the other's optimal choice. Private's objective is to choose the optimal level of fuel treatment effort to maximize expected value, also subject to a budget constraint ($B^{\mathrm{p}}$). Taking Public's choice of effort as given; this is the flipside of Public's problem. Private's optimization problem is:

$$\max_{e_{\mathrm{w}}^{\mathrm{p}}}(1-\phi)(v+A)\pi(e_{\mathrm{w}}^{\mathrm{g}}+e_{\mathrm{w}}^{\mathrm{p}}) \tag{6}$$

s.t.

$$ce_{\mathrm{w}}^{\mathrm{p}} \leq B^{\mathrm{p}}$$

$$e_{\mathrm{w}}^{\mathrm{p}} \geq 0$$

where $e_{\mathrm{w}}^{\mathrm{p}}$ private fuel reduction effort; $1-\phi$ private's fraction of liability for private property value and $B^{\mathrm{p}}$ private budget. Again, assuming fires ignite on public land, private value "at risk" $(1-\phi\ (v+A))$ is the fraction of total private property value uncompensated by public liability and ranges from zero liability, when $\phi=1$, up to full liability $(v+A)$, when $\phi=0$. The first order condition for the maximization of Private's problem when Private's budget constraint is non-binding is:

$$(1-\phi)(v\ +\ A)\frac{\partial\pi}{\partial(e_{\mathrm{w}}^{\mathrm{g}}+e_{\mathrm{w}}^{\mathrm{p}})}=c \tag{7}$$

This condition states that at the optimal level of fuel treatment effort, the marginal net benefit from the last unit of fuel treatment effort in the WUI is equal to its marginal cost, given Public's choice of effort. When Private's budget constraint is binding, the entire budget is spent on fuel treatment effort, and optimal private effort in the WUI is equal to:

$$e_{\mathrm{w}}^{\mathrm{p}}=\frac{B^{\mathrm{p}}}{c} \tag{8}$$

Differences between public and private WUI values create a divergence in the desired level of fuel treatment effort in the WUI. If Public's WUI values $(PG_{\mathrm{w}}^{\mathrm{g}}+\phi(v+A))$are greater than Private's WUI values $(1-\phi)(v+A)$, then Public is willing to spend more fuel treatment 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 treatment effort in the WUI than Public.

## Strategic Interaction of Public and Private

"Strategic" interaction between the public land manager and private landowner in the fuel treatment effort decision arises because each landowner's fuel treatment decision affects the other's decision (see Eqs. 4 and 6). Because neighbors can free ride on other's fuel treatment effort, one landowner's effort creates a disincentive for the other's effort. In effect, the more effort your neighbor spends on fuel treatment, the better protected your property is and the less you need to do.

We model the strategic interaction between the two landowners as a single-stage simultaneous move game with perfect information. In this game, the public land manager and private landowner make their fuel management decisions simultaneously, without knowing the level of fuel treatment effort that will be chosen by the other individual. Although neither individual knows the amount of fuel treatment effort the other will actually choose, both have information on the other's available fuel treatment choices, their value at risk of fire damage, and the effect fuel treatment has on the probability these values will survive a fire.

To solve for the outcome of the game, first the public land manager and private landowner must determine their own best fuel treatment effort choice for all possible effort levels of the other decision-maker, and vice versa. That is, we identify the "best response" of each landowner to the strategy choice of the other. The best response to all possible strategy choices of the other landowner is called the response function. The response function for Public gives the optimal fuel treatment effort as a function of Private's effort. Similarly, the response function for Private gives the optimal fuel treatment effort as a function of Public's effort. When each landowner's strategy choice is a best response to the strategy choice of the other landowner, we have a Nash equilibrium (NE). Graphically, the NE exists where the two response functions intersect. A NE means that at that point, neither landowner has an incentive to change their fuel treatment choice because their choice is the best that they can do, given what the other landowner chose.

## Results and Discussion

In this section, we examine the landscape of fuel treatment effort that results from the uncoordinated activities of the private and public landowners and compare it to that of the social planner. Because each owner makes a decision that is a function of the other's decision, we use game theory to find the equilibrium outcomes that result from this interaction. We determine the optimal fuel treatment decision for Public and Private, describe the three types of NE that determine who pays for fuel treatment, and compare the level and location of fuel treatment effort from the game to the socially optimal outcome.

### Optimal Fuel Treatment Decisions

To derive the response functions, and compute Public and Private's optimal fuel treatment decisions, we use a functional form for fire resilience that satisfies the conditions described in the second section: $\pi(e) = \ln(e)$. This functional form permits analytically tidy results without loss of generality because the public good nature of fuel treatment—that there are diminishing returns to *total* effort and to an individual's effort—drives the results of this game, as well as other public good games (Albers and others 2008). Fuel treatment effort in the WUI is a public good and individuals make decisions based on total effort in the WUI. Given the chosen functional form for fire resilience, Public's objective function becomes:

$$\max_{e_{\mathrm{w}}^{\mathrm{g}}, e_{\mathrm{o}}^{\mathrm{g}}} \{\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}} \ln(e_{\mathrm{o}}^{\mathrm{g}}) + (\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}} + \phi(v+A)) \ln(e_{\mathrm{w}}^{\mathrm{g}} + e_{\mathrm{w}}^{\mathrm{p}})\} \tag{9}$$

s.t.

$$c(e_{\mathrm{o}}^{\mathrm{g}} + e_{\mathrm{w}}^{\mathrm{g}}) = B^{\mathrm{g}}$$

$$e_{\mathrm{o}}^{\mathrm{g}}, e_{\mathrm{w}}^{\mathrm{g}} \geq 0$$

And Private's objective function becomes:

$$\max_{e_{\mathrm{w}}^{\mathrm{p}}} (1-\phi)(v+A) \ln(e_{\mathrm{w}}^{\mathrm{g}} + e_{\mathrm{w}}^{\mathrm{p}}) \tag{10}$$

s.t.

$$c e_{\mathrm{w}}^{\mathrm{p}} \leq B^{\mathrm{p}}$$

$$e_{\mathrm{w}}^{\mathrm{p}} \geq 0$$

The response functions for each landowner are derived by solving the landowner's optimization problem in terms of the other landowner's decision variable. For our problem, when the private landowner's budget constraint is non-binding, a NE is a set of effort contributions $(e_{\mathrm{w}}^{\mathrm{p}*}, e_{\mathrm{w}}^{\mathrm{g}*})$ such that:

$$e_{\mathrm{w}}^{\mathrm{p}*} = \frac{(1-\phi)(v+A)}{c} - e_{\mathrm{w}}^{\mathrm{g}*} \tag{11}$$

$$e_{\mathrm{w}}^{\mathrm{g}*} = \frac{\phi(v+A) + \mathrm{PG}_{\mathrm{w}}^{\mathrm{g}}}{(\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}} + \mathrm{PG}_{\mathrm{w}}^{\mathrm{g}} + \phi(v+A))} \frac{B^{\mathrm{g}}}{c} - \frac{\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}}{(\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}} + \mathrm{PG}_{\mathrm{w}}^{\mathrm{g}} + \phi(v+A))} e_{\mathrm{w}}^{\mathrm{p}*} \tag{12}$$

These equations demonstrate that as Public effort in the WUI increases, Private effort in the WUI 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 landowner's response function is downward sloping (Fig. 1a, b).

When the private landowner's budget constraint is binding, the private landowner's response function becomes:

$$e_{\mathrm{w}}^{\mathrm{p}*} = \frac{B^{\mathrm{p}}}{c} \tag{13}$$

while the public landowner's remains as described in Eq. 12. Graphically, the private landowner's response function remains downward sloping up to the point where the budget constraint becomes binding, at which point reductions in public effort are no longer associated with increases in private effort, as illustrated in Fig. 2. The public landowner's budget constraint is always binding and because fuel treatment effort is allocated between the WUI and the area outside the WUI, Public's response function does not have the same shape as Private's budget-constrained response function (Fig. 2).

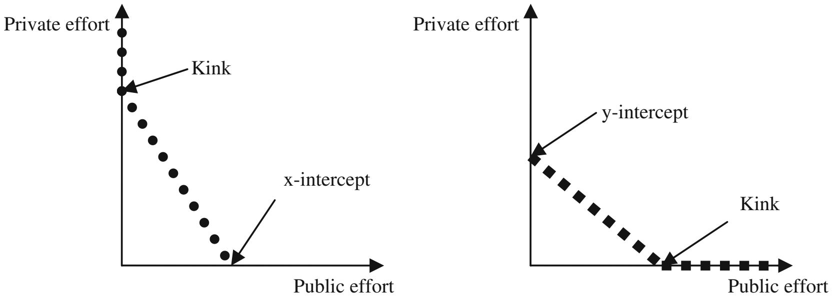

**Fig. 1** **a** Public's best response function; **b** private's best response function

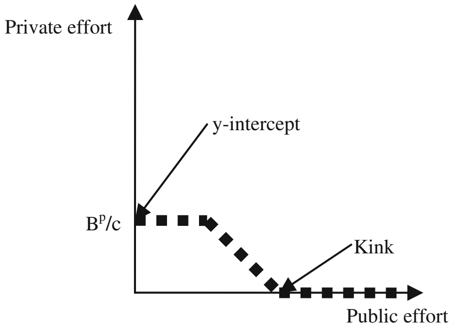

**Fig. 2** Private's best response function when the private budget constraint is binding

The slope of the individual's best response function describes how the decision-maker optimally adjusts to changes in the other's fuel treatment effort. Both decision-makers' optimal choice of effort is a non-increasing function of the other's choice of effort. The slope of Public's response function, $-\left(\frac{\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}+\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}}+\phi(v+A)}{\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}}\right)$, is always greater (steeper, when public effort is on the *x*-axis and private effort is on the *y*-axis) than the slope of Private's response function when the budget constraint is non-binding. This relationship, however, will not hold for cases where Public is not budget constrained, which is discussed in the Appendix 1. When Private's budget constraint is non-binding, the slope of Private's response function implies that for every unit decrease in Public effort, Private increases effort by an equal amount. When the private landowner's budget constraint is binding, decreases in Public effort do not increase Private effort. The slope of Public's response function is greater than one because, when deciding how to allocate limited funds, the public landowner must also consider values at risk of fire damage outside the WUI. Because the slope of Public's response function is greater than one, when Private effort in the WUI increases (decreases) by one, Public effort in the WUI decreases (increases) by less than one. A kink (identified in Figs. 1a, b, and 2) occurs in the response functions when the non-negativity constraint on fuel treatment effort binds and the landowner optimally chooses zero effort. Each landowner's maximum choice of effort is a best response when the other landowner chooses zero effort.

Examination of Eqs. 11–13 demonstrates that optimal contributions of effort depend on landowners' budgets ($B^{\mathrm{g}}$, $B^{\mathrm{p}}$), the assignment of liability ($\phi$), and values at risk both in and outside the WUI $(v, A, \mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}, \mathrm{PG}_{\mathrm{o}}^{\mathrm{g}})$. As these parameters vary, interaction between the public land manager and private landowner will vary.

## Who Pays for Fuel Treatment? Three Types of Outcomes

We identify three possible NE outcomes of the game between Public and Private. Varian (1994) finds that in a game with two or more agents where public good provision depends on the sum of effort, the agent with the highest benefit-cost ratio will contribute and all other agents free ride on this agent. Our first two equilibria demonstrate this extreme free riding in which only one landowner contributes to fuel treatment effort in the WUI and the other free rides without contributing any effort. Our problem, however, is distinct in that we have two landowners with different benefit functions—the public land manager considers fuel treatment effort both in the WUI and outside the WUI while the private landowner considers only fuel treatment effort within the WUI. Because of this difference, the equilibria that emerge from our game are not limited to extreme free riding. The third, shared effort, equilibrium makes our problem unique. In this section we look at the conditions that lead to each of the three equilibria.

Of the three possible equilibria, the one that emerges will depend on the size of the landowners' budgets, values in the WUI, and Public's relative values in and outside the WUI. The first equilibrium, characterized by extreme free riding where only Public spends fuel treatment effort (Fig. 3a), will emerge when the x-intercept of Public's response function is to the right of the kink in Private's response function; when $B^{\mathrm{g}} \geq \frac{(1-\phi)(v+A)(\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}+\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}}+\phi(v+A))}{\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}}+\phi(v+A)}$. Using this condition, we see that Public is most likely to

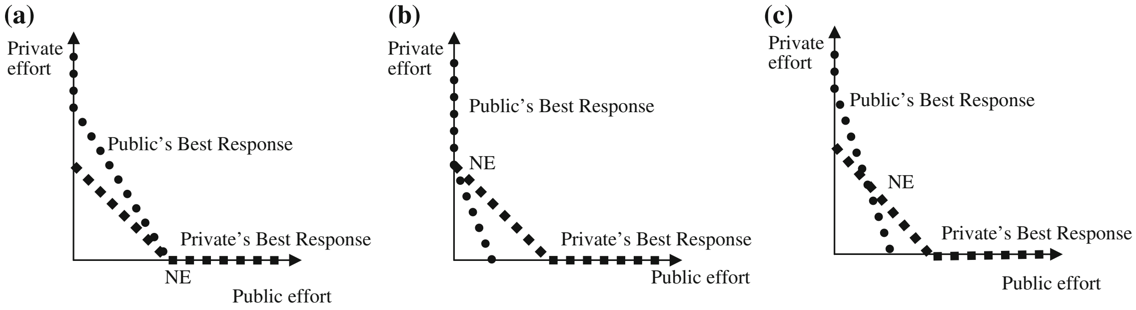

**Fig. 3** **a** Extreme free riding equilibrium; **b** extreme free riding equilibrium; **c** shared effort equilibrium

provide all fuel treatment effort when Private values in the WUI ($(1-\phi)(v+A)$) are low (either private property value is low or public liability is high), Public's budget ($B^{\mathrm{g}}$) is large, and/or Public's values outside the WUI ($\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}$) are low.

At other parameter values, a different NE arises in which only Private contributes effort in the WUI (Fig. 3b). 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 satisfy the inequality: $\frac{(1-\phi)(v+A)\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}}{\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}}+\phi(v+A)} \geq B^{\mathrm{g}}$ or $\frac{\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}}{\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}}+\phi(v+A)}B^{\mathrm{p}} \geq B^{\mathrm{g}}$, when Private is budget constrained. At this equilibrium, Public spends effort outside the WUI only. This outcome is the result of Private's willingness and ability to spend fuel treatment effort in the WUI, relative to the public landowner. This extreme free riding equilibrium is most likely to emerge when public budgets are small, private values in the WUI are large relative to public values, and/or public value outside the WUI is large.

Finally, at other parameter values, a third NE exists where both Public and Private spend effort in the WUI (Fig. 3c). This equilibrium emerges when the y-intercept of Private's response function is below the kink in Public's response function; in mathematical terms, these parameter values occur when$B^{\mathrm{g}} \in \left[\frac{(1-\phi)(v+A)\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}}{\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}}+\phi(v+A)}, \frac{(1-\phi)(v+A)(\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}+\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}}+\phi(v+A))}{\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}}+\phi(v+A)}\right]$ or, for cases where Private is budget constrained, when $B^{\mathrm{g}} \in \left[\frac{\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}}{\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}}+\phi(v+A)}B^{\mathrm{p}}, \frac{(1-\phi)(v+A)(\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}+\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}}+\phi(v+A))}{\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}}+\phi(v+A)}\right]$. At the shared effort equilibrium, every additional unit of public fuel treatment effort crowds out private effort, one-for-one when Private's budget constraint is non-binding.

All three NE outcomes for the case where public liability is zero and the private budget constraint is non-binding are depicted in Fig. 4. When Public's budget is small (between zero and one with the chosen parameter values) the extreme free riding equilibrium with only Private effort in the WUI emerges. Here all public funding is spent outside the WUI and increases in the public budget lead to increases in public effort outside the WUI. Once Public's budget increases sufficiently to fund the socially optimal level of effort outside the WUI, additional public funding leads to increases in public effort in the WUI, which are matched with equivalent reductions in private effort, thus illustrating the crowding out of private effort. Increases in publicly funded WUI effort eventually drive private effort to zero and the second extreme free riding equilibrium results. Because marginal changes in actions do not make either actor better off nor lead to non-marginal changes in the reaction of the other actor, all three NE are stable across actions. Figures 5, 6, 7, 8, 9 demonstrate the response of the NE to changes in the parameter values.

The three characteristic NE outcomes are again depicted in Fig. 5 for the case where public liability is zero and the private budget constraint is binding over a range of public budgets (i.e., when Public's budget is less than three with the chosen parameter values). Only after total effort in the WUI is sufficient to satisfy the first order condition for the maximization of Private's problem is the private landowner's budget constraint no longer binding and do we observe private effort in the WUI begin to decrease in response to increases in Public effort in the WUI. There are two major differences between the case where the private budget constraint is non-binding, as illustrated in Fig. 4, and the case where it is binding over some range of parameter values, as illustrated in Fig. 5. First, when the private landowner's budget constraint is non-binding, we observe the shared effort equilibrium over a smaller range of public budgets. And second, the socially optimal level of fuel treatment effort outside the WUI is achieved at lower public budget levels when the private landowner's budget constraint is non-binding.

## How Does the Outcome of the Game Compare to the Social Optimum?

Using the results derived in the previous section and results presented in this section for cases where public liability is positive, we examine how observed equilibrium effort

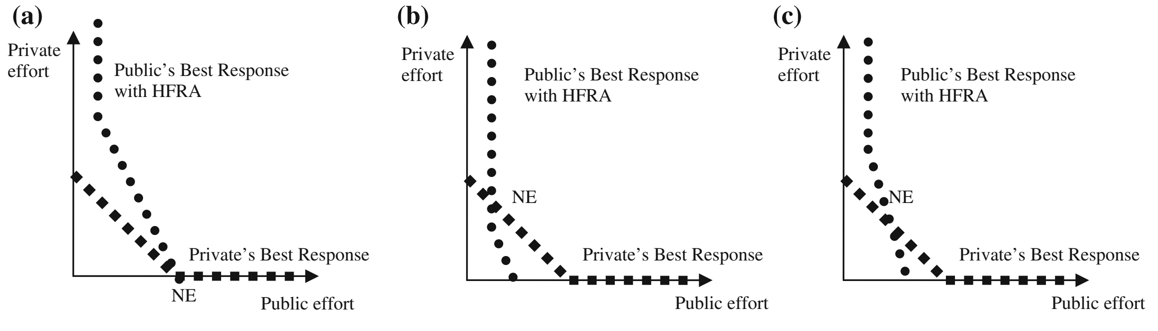

**Fig. 4** **a** Extreme free riding equilibrium; **b** shared effort equilibrium (HFRA binding); **c** shared effort equilibrium (HFRA non-binding)

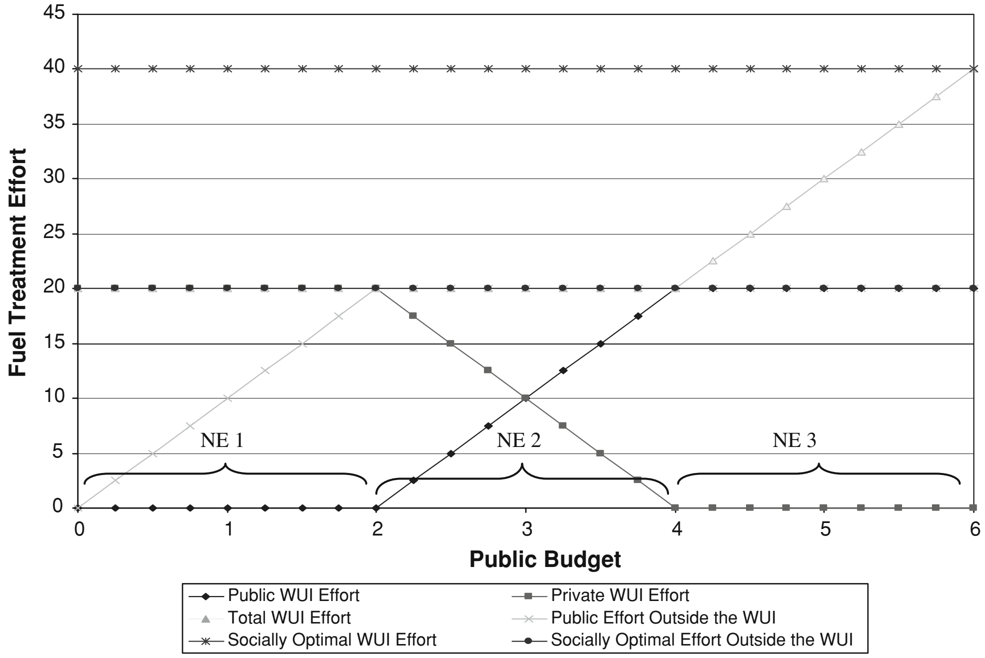

**Fig. 5** Fuel treatment effort as a function of public budget when public liability is 0 and private budget constraint is non-binding (equilibrium effort calculated using parameter values: $\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}} = 2;\ \mathrm{PG}_{\mathrm{w}}^{\mathrm{g}} = 2;\ A + v = 2;\ B^{\mathrm{p}} = 2;\ c = 0.1$)

inside and outside the WUI compares to the socially optimal outcomes in each area. Total effort in the WUI is the sum of the private and public effort at the NE. 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 treatment effort.

### *Effort in the WUI*

Because of the free rider problem, strategic interaction between the two uncoordinated landowners in the WUI generally leads to a socially suboptimal, or inefficient, level of effort in the WUI. The inefficiency results because, unless Public has full liability for private values and therefore considers those values in decisions, neither landowner considers the full value of amenities and private property in the WUI. That is, Public considers only public good amenity value and public liability ($\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}} + \phi(v + A)$) while Private considers only property and amenity value liability ($(1 - \phi)(v + A)$) when making fuel treatment decisions. Because the socially optimal level of effort in the WUI considers the benefit from protecting *all* values in the area, the social planner will always choose to spend more fuel treatment effort in the WUI than the amount that results from the game, when Public's liability is <1.

The inefficiencies created by budget constraints cannot be entirely separated from the interaction in the game and both are illustrated in Figs. 5 and 6. In both settings, there is no opportunity for private free riding until Public's budget is big enough to begin funding fuel treatment in the WUI. In Fig. 5, Private begins to free ride on public fuel treatment effort when Public's budget is greater than or equal to 2, but in Fig. 6, private free riding begins when Public's budget is greater than or equal to 3. The extreme free riding equilibrium emerges when Public's budget is greater than or equal to 4 (in both Figs. 5 and 6) and big enough to fully fund Private's individually optimal level of fuel treatment, 20 units of fuel treatment effort. The budget constraint, therefore, contributes to the type of equilibrium attained and to the degree of free-riding possible (Albers and others 2008).

Effort by both landowners changes with Public's fraction of liability and the greater public liability for private values at risk, the greater the inefficiencies that result from the game because Private has more opportunity to free-ride. This aspect of the problem is illustrated in Fig. 7, which describes the equilibrium outcomes for the case where Public's fraction of liability ranges from zero to one. For the chosen parameters, when public liability is zero, public and private WUI values are equal, but as public liability increases, private value—and the resulting level of private fuel treatment—in the WUI decrease because Public' liability means that Private faces less risk. In Fig. 7, when public liability is greater than 0.3, public effort in the WUI begins to increase, the cost of which is offset by reductions in public effort outside the WUI. Because the NE at low levels of liability (see Fig. 7) is the extreme free riding on

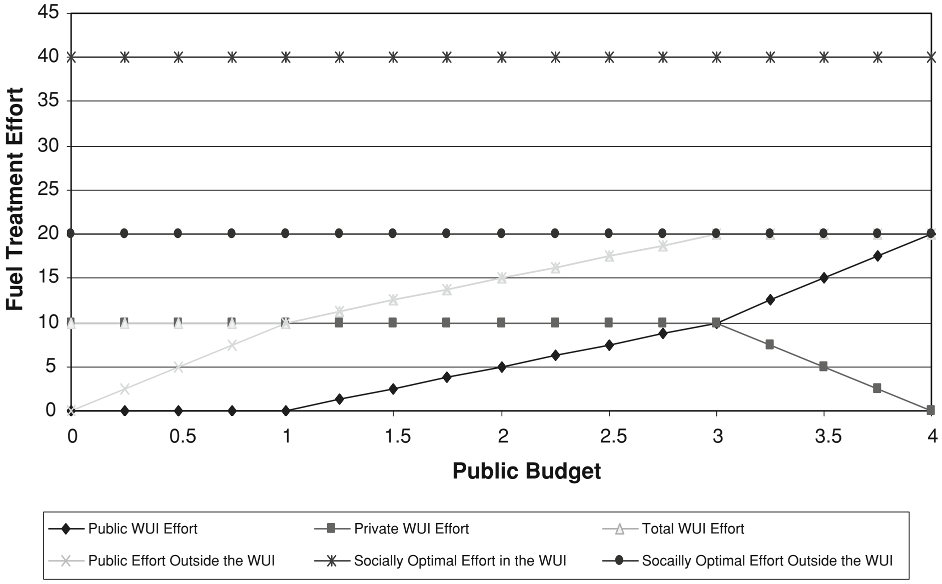

**Fig. 6** Fuel treatment effort as a function of public budget when public liability is 0 and private budget constraint is binding over a range of public budgets (equilibrium effort calculated using parameter values: $\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}} = 2;\ \mathrm{PG}_{\mathrm{w}}^{\mathrm{g}} = 2;\ A + v = 2;\ B^{\mathrm{p}} = 1;\ c = 0.1$)

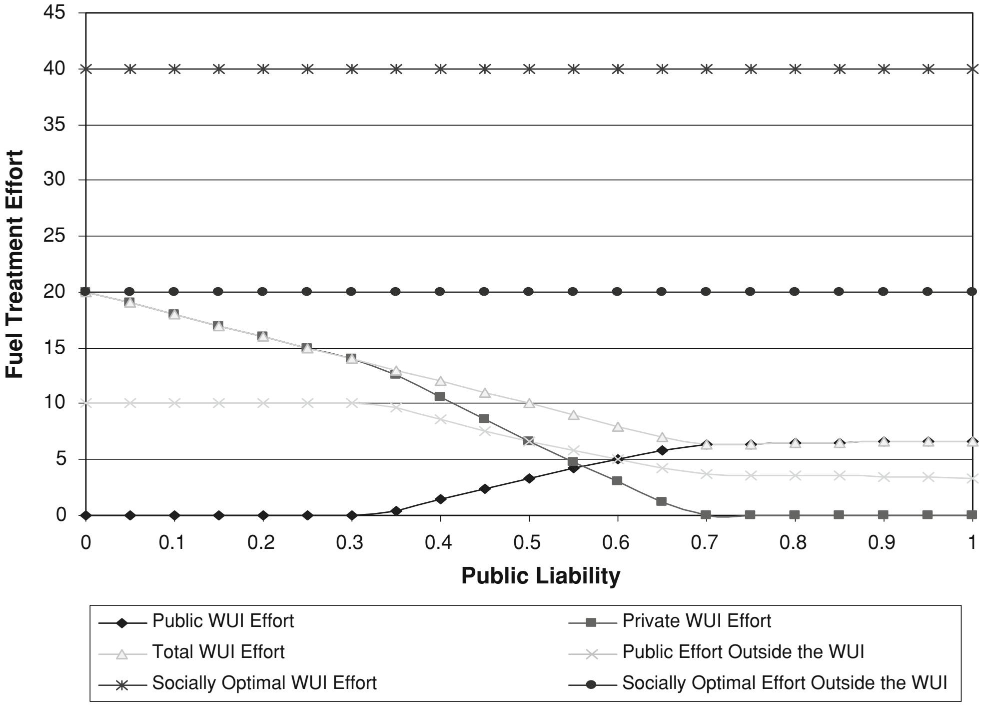

**Fig. 7** Fuel treatment effort as a function of public budget when public liability is 1.0 and private budget constraint is non-binding (equilibrium effort calculated using parameter values: $\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}} = 2;\ \mathrm{PG}_{\mathrm{w}}^{\mathrm{g}} = 2;\ A + v = 2;\ c = 0.1; B^{\mathrm{p}} = 2$)

Private, Public has no budget to offset reductions in private fuel treatment effort in the WUI. With the same values except a larger public budget, we wouldn't see the immediate steep decline in WUI effort levels. However, with a binding public budget constraint, increasing public liability for private value in the WUI moves the outcome further from the socially optimal level of treatment both in the WUI and outside the WUI.

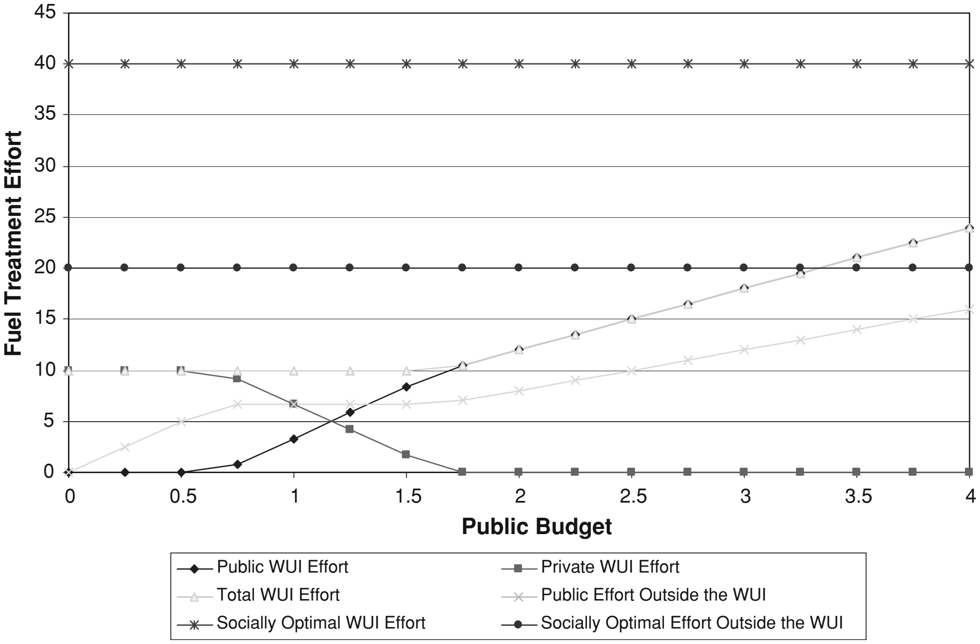

**Fig. 8** Fuel treatment effort as a function of public budget when public liability is 0.5 and private budget constraint is non-binding (equilibrium effort calculated using parameter values: $\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}} = 2$; $\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}} = 2$; $A + v = 2$; $B^{\mathrm{p}} = 2$; $c = 0.1$) (results would be identical if $B^{\mathrm{p}} = 1$)

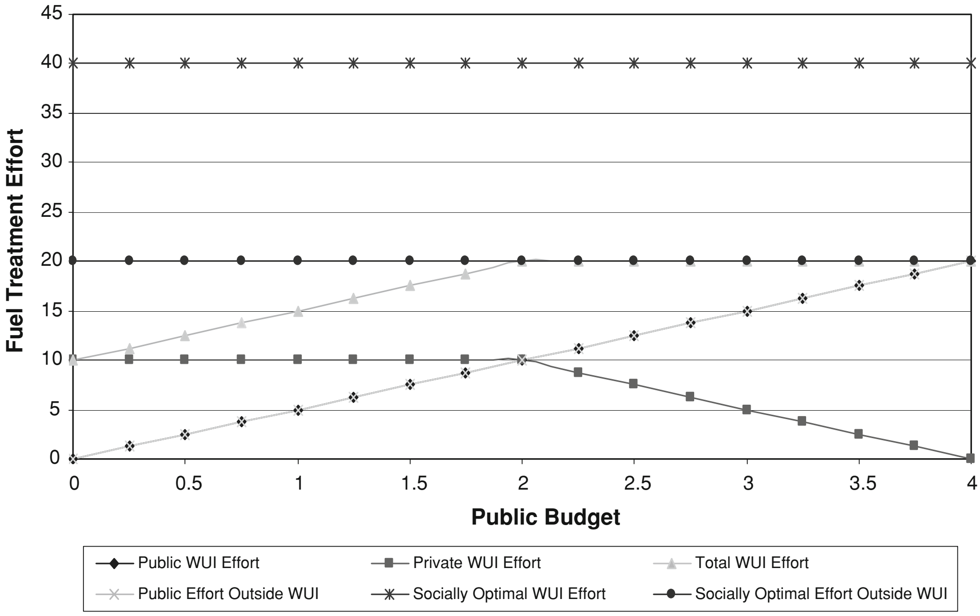

**Fig. 9** Fuel treatment effort as a function of public liability when private budget constraint is binding and HFRA requirement is enforced (equilibrium effort calculated using parameter values: $\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}} = 2; \mathrm{PG}_{\mathrm{w}}^{\mathrm{g}} = 2; A + v = 2; c = 0.1$; $B^{\mathrm{p}} = 1$)

### *Effort outside the WUI*

Public carries full responsibility for the protection of 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 $\frac{\mathrm{PG}_{\mathrm{o}}^{\mathrm{g}}}{c}$, where the marginal net benefits from the last unit of effort is equal to its marginal cost. However, Public effort outside the WUI depends on budgetary constraints, liability assignment, and relative values in and outside the WUI.

The divergence between the observed effort outside the WUI and the socially optimal amount increases as public liability approaches one. Increasing public liability increases WUI value relative to non-WUI value for Public, thereby increasing the rate at which additional public funds are directed to this area. This situation is starkly illustrated in Fig. 8 where, over a range of public budget increases (0.75 and 1.5 with the chosen parameter values), 100% of additional funds are allocated to fuel treatment effort in the WUI. Public values outside the WUI are neglected as

Private's free riding in the WUI increases. This example illustrates how free riding in the WUI, compounded by public liability there, leads to the under-protection of high-value non-WUI resources.

## Policy Implications and Concluding Remarks

Using the analytical framework developed in this paper, we gain insight into the nature of the strategic interaction between public land manager and private landowner when making fire risk management decisions. Because fuel treatment effort has public good characteristics, in the WUI, where there is a mix of public and private land, both landowners have an incentive to free ride on the other's effort. The outcome of the strategic interaction in the WUI affects the ability of the public land manager to protect values outside the WUI due to the public budget constraint. The budget constraint limits the amount of effort the public land manager can spend in each area and when the private landowner free rides on public effort in the WUI, less funding is available to protect public values outside the WUI.

The Healthy Forest Restoration Act (HFRA) directs fuel management policy and prioritizes the WUI by requiring that at least 50% of fuel treatment budgets be spent in the WUI. Graphically, this requirement is illustrated in Fig. 4a–c, depicting the two response functions and two possible NE; with HFRA, the extreme free riding on private effort is no longer feasible. The results of our strategic game between a private and a public land manager demonstrate that, from a societal perspective, any such requirement can cause two types of inefficiencies in fuel treatment decisions. First, this rule creates inefficiencies because, when binding, it does not allow public land managers to compare the marginal net benefits of fuel treatment effort in the WUI to those outside the WUI; it simply requires spending in the WUI. In some situations, this requirement leads to the under-protection of resources outside of the WUI, for which public land managers are solely responsible. Second, within the WUI, the HFRA requirement increases the ability of the private landowner to free ride on public fuel treatment, which moves fuel treatment levels in the WUI further from the socially optimal level. For example, with HFRA but with the same parameter values as those used for Fig. 6 without HFRA, Private begins free riding when Public's budget is 2 rather than 3 without HFRA and the socially optimal level of fuel treatment outside the WUI is not realized until Public budget is 4 rather than 2 without HFRA (Fig. 6 compared to Fig. 9). Not only might public effort be better spent outside the WUI, but each additional unit of public effort in the WUI increases the private landowner's ability to free ride, shifting the burden of fuel treatment effort from private to public agents without necessarily increasing the level of those efforts.

While fuel treatment budgets remain low for public forestland managers, fire suppression costs have skyrocketed in recent years as more large, uncharacteristically severe fires burn and as more people move to the WUI, increasing suppression costs there. Within the framework developed here, suppression could be considered in a number of ways. For example, one possible interpretation of the impact of fuel treatment effort could be reduced suppression expenditures, which could be incorporated into our framework through, for example, higher public goods values within and outside of the WUI. Similarly, if more expected expenditures on suppression leads to the expectation of significantly higher fractions of value surviving fires, that relationship translates to lower values at risk during fire, as suppression substitutes, to some extent, for preventive fuel treatments. However, under extreme fire conditions, suppression may not provide an effective substitute for fuel treatment.

One next step in modeling might include budgetary tradeoffs between fuel treatment and suppression costs; however, adding suppression efforts in our framework would not change our basic result about fuel treatment and forest management in the WUI's impact on non-WUI fire management. First, current fuel levels and policies that decouple fuel treatment budgets and suppression budgets reduce the link that managers see between fuel treatment and suppression (Government Accountability Office 2008; Hesseln 2001). Second, if in the long run regular natural fires could maintain the non-WUI forests, then monies could be transferred towards suppression and fuel treatment in the WUI but current fuel loads will not permit natural fire regimes in non-WUI forests; because non-WUI forests require major investments in fuel treatments before natural fire regimes can be restored, no monies that currently support non-WUI activities are forthcoming soon. Third, suppression is another form of hazard mitigation with public good characteristics. Including a publicly funded suppression program in the strategic model would further reduce private fuel treatment effort in the WUI and, as a result, would decrease public effort outside the WUI. Although one goal of public fuel treatment effort in the WUI is to reduce later fire suppression costs, those cost savings do not arise if increases in public fuel treatment effort are offset by equivalent reductions in private effort, as occurs in several scenarios presented here.

WUI-focused regulations and liability rules will be most inefficient when public land managers would otherwise choose to allocate its budget outside the WUI, such as when public good values outside the WUI are high. This situation might arise in areas where there are endangered species, unique ecosystems, or high-value watershed services. Our results show that when public budgets are small, increases in public effort will optimally be spent outside the WUI, leaving the private landowner as the sole contributor to fuel treatment effort in the WUI. For any policy with a WUI-emphasis to be socially appropriate, public budgets must be large enough to protect resources outside of the WUI.

Relaxing our assumptions related to the cost of fuel treatment effort and the absence of spatial externalities between the WUI and the area outside the WUI does not change our main result, but removing risk neutrality of the landowners works in the opposite direction of our main result. First, in the model we assume equal cost of fuel treatment in and outside the WUI but evidence suggests that fuel treatment cost is sometimes higher in the WUI, primarily due to precautions that must be taken to avoid damaging private values (Berry and Hesseln 2004). In this case, the public land manager optimally spends even more fuel treatment effort outside the WUI and less in the WUI. This shift creates a larger wedge between optimal public actions in the WUI and WUI-focused policy requirements and supports our main result that the area outside the WUI is under-protected. Second, we assume that the two areas are not spatially linked and that fuel treatment outside the WUI provides no additional protection for values in the WUI. Where public effort outside the WUI protects WUI values due to spatial links, public land managers optimally increase effort outside the WUI, an outcome that again supports our main result. Third, a risk-averse private landowner—as opposed to our risk neutral private landowner—spends more fuel treatment effort in the WUI to avoid the possibility of fire damage. Similarly, public land managers with risk aversion that focuses on the WUI risks—such as those who fear political and media backlash from WUI fires—put more fuel treatment effort in the WUI. The additional effort in the WUI by both risk-averse public land managers and private landowners works in the opposite direction of our main result and shrinks the wedge between the optimal and equilibrium levels of fuel treatment effort.

Placing the responsibility for fuel treatment on public land managers may be desirable from a broader social perspective or from a political perspective but the cost in terms of forgone fuel treatment in other areas should be acknowledged. Without removing the safety net for private landowners, policies that require some level of private risk mitigating activities could reduce the public burden and increase social welfare by allowing public land managers to provide resource protection away from the WUI where desirable. This policy option would be similar in spirit to existing statutory laws in Montana, Minnesota, New Mexico, and Washington that require fuel treatment on private land (Yoder and others 2003). Our results suggest that such policies are especially appropriate in areas where public land managers face limited budgets and where values outside the WUI are significant. Together, regulation requiring public fuel treatment and public liability for private values in the WUI act as a subsidy to private landowners and force the public land manager—and society at large—to pay the cost of fire protection in terms of fuel treatment costs and lost values outside the WUI. In the long-term, this subsidy creates further inefficiencies because it induces socially undesirable levels of migration to the WUI. Recognizing that public and private values in the WUI can be protected by both the public land manager and the private landowner, but that only public land managers protect resources outside the WUI, raises questions about HFRA's WUI-emphasis, public liability, and disaster aid while supporting regulation to induce private fuel treatment within the WUI.

## Appendix 1

### Equilibrium Outcomes when Public is not Budget Constrained

When Public is not budget constrained, the landowners' response functions are parallel. Without a budget constraint, Public has sufficient funding for fuel treatment in both areas and no longer has to tradeoff between fuel treatment effort within and outside the WUI. When the Public and Private WUI values are equal ($\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}} + \phi(v + A) = (1 - \phi)(v + A)$), the two response functions overlap and there are infinitely many NE (Fig. 10). Because the landowners have the same amount of value at risk in the WUI, each landowner values improvements in WUI fire resilience equally.

In the case where the Public and Private WUI values are not equal, there are two possible equilibria, illustrated in Fig. 11a and b. 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 $((1 - \phi)(v + A)/c)$ and Public will contribute nothing. If the opposite is true, then Public will contribute effort equal to $(\mathrm{PG}_{\mathrm{w}}^{\mathrm{g}} + \phi(v + A))/c$ in the WUI and Private will

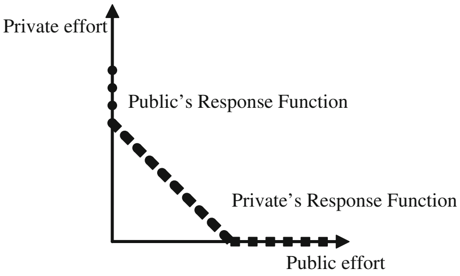

**Fig. 10** Overlapping best response functions

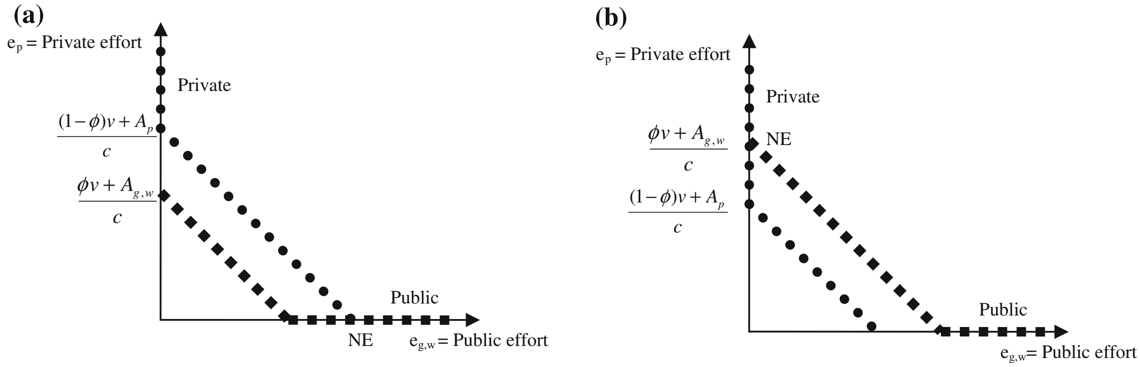

**Fig. 11** **a** Private WUI values greater; **b** public WUI values

contribute nothing. At both equilibria, Public spends the efficient level of effort outside the WUI.

## References

Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. For Ecol Manag 211:83–96

Albers HJ, Ando AW, Batz M (2008) Equilibrium patterns of land conservation: crowding in/out, agglomeration, and policy. Resour Energy Econ 30(4):492–508

Amacher GS, Malik AS, Haight RG (2006) Reducing social losses from forest fires. Land Econ 82(3):367–383

Associated Press (AP) (2008) Federal government wins lawsuit over Hayman fire. Accessed online February 24, 2009: www.insurancejournal.com

Berry AH, Hesseln H (2004) The effect of the wildland urban interface on prescribed burning costs in the Pacific Northwestern United States. J For 102(6):33–37

Buckley M, Haddad BM (2006) Socially strategic ecological restoration: a game-theoretic analysis. Environ Manag 38(1):48–61

Cary v. United States, 79 Fed. Cl. 145 (2007) United States Court of Appeals for the Federal Circuit, Decided: January 16, 2009. http://www.cafc.uscourts.gov/opinions/08-5022.pdf. Accessed 24 Feb 2009

Crowley CSL, Malik AS, Amacher GS, Haight RG (2009) Adjacency externalities and forest fire prevention. Land Econ 85(1):162–185

Deeming JE, Burgan RE, Cohen JD (1977) The National Fire Danger Rating System—1978. U.S. Department of Agriculture Forest Service General Tech. Rep. INT-39, Intermountain Forest and Range Experiment Station, Ogden, UT, 63 pp [Available from USDA Forest Service-RMRS, 324 25th St., Ogden, UT 84401.]

Figueroa T (2005) Judge dismisses $100 million Cedar Fire lawsuit. North County Times, Monday, November 28, 2005

Finney MA (2001) Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. For Sci 47(2):219–228

Gill AM, Bradscock RA (1998) Prescribed burning: patterns and STRATEGIES. In: 13th conference on fire and forest meteorology, Fairfax, VA: International Association of Wildland Fire, USA, pp 3–6

Government Accountability Office (GAO) (2008) Wildland Fire Management: interagency budget tool needs further development to fully meet key objectives. Report to the Chairman, Committee on Energy and Natural Resources, U.S. Senate GAO-09-68

Graham RT, Harvey AE, Jain TB, Tonn JR (1999) The effects of thinning and similar stand treatments on fire behavior in western forests. USDA Forest Service General Technical Report PNW-GTR463

Hann WJ, Strohm DJ (2003) Fire regime condition class and associated data for fire and fuels planning: methods and applications. In: USDA Forest Service Proceedings RMRS-P-29, pp 397–434

Healthy Forest Restoration Act of 2003 (HFRA) (2003) Public Law 108-148, 117 Stat 1887

Healthy Forests Report FY2006 (2007) Healthy Forests and Rangelands. www.forestsandrangelands.gov. Accessed 6 Mar 2007

Hesseln H (2001) Refinancing and restructuring federal fire management. J For 99:4–8

Hirshleifer J (1983) From weakest link to best shot: the voluntary provision of public goods. Public Choice 41:371–386

Konoshima M, Montgomery CA, Albers HJ, Arthur JL (2008) Spatial endogenous fire risk and efficient fuel management and timber harvest. Land Econ 84(3):449–468

Kunreuther H (2000) Insurance as cornerstone for public-private sector partnerships. Nat Hazards Rev 1(2):126–136

Kunreuther H, Slovic P (1978) Economics, psychology, and protective behavior. Am Econ Rev 68(2):64–69

Laverty L (2003) Congressional field hearing testimony: environmental effects of catastrophic wildfires, March 7, 2003. http://bulk.resource.org/gpo.gov/hearings/108h/85487.pdf. Accessed 24 Feb 2009

Lewis T, Nickerson D (1989) Self-insurance against natural disasters. J Environ Econ Manag 16:209–223

McGee TK (2005) Completion of recommended WUI fire mitigation measures within urban households in Edmonton, Canada. Glob Environ Change B 6(3):147–157

National Interagency Fire Center (NIFC) (2009) Wildland fire statistics. http://www.nifc.gov/fire_info/fire_stats.htm. Accessed 25 Feb 2009

Oregon Department of Forestry (ODF) (2007) Landowner fire liability. Oregon Department of Forestry in partnership with Oregon Small Woodlands Association, Oregon Forest Resources Institute, and Oregon Forest Industries Council, 4 pp. http://www.oregon.gov/ODF/PUBS/docs/Landowner_Fire_Liability_reduced.pdf. Accessed 24 Feb 2009

Reddy SD (2000) Examining hazard mitigation within the context of public goods. Environ Manag 25(2):129–141

Ring R (2003) Who should pay when houses burn? High Country News, 26 May 2003, vol 35(10)

Schmidt KM, Menakis JP, Hardy, CC, Hann WJ, Bunnell DL (2002) Development of coarse-scale spatial data for wildland fire and fuel management. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station General Tech. Rep. RMRS-GTR-87, p 46

Stephens SL, Ruth LW (2005) Federal forest fire policy in the United States. Ecol Appl 15(2):532–542

Stewart S, Radeloff V, Hammer R, Fried, J, Holcomb S, McKeefry J (2005) Mapping the Wildland Urban Interface and Projecting its Growth to 2030: summary statistics. http://www.silvis.forest.wisc.edu/Library/Stats/uswuistats.pdf. Accessed 24 Feb 2009

Talberth J, Barrens R, McKee M, Jones M (2006) Averting and insurance decisions in the wildland urban interface: implications of survey and experimental data for wildfire risk policy. Contemp Econ Policy 24(2):203–223

United States Forest Service (USFS) (2004) Healthy Forests Restoration Act (HFRA) Wildland Urban (WUI) Interface for North Idaho and Montana, 2004. www.fs.fed.us/r1/gis. Accessed 24 Feb 2009

Varian H (2004) System reliability and free riding. http://www.ischool.berkeley.edu/∼hal/Papers/2004/reliability. Accessed 24 Feb 2009

Yoder J (2008) Liability, regulation, and endogenous risk: the incidence and severity of escaped fires in the United States. J Law Econ 51:297–325

Yoder J, Tilley M, Engle D, Fuhlendorf S (2003) Economics and prescribed fire law in the United States. Rev Agric Econ 25(1):218–233