Preemptive Incentives and Liability Rules for Wildfire Risk Management

Christian Langpap
Department of Applied Economics
Oregon State University
christian.langpap@oregonstate.edu

JunJie Wu
Department of Applied Economics
Oregon State University
Junjie.wu@oregonstate.edu

Running Title:
Policy for Wildfire Risk Management

Abstract: Wildfires in the U.S. are growing in extent and severity, causing billions of dollars in damage each year. Wildfire policy has increased its focus on integrating fire suppression with risk mitigation through fuel reduction. In this context incentives to elicit management activities that mitigate fire risk are critical, because landowners may not carry out sufficient risk mitigation on their own. We examine the effectiveness and welfare implications of several incentive policies, including two novel approaches not studied in the context of wildfire management: liability rules and voluntary agreements. Our analysis uses a threshold model of public good provision, which allows for each landowner's mitigation choices to depend on the total amount of mitigation in the landscape. Our results suggest that the risk mitigation threshold is critical in determining the effectiveness and welfare effects of different incentive programs. When the threshold is high, only voluntary agreements and cost sharing can increase mitigation effort and welfare. Negligence standards can also be effective and welfare enhancing, but only when the mitigation threshold is sufficiently low.

Key Words: Wildfire; Incentives; Liability; Voluntary Agreements; Non-industrial private forests.

JEL Codes: Q28, Q58

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Abstract: Wildfires in the U.S. are growing in extent and severity, causing billions of dollars in damage each year. Wildfire policy has increased its focus on integrating fire suppression with risk mitigation through fuel reduction. In this context incentives to elicit management activities that mitigate fire risk are critical, because landowners may not carry out sufficient risk mitigation on their own. We examine the effectiveness and welfare implications of several incentive policies, including two novel approaches not studied in the context of wildfire management: liability rules and voluntary agreements. Our analysis uses a threshold model of public good provision, which allows for each landowner's mitigation choices to depend on the total amount of mitigation in the landscape. Our results suggest that the risk mitigation threshold is critical in determining the effectiveness and welfare effects of different incentive programs. When the threshold is high, only voluntary agreements and cost sharing can increase mitigation effort and welfare. Negligence standards can also be effective and welfare enhancing, but only when the mitigation threshold is sufficiently low.

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The frequency and extent of wildfires in the United States and the severity of their impacts have become an important policy issue. The 2020 wildfire season was the most destructive on record. More than 13 million acres burned across the U.S., and over 14,000 structures were destroyed. According to data from the National Interagency Fire Center, which divides the country into Geographic Area Coordination Centers (GACCs), fires burned roughly a million acres in the Great Basin, Southwest, Northern Rockies and Rocky Mountains, and over 2.5 million acres in the Southern GACC (National Interagency Fire Center 2020). The Northwest GACC (Washington and Oregon) was hit particularly hard. More than 800,000 acres burned in Washington alone, where the Babb Road fire destroyed the town of Malden in just a few hours. Over 1.2 million acres burned in Oregon, doubling the 10-year average. Nine people died, five towns were substantially destroyed, prompting the evacuation of around 40,000 residents, and the air quality in urban areas of the state was hazardous for well over a week (Slotkin 2020). The two California GACCs (Northern and Southern) experienced their worst wildfire season on record, with over 4 million acres burned (4% of the state's land area), which more than doubled the acreage burned in 2018, the previous record-breaking season. Five of the six largest fires on record occurred this year. This included the August complex fire in Northern California, which grew beyond a million acres and required a new classification as a "gigafire". Furthermore, the season was long, as fires continued burning in southern California into late October, prompting the evacuation of over 100,000 residents in Orange County (Freedmand and Leonard 2020).

While this was a particularly active fire season, it was not entirely extraordinary. For example, over one million acres were burned in seven out of the past ten fire seasons in

California. The Mendocino Complex Fire broke records in 2018, and the Camp Fire caused at least 86 fatalities and destroyed the entire town of Paradise (CalFire 2018). In the country as a whole, fires burned over ten million acres in 2015 and 2017, with an average of over 6.8 million acres burned annually between 2008 and 2018 (National Interagency Fire Center 2019a).

Wildfires also trigger large expenditures on fire suppression and damage mitigation. Federal suppression expenditures have exceeded $1 billion in all but three of the last fifteen years (National Interagency Fire Center 2019b), and fire-related costs added up to over half of the US Forest Service's budget in 2019, to the detriment of recreation, restoration, and other priorities (USDA Forest Service 2018). Increasing costs can be traced to the growing extent and severity of wildfires, which in turn are attributed to changing climate and weather patterns, fuel buildup from extensive past fire suppression, and an expanding wildland-urban interface (Mercer et al. 2007; Prante et al. 2011).[1]

Given rising costs and the growing recognition that fire plays a beneficial role in sustaining ecological processes, wildfire policy in the U.S. is shifting away from focusing on suppression to an approach that integrates fire suppression with fuel reduction (O'Donnell et al. 2014). The Federal Land Assistance, Management and Enhancement (FLAME) Act of 2009 mandated the development of a national cohesive wildland fire management strategy. The resulting national strategy addresses the challenges of managing vegetation and fuels, protecting homes and communities, managing human-caused fires, and effectively responding to wildfire (USDA and DOI 2014). Non-industrial private forest owners are critical to the success of this policy because they hold the majority of forestland in the U.S. Their forest management decisions can decrease fire-related losses by reducing the intensity of fires and the severity of resulting burns (Reinhardt et al. 2008). Landowners can mitigate fire risk through fuel treatment activities such as pruning, thinning, clearing brush, prescribed burning of surface fuels, and removing ladder fuels. They can also use flame-resistant or retardant materials for structures on their property and create strategic breaks in fuel sources (Yoder 2004; Amacher et al. 2005; 2006; Shafran 2008; Crowley et al. 2009; Prante et al. 2011).

Private forest owners may not carry out sufficient risk mitigation for a variety of reasons (Montgomery 2014; Kousky, Olmstead, and Sedjo 2012). They may be misinformed about wildfire risk (Talberth et al. 2006), have short-lived risk perceptions (McCoy and Walsh 2018); be excessively optimistic about government suppression (Fried et al. 1999), or believe that insurance will cover damages (Brenkert-Smith et al. 2006). Additionally, fire suppression is publicly supplied, and the costs are not generally tied to the risk contribution of individual landowners (Lueck 2012; Bradshaw 2012). Fuel reduction is costly and can entail aesthetic and amenity tradeoffs (McKee et al. 2004; Amacher et al. 2006). Furthermore, fire risk mitigation is a public good because the resulting reduction in fire risk is non-rival and non-excludable (Busby and Albers 2010). It also generates adjacency externalities because a landowner's fuel treatment activities benefit nearby landowners by reducing fire risk (Taylor et al. 2019; Crowley et al. 2009; Busby et al. 2012; 2013; Shafran 2008; Spyratos, Bourgeron, and Ghil 2007).

One policy approach for addressing the under-provision of risk mitigation is to provide landowners with incentives that elicit mitigation effort. Possible incentives include subsidies, compensation, cost-sharing for fuel treatment expenditures, and liability for inadequate fuel management. Understanding how landowners respond to such incentives, and how their responses may be conditioned on the behavior of neighboring landowners, is critical to the design of successful policy. Indeed, modeling of landowner behavior, spillover effects, and the effects of these incentives on wildfire risk has been an important area of research for many years

(Amacher et al. 2005; 2006; Mercer et al. 2007; Shafran 2008; Konoshima et al. 2008; Crowley et al. 2009; Busby and Albers 2010; Kousky, Olmstead, and Sedjo. 2012; Busby et al. 2013, Taylor 2019; Taylor et al. 2019).

In this paper we develop a model in which a fire manager uses incentives to elicit risk mitigation by landowners. The probability of wildfire occurrence and its potential damage are endogenous, as they depend on landowners' collective risk mitigation actions. We explicitly account for two key factors that drive landowners' fuel management choices: the public good nature of fire risk mitigation and the role played by nearby landowners' management decisions. We use a model of threshold provision of a public good to emphasize that fuel management on a given parcel will only make meaningful contributions to risk mitigation on the broader landscape if sufficient fuel management has taken place on nearby properties, and landowners account for this when making management decisions.

We use this setup to assess the effectiveness of two novel approaches to wildfire risk mitigation: voluntary agreements and liability rules for fuel management. Although voluntary agreements are used in the context of endangered species conservation, they have not been considered for wildfire risk management. Likewise, although negligence rules have long been the dominant liability rule for all sorts of torts, they have received only limited attention in the context of wildfire risk mitigation (Yoder 2004, 2012; Epstein 2012; Lauer 2017).

This paper makes several contributions to the wildfire risk mitigation literature. First, we use a novel approach to model the interaction between landowners in a landscape by using a model of threshold provision of a public good. In this model, a landowner's fuel management will make meaningful contributions to risk mitigation on the broader landscape only if enough additional landowners do so as well; that is, if total mitigation in the landscape reaches a given threshold. This modeling approach has not been used in the fire risk management literature before, but aligns well with evidence suggesting that landowners' risk mitigation decisions are influenced by those of their neighbors (Monroe and Nelson 2004; Brenkert-Smith et al. 2006; Butry and Donovan 2008; Konoshima et al. 2008; 2010; Shafran 2008; Busby et al. 2012; Taylor 2019; Taylor et al. 2019). Second, we examine the effectiveness and efficiency of voluntary mitigation agreements. This type of incentive has been studied in the literature on incentives for endangered species conservation on private land, but has not been considered in the context of wildfire risk mitigation before. Finally, we add to the literature on the use of liability rules for wildfire risk mitigation by examining the effectiveness and welfare impacts of this approach.

Our results suggest that the mitigation threshold is critical in determining the effectiveness and welfare effects of different incentive programs. When this threshold is relatively low, all the incentives, except a strict liability rule, can increase mitigation effort and expected welfare above a baseline. However, with a sufficiently high threshold and large deadweight loss of government cost sharing, only a voluntary agreement can elicit mitigation effort and increase expected welfare. Furthermore, effectiveness and welfare effects of different incentives are shown to depend on other factors as well, such as the bargaining power of the fire manager, the extent of cost-sharing, and the landowner's liability.

Background

Adjacency Externalities and Spatial Spillovers

Spatial externalities related to fuel management are particularly relevant in the context of fire risk mitigation on private land (Montgomery 2014). Some studies explicitly recognize the role of adjacency externalities (Crowley et al. 2009; Shafran 2008; Busby et al. 2013), and others focus on the effect of these spillovers on fuel management decisions for neighboring landowners

(Butry and Donovan 2008; Konoshima et al. 2008; 2010; Busby and Albers 2010; Busby et al. 2012; Lauer et al. 2017; Taylor 2019). Furthermore, survey data and empirical evidence suggest that landowners' risk mitigation decisions are influenced by those of their neighbors. For instance, interviews of landowners in Colorado (Brenkert-Smith et al. 2006), Minnesota, and Florida (Monroe and Nelson 2004) highlight the importance of the social context and norms in which risk, mitigation options, and implementation strategies are discussed and negotiated. Furthermore, homeowners noted that they view their own mitigation actions as having little value given fuel loads on neighboring properties (Brenkert-Smith et al. 2006). Shafran (2008) finds evidence of strategic interactions in risk mitigation. His results suggest that defensible space decisions of neighboring homes positively affect a homeowner's defensible space outcome. Finally, Taylor et al. (2019) examine the role of externalities in homeowners' decisions in wildland-urban interface communities in Nevada and find evidence that defensible space investments are strategic complements (benefits from investment are increasing in neighbors' investments) in several of the communities in their sample.

Incentives for Fire Risk Mitigation

The economics literature on fire risk mitigation has examined the effectiveness of several types of incentives using theoretical models and numerical simulations (Amacher et al. 2005; 2006; Crowley et al. 2009), as well as laboratory experiments (McKee et al. 2004; Talberth et al. 2006; Prante et al. 2011). Results from these studies suggest that incentive policy can be effective in inducing private risk mitigation, but that there is potential for public policy crowding out private mitigation (McKee et al. 2004; Crowley et al. 2009; Prante et al. 2011). Taylor et al. (2019) use econometric estimates to simulate the effect of tipping policies that provide incentives for early investors in defensible space and find that such policies are unlikely to encourage substantial additional investment when investments are strategic complements.

In recent years, federal and state legislation has also been proposed or implemented to set up liability rules in the context of wildfire risk. At the federal level, the Enhanced Safety from Wildfire Act, proposed in 2005 (but never passed), would have established stricter negligence standards for fuel conditions on private and federal land (Lauer 2017). Similarly, some states have established increased liability against landowners who do not carry out adequate vegetation clearing practices. For instance, the Oregon Forestland-Urban Interface Fire Protection Act allows the state to collect up to $100,000 in suppression costs from a landowner if a wildfire originates on their property and spreads through an area that does not meet fuel-reduction standards (Bradshaw 2010; Legislative Counsel Committee 2018).

The recent legislation can be viewed as attempts to tighten the liability rules for wildfire management under the exiting tort law (Epstein 2012). Under the widely adopted joint and several liability rule (referred to as the strict liability rule henceforth), each tortfeasor is liable for all of the plaintiff's damages, regardless of his degree of fault or mitigation effort. In contrast, under the comparative negligence doctrine (referred to as the negligence standard henceforth), a tortfeasor may be responsible for only a portion of the damage depending on his degree of fault or mitigation effort. Although these liability rules have long been the dominant standards for all sorts of torts, including fire-related torts, relatively few studies have examined their effectiveness as an incentive for wildfire risk mitigation. Noticeable exceptions include Yoder et al. (2003) and Yoder (2004), which discuss the role of liability in the context of escaped prescribed fires, and Lauer (2017), which examines optimal timber harvest and fuel treatment decisions for two landowners who face liability regulations. Lauer (2017) finds that the form of the liability rule matters: a negligence standard incentivizes fuel treatment, whereas a strict liability rule provides more complicated incentives that can lead to less fuel treatment.

Finally, while voluntary agreements have been studied in the context of pollution abatement (Segerson and Miceli 1998; Wu and Babcock 1999; Maxwell and Decker 2006; Fleckinger and Glachant 2011) and endangered species conservation (Langpap and Wu 2004; 2017), they have not been applied in the context of fire risk management.

Policy Scenarios

We consider a baseline scenario and four additional policy scenarios for eliciting voluntary wildfire risk mitigation effort. In the baseline, landowners pay a "forest patrol assessment" and receive firefighting services from the local forest protection district and state forestry agencies at no additional cost to them (Oregon Department of Forestry 2007). The regulator does not assign liability or provide additional incentives. This scenario serves as the fallback scenario for both the policymaker and the landowners. Specifically, the policymaker does not accept any management policy that leads to lower expected social welfare than the baseline, and the landowners do not voluntarily mitigate fire risk if it results in higher expected cost. The four policies proposed to create incentives for fire risk mitigation are:[2]

a. Cost-sharing (CS): Landowners choose a level of risk-mitigation effort and the policymaker covers a percentage of the mitigation costs.
b. Strict Liability (SL): Landowners are liable for damage caused by a fire originating on their land, regardless of their risk mitigation effort.
c. Negligence Standard (NS): Landowners are liable for damage caused by a fire originating on their land if their mitigation effort is below the due standard of care.
d. Voluntary Agreements (VA): The policymaker and the landowner negotiate the level of risk-mitigation effort. If an agreement is reached, the policymaker guarantees to the landowner

that he will not face any additional regulation, liability or cost in the future. However, if an agreement is not reached, he must pay a higher rate of forest patrol assessment to cover the cost of firefighting services.

The Model

Consider a landscape with n landowners faced with wildfire risk.[3] The probability of wildfire occurrence on the landscape and its potential damage depend on the landowners' collective risk mitigation actions. Let q_i denote landowner i's risk-mitigation effort. To fix ideas, we assume that q_i represents mechanical fuel reduction treatments, which may include flailing, chipping, breaking, thinning, raking, and tree removal, depending on individual settings and objectives. Then $Q = \sum_{i=1}^{n} q_i$ is the total amount of effort for all landowners, $Q_{-i} = \sum_{j \neq i} q_j$ is total effort for all landowners except landowner i, and $Q_{-i} + q_i = Q$. The spatial configuration of mitigation effort may affect its effectiveness. In such a case, we can modify the definition of aggregate mitigation as $Q = \sum_{i=1}^{n} w_i q_i$, where $(w_1, \dots, w_n)$ are the spatial weights, which reflect the importance of spatial configuration of mitigation efforts. To simplify notation, we reinterpret q_i as measuring the weighted effort in such cases, instead of introducing spatial weights explicitly.

Wildfire occurrence is uncertain. Let $p_{ik}^{F}(q_i, q_k, Q)$ denote the probability that a fire ignites on parcel i and spreads to parcel k. We assume a landowner can undertake mitigation efforts to reduce both ignition risk and spread risk. However, individual landowners' averting effort may not be effective at preventing fire damage if other landowners in the landscape do not mitigate risk as well. For instance, even when a landowner has reduced fuels on his property, fire will spread through nearby properties that have not carried out similar management, and damage the managed property as well. To represent this setting, let $D_i^F(q_i, Q_{-i})$ denote the amount of damage to landowner i if a wildfire occurs on his parcel. Then landowner i's expected wildfire damage equals

$$D_i(q_i, Q_{-i}) = \sum_{k=1}^{n} p_{ki}^F(q_k, q_{i,} Q) D_i^F(q_i, Q_{-i}).$$

which depends not only on landowner i's mitigation effort, but also on the total averting effort from other landowners. When the total averting effort Q is below a certain threshold, a small additional effort by landowner i may have no effect on the probability of wildfire risk, particularly when there are a large number of landowners in the landscape. Likewise, when the total averting effort is below a certain threshold, individual landowners' averting effort may not be effective at preventing fire damage because wildfire may spread from nearby properties. This suggests that there is a minimum amount of total effort, $\bar{Q}$, below which additional effort is insufficient to have any effect on the expected wildfire damage, and above which additional effort reduces the expected damage:

$$\frac{\partial D_i(q_i, Q_{-i})}{\partial q_i} = \begin{cases} = 0 & if\ Q < \bar{Q} \\ < 0 & if\ Q \geq \bar{Q} \end{cases}. \tag{1}$$

In addition, we assume when $Q \geq \bar{Q}$, risk-mitigation effort has a larger marginal effect on expected damages locally, which implies $\frac{\partial(p_{ki}^F D_i^F)}{\partial q_i} < \frac{\partial(p_{ik}^F D_k^F)}{\partial q_i} \leq 0$ and $\frac{\partial(p_{ki}^F D_i^F)}{\partial q_i} < \frac{\partial(p_{ki}^F D_i^F)}{\partial q_k} \leq 0$ for any $k \neq i$. This occurs because a landowner's mitigation effort reduces both the risk of ignition and spread and damages to his property if a wildfire occurs on his parcel. The marginal effect of mitigation tends to decrease with increasing effort. Therefore, we assume $\frac{\partial^2(p_{ki}^F D_i^F)}{\partial q_i^2} > 0, \frac{\partial^2(p_{ik}^F D_k^F)}{\partial q_i^2} > 0.$ However, the mitigation of other landowners tends to make landowner i*'s* effort more effective, which implies $\frac{\partial^2(p_{ki}^F D_i^F)}{\partial q_i \partial q_k} \leq 0$ and $\frac{\partial^2(p_{ik}^F D_k^F)}{\partial q_i \partial q_k} \leq 0$ for any $k \neq i$ (*i.e.*, an increase in q_k cannot make $\frac{\partial(p_{ki}^F D_i^F)}{\partial q_i}$ and $\frac{\partial(p_{ik}^F D_k^F)}{\partial q_i}$ less negative).

It is important to note that the case of no threshold or a "soft kink" (*i.e.*, $D_i(q_i, Q_{-i})$ is quite, but not perfectly, flat initially when Q is small but then gets steeper as Q increases) is a special case of the current specification for $\overline{Q} = 0$.

To get an intuitive sense of what determines the level of the threshold, it may help to think of the level of effort as acres of forest treated for fuel reduction. In this case, the threshold would correspond to the acreage of forest treated beyond which additional treatment lowers wildfire damage. Whether a particular threshold is high would then depend on factors such as the weather, underlying vegetation, and government mitigation effort. For instance, Taylor et al. (2019) show that the nature of the externalities associated with defensible space investments in Nevada depend on the predominant vegetation. Additionally, if the weather is extremely dry and little mitigation takes place on public forests, it would take a considerable amount of effort to lower the probability of wildfire and damages, and the threshold would be relatively high. The mitigation threshold also depends on the spatial pattern of development. When the landscape features a relatively densely populated wildland-urban-interface community, a concentrated fuel treatment effort could effectively reduce the risk of large wildfire damage. However, when the same population is scattered over the landscape, more widespread mitigation efforts will be needed to reduce the expected wildfire damage to individual landowners. In this case, the mitigation threshold will be relatively high. It is worth noting that, while policy makers might be able to ascertain whether the threshold $\overline{Q}$ is relatively high or low based on the factors just discussed, actually measuring the threshold would likely be unfeasible.

Landowner Decisions

Each landowner is assumed to choose risk-mitigation effort to minimize the sum of mitigation cost, expected fire damages, and expected liability. The mitigation cost function for landowner i is $C_i(q_i)$, with $C_i(0) = C_i'(0) = 0$, $C_i'(q_i) > 0$, and $C_i''(q_i) > 0$ for $q_i > 0$. To incorporate cost-sharing into this framework, let $\gamma \in [0,1]$ be the portion of mitigation costs covered by the policymaker.

When a wildfire ignites on a landowner's property and then spreads to other landowners' parcels, he may be liable for all or a portion of damage to other landowners depending on liability rules and his mitigation effort. Let $\theta_i(q_i)$ denote the portion of damages to other landowners that landowner *i* is liable for when the damages are caused by a fire that ignites on landowner *i*'s property. Then under a strict liability rule, $\theta_i(q_i) = 1$ for any q_i, while under a negligence standard, $\theta_i(q_i) = 1$ if $q_i < \bar{q}_i$, $\theta_i(q_i) = 0$ if $q_i \geq \bar{q}_i$, where $\bar{q}_i$ is the due standard of care. Thus, landowner *i*'s expected liability equals

$$ED_{-i}(q_i|Q_{-i}) = \theta_i(q_i) \sum_{k \neq i} [p_{ik}^F(q_i, q_{k,} Q)\, D_k^F(q_k, Q_{-k})].$$

Under a liability rule, a landowner may also be entitled to receive compensation for fire started on other landowners' parcels and spread to his parcel. Specifically, landowner *i*'s expected compensation equals

$$ER_{-i}(q_i|Q_{-i}) = \sum_{k \neq i} \theta_k(q_k) p_{ki}^F(q_k, q_{i,} Q) D_i^F(q_i, Q_{-i}).$$

Each landowner chooses risk-mitigation effort to minimize the sum of mitigation cost, expected fire damages after compensation, and expected liability:

$$EC_i(q_i|Q_{-i}) = (1-\gamma)C_i(q_i) + D_i(q_i, Q_{-i}) - ER_{-i}(q_i|Q_{-i}) + ED_{-i}(q_i|Q_{-i}) \qquad (2)$$

where γ is the percentage of mitigation costs shared by the policymaker. When $\theta_i(q_i) = 0$ for any $q_i \geq 0$, $EC_i(q_i|Q_{-i}) = (1-\gamma)C_i(q_i) + D_i(q_i, Q_{-i})$. This corresponds to the prevailing situation for unintentional wildfire ignition, where each landowner is liable for damage to their own property and only their property regardless of fire sources. Under a strict liability rule, $\theta_i(q_i) = 1$ for any q_i, $D_i(q_i, Q_{-i}) - ER_{-i}(q_i|Q_{-i}) + ED_{-i}(q_i|Q_{-i}) = \sum_k [p_{ik}^F(q_i, q_{k,} Q)\, D_k^F(q_k, Q_{-k})]$, which represents the expected total damages to all landowners caused by fire that ignites on landowner i's parcel and spreads to other landowners' parcels.

Social Welfare

When making policy decisions, the policymaker considers both benefits and costs of risk-mitigation efforts. The benefits include the potential fire damage avoided and other benefits from mitigation activities, such as improvement of wildlife habitat. The costs include landowners' out-of-pocket and opportunity costs of effort and deadweight losses from raising funds for any government expenditures.

Let $B_i(q_i)$ denote other social benefits from landowner i's effort, with $B_i(q_i)$ assumed to be increasing, concave, twice differentiable, and normalized such that $B_i(0) = 0$.[4] The policymaker's expected social welfare from landowner i's risk-averting effort equals the net benefit from the mitigation effort minus the expected fire damages and any social cost of policy:

$$EW_i = B_i(q_i) - (1 + \delta\gamma)C_i(q_i) - \sum_k [p_{ik}^F(q_i, q_k, Q)\, D_k^F(q_k, Q_{-k})] \tag{3}$$

where δ represents the deadweight loss associated with raising tax revenue for cost sharing.[5] The last term in (3) presents the expected total damages to all landowners caused by a fire that ignites and starts on landowner i's parcel. When $B_i(q_i) = 0$, $EW_i = -EC_i(q_i|Q_{-i})$ under a strict liability rule, and maximizing social welfare is equivalent to minimizing the mitigation costs plus the expected fire damages the landowner is liable for.

The baseline, cost sharing, and liability scenarios can be written as special cases of the above general setup, in which the parameters γ and $\theta = (\theta_1(q_1), \dots, \theta_N(q_n))$ take on specific values:

- Baseline (BL): $\gamma = \theta = 0$.
- Cost-sharing (CS): $0 < \gamma < 1, \theta = 0$.

- Strict liability (SL): $\gamma = 0, \theta_i(q_i) = 1$ for any q_i.
- Negligence standard (NS): $\gamma = 0$, $\theta_i(q_i) = 1$ if $q_i < \overline{q_i}, \theta_i(q_i) = 0$ if $q_i \geq \overline{q_i}$.

To compare the equilibrium outcomes under different policies, we first derive the equilibrium outcomes under the general setup and then examine how the equilibrium outcomes change with parameters γ and θ.

Equilibrium Outcomes

In this section, we derive the equilibrium outcomes for a given set of policy parameters (γ, θ), where $\theta_i(q_i) = 1$ or 0 for any q_i. Therefore, the results derived this section directly apply to the baseline, cost-sharing, and strict liability scenarios. Based on these results, we then explore the equilibrium outcomes under the negligence standards and voluntary agreements scenarios. We assume the landscape includes many small landowners. Each makes wildfire-mitigation decisions taking other landowners' choices as given. In this game $\boldsymbol{q} = (q_1, \ldots, q_n)$ is a Nash equilibrium if, given Q_{-i}, q_i is landowner *i's* best choice, i.e.,

$$q_i = q_i(Q_{-i}) = \text{argmin}_{q_i}\{EC_i(q_i|Q_{-i})\} \tag{4}$$

We start by considering equilibrium outcomes under two special cases: a) $\overline{Q} = +\infty$ and $p_i'(q_i) = 0$ for any Q, and b) $\overline{Q} = 0$, and $p_i'(q_i) < 0$ for all Q, and then focus on the general case of $0 < \overline{Q} < +\infty$. The equilibrium outcomes under the two special cases are summarized in lemma 1 (all proofs are in the appendix).

Lemma 1:

i. *If* $\overline{Q} = +\infty, (q_1, \ldots, q_n) = (0, \ldots, 0)$ *is the only Nash equilibrium, and the aggregate mitigation effort equals* $Q(\gamma, \theta) = \sum_{i=1}^{n} q_i = 0$.

ii. *If* $\overline{Q} = 0$, *there is a unique Nash equilibrium,* $(q_1^*, \ldots, q_n^*) = \left(q_1^c(\gamma, \theta), \ldots, q_n^c(\gamma, \theta)\right)$, *with*

$q_i^c(\gamma, \theta) > 0$ *for all i and defined by* $\frac{\partial EC_i(q_i|Q_{-i})}{\partial q_i} = 0, i = 1, \dots, n.$

The equilibrium outcome under case (*i*) is not surprising; when mitigation is ineffective in reducing wildfire risk, no landowner is willing to exert any risk-mitigation effort. In case (*ii*), the mitigation threshold $\overline{Q}$ is zero, which implies that the marginal benefit of risk mitigation (reduction in expected damage and liability) is positive for $Q_{-i} \geq 0$, while the marginal cost $C_i'(q_i)$ is assumed to be minimal when q_i approaches zero. Therefore, each landowner is willing to carry out some mitigation, regardless of other landowners' effort level. Both of these are special cases. In practice, in a landscape characterized by many small landowners, the risk-averting threshold $\overline{Q}$ is positive and finite.

To derive equilibrium outcomes for this general case, we define $q_i^{max}(\gamma, \theta)$ as the maximum q_i that solves

$$EC_i(q_i|0) \leq EC_i(0|0) \tag{5}$$

That is, $q_i^{max}(\gamma, \theta)$ is the maximum effort that landowner *i* is willing to exert to provide the public good by himself. Figure 1 shows the case of $q_i^{max}(\gamma, \theta) > 0$. We assume landowners prefer more mitigation if doing so does not increase their expected costs. We define $q_{max}(\gamma, \theta)$ as

$$q_{max}(\gamma, \theta) = \max\{q_1^{max}(\gamma, \theta), \dots, q_n^{max}(\gamma, \theta)\}.$$

Similarly, we define $q_i^{min}(\gamma, \theta)$ as the minimum q_i that satisfies

$$EC_i\left(q_i \middle| Q_{-i}^c(\gamma, \theta)\right) \leq EC_i\left(q_i^c(\gamma, \theta) \middle| Q_{-i}^c(\gamma, \theta)\right) \tag{6}$$

$q_i^{min}(\gamma, \theta)$ represents the minimum effort the landowner would carry out given the effort by other landowners $Q_{-i}^c(\gamma, \theta)$. If $q_i^{min}(\gamma, \theta) = q_i^c(\gamma, \theta)$, landowner *i* will have no incentive to deviate from $q_i^c(\gamma, \theta)$ given the effort by other landowners $Q_{-i}^c(\gamma, \theta)$. We define $Q_{min}(\gamma, \theta)$ as:

$$Q_{min}(\gamma,\theta) = \min\{[q_1^{min}(\gamma,\theta) + Q_{-1}^c(\gamma,\theta)], \ldots, [q_n^{min}(\gamma,\theta) + Q_{-n}^c(\gamma,\theta)]\}$$

which is the minimum total averting effort that would result given the effort by other landowners $Q_{-i}^c(\gamma,\theta)$. When the total number of landowners is sufficiently large, $Q_{min}(\gamma,\theta) > q_{max}(\gamma,\theta)$, which we assume henceforth. With these definitions, we can derive the following result:

Proposition 1. *The equilibrium outcomes are as follows:*

i. *If $\bar{Q} > Q_{min}(\gamma,\theta)$, $q_i^* = 0$ for all i is the only Nash equilibrium, and the aggregate mitigation effort equals $Q^*(\gamma,\theta) = \sum_{i=1}^n q_i^* = 0$.*

ii. *If $\bar{Q} \le q_{max}(\gamma,\theta)$, $q_i^* = q_i^c(\gamma,\theta) > 0$ for all i is the only Nash equilibrium and the aggregate mitigation effort equals $Q^*(\gamma,\theta) = \sum_{i=1}^n q_i^c(\gamma,\theta) > 0$.*

iii. *If $q_{max}(\gamma,\theta) < \bar{Q} \le Q_{min}(\gamma,\theta)$, there are exactly two Nash equilibria: One at $q_i^* = q_i^c(\gamma,\theta) > 0$ for all i and another at $q_i^* = 0$ for all i.*

As in the classic threshold model of public good provision (Andreoni 1998), the magnitude of the threshold determines the equilibrium outcomes. To understand the logic behind Proposition 1, note that when the risk-averting threshold $\overline{Q}$ is positive and finite, each landowner's expected cost function $EC_i(q_i|Q_{-i})$ has two local minimization points, one at $q_i = 0$ and the other at $q_i^c(\gamma,\theta)$ (see figure 1). When $\bar{Q} > Q_{min}(\gamma,\theta)$, $q_i = 0$ is a global minimization point of $EC_i(q_i|Q_{-i})$ for any Q_{-i} and therefore $(q_1^*, \ldots, q_n^*) = (0, \ldots, 0)$ is the only Nash equilibrium. When $\bar{Q} \le q_{max}(\gamma,\theta)$, $q_i^* = q_i^c(\gamma,\theta)$ is a global minimization point of $EC_i(q_i|Q_{-i})$ for any Q_{-i} and therefore $q_i^* = q_i^c(\gamma,\theta)$ for all *i* is the only Nash equilibrium. When $q_{max}(\gamma,\theta) < \bar{Q} \le Q_{min}(\gamma,\theta)$, $q_i = 0$ is a global minimization point of $EC_i(q_i|Q_{-i})$ for any *i* when $Q_{-i} = 0$ and $q_i^* = q_i^c(\gamma,\theta)$ is the global minimization point of $EC_i(q_i|Q_{-i})$ when $Q_{-i} = Q_{-i}^c$. In this case, we have two Nash equilibria.

To further understand the intuition behind proposition 1, consider the reaction functions of two landowners. When the risk-averting threshold is large enough ($\bar{Q} > Q_{min}$), as shown in panel (a) of figure 2, the reaction functions for the two landowners intersect only at (0, 0), and in equilibrium neither landowner carries out any mitigation effort. With a sufficiently high threshold, individual landowners cannot decrease wildfire risk. Hence, risk-mitigation effort does not pay off for individual landowners, and no risk mitigation is the preferred choice.

When the risk-averting threshold is sufficiently low ($\overline{\mathrm{Q}} < q_{max}$), as shown in panel (b) of figure 2, the reaction functions of the two landowners intersect only at (q_1^c, q_2^c). The no-mitigation scenario is no longer an equilibrium, because there is at least one landowner who engages in risk-mitigation effort to shift the equilibrium away from the no-effort scenario ($q_1(0) > q_1^c$ and/or $q_2(0) > q_2^c$).

An interesting case is the intermediate one, where the threshold is large enough to make the no-mitigation scenario possible, but not so large as to prevent risk-mitigation effort from occurring ($q_{max} < \bar{Q} \leq Q_{min}$). In this case, the reaction functions for the two landowners intersect at both (q_1^c, q_2^c) and (0, 0). This scenario is shown in panel (c) of figure 2. When all other landowners engage in preemptive risk-mitigation, each landowner's best response is to do the same. Likewise, when no other landowners engage in risk-mitigation, each landowner's best response is also to do nothing.

The intuition behind these results is straightforward. When risk-mitigation effort is not effective, it increases the expected cost of wildfire (because fire destroys the risk-mitigation investment), and landowners will not engage in mitigation behavior. On the other hand, if risk-mitigation effort lowers the expected cost of wildfire, landowners will engage in mitigation behavior. Which of these scenarios occurs depends on how high the risk-mitigation threshold is and on the opportunity costs of risk-mitigation effort.

In the following sections, we examine how $Q_{min}(\gamma,\theta)$, $q_{max}(\gamma,\theta)$, and the equilibrium efforts of individual landowners $\left(q_1^*(\gamma,\theta),\ldots,q_n^*(\gamma,\theta)\right)$ change with (γ,θ). This will enable us to compare the equilibrium outcomes under alternative incentive programs.

Equilibrium Outcomes under Alternative Incentive Programs

Cost Sharing

Cost sharing (CS) corresponds to the case where $0<\gamma<1$ and $\theta=0$, while the baseline (BL) corresponds to $\gamma=\theta=0$. Hence, to understand the effect of cost sharing on equilibrium outcomes, we start by examining how the cost-sharing percentage γ affects q_{max} and Q_{min}.

By definition, $q_i^c(\gamma,0)=\text{argmin}_{q_i}\{EC_i(q_i|Q_{-i}^c)\}>0$, and it is straightforward to verify that $\partial q_i^c(\gamma,0)/\partial\gamma>0$. This suggests that cost sharing increases the mitigation effort landowners will carry out if positive mitigation is an equilibrium. As proved in the appendix, we can further show that $\partial q_i^{max}(\gamma,0)/\partial\gamma>0$ if $q_i^{max}(\gamma,0)>0$. This suggests that cost sharing increases the maximum effort that an individual landowner is willing to exert provided that he is willing to produce the public good by himself. Finally, by definition if $q_i^{min}(\gamma,\theta)$ is positive, then $q_i^{min}(\gamma,\theta)$= $q_i^c(\gamma,0)$, and it follows that $\partial q_i^{min}(\gamma,0)/\partial\gamma>0$ if $q_i^{min}(\gamma,0)>0$. Together, these findings imply the following result.

Lemma 2. $q_{max}^{CS}\geq q_{max}^{BL}$ and $Q_{min}^{CS}>Q_{min}^{BL}$.

In addition, when γ is sufficiently large, $\bar{Q}\leq q_{max}(\gamma,0)$. Combining these results with proposition 1, we obtain the following:

Corollary 1.

i. *Cost sharing reduces the likelihood of a no-mitigation equilibrium relative to the baseline* *and increases the mitigation effort of individual landowners when positive mitigation is an equilibrium:* $q_i^c(\gamma, 0) > q_i^c(0, 0)$ *for any* $\gamma > 0$.

ii. *When cost sharing is sufficiently large,* $q_i^* = q_i^c(\gamma, 0) > 0$ *for all i is the only Nash equilibrium, and the mitigation level increases with cost sharing.*

Cost sharing increases both q_{max} and Q_{min}, making the condition for an equilibrium without mitigation ($\bar{Q} > Q_{min}$) less likely and the condition for an equilibrium with positive mitigation ($\bar{Q} \leq q_{max}$) more likely. Furthermore, cost sharing can prevent the no-mitigation equilibrium from happening when the proportion of the cost shared is sufficiently large. When positive mitigation is an equilibrium outcome, cost sharing can increase the level of individual landowners' mitigation efforts, reducing the expected wildfire damage. Finally, when the risk-mitigation effort threshold is in the intermediate range, a cost sharing incentive can shift the outcome from a no-mitigation equilibrium to an equilibrium with positive risk-mitigation effort. This happens when cost sharing sufficiently raises the maximum mitigation effort level at which landowners are willing to switch from no action to providing mitigation effort. To understand the intuition behind these results, it is important to note that a landowner is willing to exert more effort to shift from the no-mitigation equilibrium to a positive mitigation equilibrium because cost-sharing on mitigation expenditures reduces his expected cost.

Strict Liability

Strict liability (SL) corresponds to the case where $\gamma = 0$ and $\theta_i(q_i) = 1$ for any q_i, i =1, …, n. Note that, in terms of liability, the baseline ($\theta_i(q_i) = 0$) corresponds to an immunity rule, in which the landowner is immune to liability regardless of his mitigation effort. To understand the effect of a strict liability incentive on equilibrium outcomes, we examine how the liability affects q_{max} and Q_{min}. We obtain the following result.

Lemma 3. $q_{max}^{SL} \leq q_{max}^{BL}$ and $Q_{min}^{SL} \leq Q_{min}^{BL}$.

Together with proposition 1, these results imply:

Corollary 2.

i. *A strict liability rule cannot reduce the likelihood of no-mitigation being the only equilibrium, nor can it increase the likelihood of positive mitigation being the only equilibrium relative to the baseline.*

ii. *A strict liability rule reduces the mitigation effort of individual landowners relative to the baseline when positive mitigation is an equilibrium:* $q_i^c(\theta = 1) < q_i^c(\theta = 0)$.

Corollary 2 suggests that a strict liability rule is ineffective and can even be counterproductive at eliciting risk-mitigation effort. These results can be understood by examining how landowners interact with each other and respond to incentives provided by a strict liability rule. For example, if a landowner reduces his mitigation effort under an immunity rule, his neighbors may have incentives to invest more in self-protection because of the elevated risk. The neighbors' responses may in turn lead the landowner to further adjust his mitigation effort. This suggests that the equilibrium levels of mitigation from individual landowners depend on how their efforts affect each other's expected losses and reciprocity. Here we assume each landowner is better at reducing his own expected losses (others' liabilities) than reducing others' losses (his own liability), because his mitigation effort reduces both the risk of ignition and spread and expected damages to his property if a wildfire occurs on his parcel. Consequently, the expected marginal net benefit from mitigation for each landowner is lower under a strict liability rule than under an immunity rule (the baseline). Therefore, each landowner undertakes less mitigation effort under a strict liability rule when positive mitigation is an equilibrium.

The reduced mitigation level from each landowner if he undertakes a positive mitigation effort means that the total mitigation level would be lower, and therefore would be less likely to reach the threshold needed for effective mitigation. As a result, a no-mitigation equilibrium is more likely to occur, while a positive-mitigation equilibrium is less likely to occur.

Negligence Standard

A negligence standard (NS) corresponds to the case where $\theta_i(q_i) = 0$ or 1 and $\gamma = 0$. Landowner *i* is liable for damage to the remaining landowners ($\theta_i(q_i) = 1$) if he does not meet the due standard of care $\overline{q_i} > 0$, but is not liable ($\theta_i(q_i) = 0$) if he meets this due standard. Thus, the expected cost for $q_i < \overline{q_i}\ \forall i$ corresponds to the cost from the strict liability scenario, whereas the expected cost for $q_i \geq \overline{q_i}\ \forall i$ corresponds to the baseline scenario. This suggests that the mitigation effort under a negligence standard, q_i^{NS}, depends on the due standard of care $\overline{q_i}$, *i* =1, …, *n*. For sufficiently high due standards of care, the equilibrium outcome will be the same as in the strict liability scenario; and for sufficiently low due standards of care, the equilibrium outcome will be close to the one from the baseline. The economic theory of tort law assumes that the optimal due standard of care is equivalent to the efficient level of care (Miceli 2004).[6] In our context this means

$$(\overline{q}_1^* \dots, \overline{q}_n^*) = argmax\{\textstyle\sum_{i=1}^{n} EW_i\} \tag{7}$$

We assume the due standards of care are set at the efficient levels, *i.e.,* $\overline{q_i} = \overline{q}_i^*\ \forall i$.

It is important to note that the efficient level of care is determined by both benefits and costs of risk-mitigation efforts. The benefits include both the potential fire damage avoided and environmental benefits from mitigation activities, such as improvement of wildlife habitat. When landowners do not take these "external benefits" into consideration when making mitigation decisions, they tend to mitigate less than the efficient level. Therefore, the mitigation levels in the baseline are assumed to be below the efficient levels, *i.e.,* $\overline{q}_i^* > q_i^{BL}\ \forall i$.

To illustrate the mitigation level under a negligence standard relative to the mitigation level under a strict liability rule, let $\tilde{q}_i$ be the maximum q_i satisfying $EC_i^{SL}\left(q_i^{SL}|Q_{-i}^{SL}\right) \geq EC_i^{BL}(q_i|Q_{-i}^{BL})$. As shown in Figure 3, if $\overline{q_i} > \tilde{q}_i\ \forall i,$ the cost minimizing mitigation under a negligence standard is $q_i^{NS}\ = q_i^{SL}\ \forall i$. If $\overline{q_i} < \tilde{q}_i\ \forall i$, the cost minimizing effort is to just meet the due standard of care (*i.e.*, $q_i^{NS}\ = \overline{q_i}$). Note that in figure 3, the distance between the expected cost in the baseline and the expected cost under a strict liability widens as the mitigation level increases because although both the expected liability and the expected compensation decrease with the mitigation effort, the latter decreases faster because mitigation has a larger local effect.

To understand the effect of a negligence standard on equilibrium outcomes, we examine how this incentive affects q_{max} and Q_{min}. We derive the following result.

Lemma 4. *If* $q_i^{BL} < \overline{q_i} < \tilde{q}_i\ \forall i,\ Q_{min}^{NS} > Q_{min}^{BL} \geq Q_{min}^{SL};\ q_{max}^{NS} > q_{max}^{BL} \geq q_{max}^{SL}$.

Together with proposition 1, these results imply:

Corollary 3. *Suppose* $q_i^{BL} < \overline{q_i} < \tilde{q}_i$.

i. *A negligence standard reduces the likelihood of a no-mitigation equilibrium compared to the baseline and the strict liability scenario.*

ii. *The equilibrium mitigation effort under a negligence standard is greater than the level under a strict liability rule and the level in the baseline.*

Corollary 3 suggests that when $q_i^{BL} < \overline{q_i} < \tilde{q}_i\ \forall i$, a negligence standard will increase the mitigation level and reduce the likelihood of a no-mitigation equilibrium relative to the baseline and strict liability. This scenario will occur when fire risk mitigation does not generate a substantial amount of environmental benefits (so that $\overline{q_i}$ is relatively low) and the expected cost increases slowly as the mitigation level increases (so that $\tilde{q}_i$ is relatively large). In this scenario, each landowner will choose to just meet the efficient due standard of care, and social welfare is maximized.

However, as shown in the proof of corollary 3, when $\overline{q_i} > \tilde{q}_i$, a negligence standard will lead to the same outcome as a strict liability rule. In this scenario, a negligence standard will be ineffective and can even be counterproductive at increasing mitigation effort above the baseline level. Specifically, a negligence standard cannot reduce the likelihood of no-mitigation equilibrium and, when positive mitigation is an equilibrium, will reduce the mitigation effort of individual landowners. An important implication of these results is that when it is costly to increase mitigation (so that $\tilde{q}_i$ is small) and mitigation generates a substantial amount of environmental benefits (so that $\overline{q_i} > \tilde{q}_i$), a policymaker cannot rely on a negligence standard to achieve the efficient level of mitigation. A policymaker could still use a negligence standard to induce mitigation above the baseline level by setting the due standard of care $\overline{q_i}$ at $\tilde{q}_i > q_i^{BL}$. Although this mitigation effort is below the efficient level, it would be an improvement over the baseline level because each landowner would choose to meet the due standard of care.

In a standard model without thresholds and environmental benefits from mitigation (*i.e.* $B_i(\cdot) = 0$), strict liability would give an efficient outcome, and a negligence rule that set the due standard of care $\overline{q_i}$ at the efficient level (*i.e.*, at q_i^{SL}) would not change the mitigation level from the baseline because when $\overline{q_i} = q_i^{SL}$, each landowner's expected cost is minimized at q_i^{BL}, which is above the efficient level q_i^{SL} (see Figure 3). This occurs because landowners have more incentives to protect themselves when the responsible party is not held liable for damages if he meets the due standard of care. However, if the landowners' efforts generate additional benefits, such as wildlife habitat improvements (*i.e.*, $B_i(\cdot) \neq 0$), strict liability will generate too little mitigation effort because landowners may not take the "externalities" into consideration when making mitigation decisions, and a negligence standard would be able to improve social welfare if the due standard of care is set at $\tilde{q}_i$.

Voluntary Agreements

Voluntary agreements (VA) are commonly used to elicit conservation of endangered species on private land (Langpap and Wu 2017). This incentive could also be used to encourage landowners to mitigate wildfire risk. Under this approach, the policymaker and a landowner negotiate over the minimum amount of fire risk mitigation effort carried out on the parcel. If they reach an agreement, the policymaker provides assurances that the landowner will not face any additional regulation or liability; otherwise, he must pay a higher rate of forest patrol assessment.[7] Thus, the landowner's expected cost function equals

$$EC_i^{VA}\left(q_i^{VA}\middle|Q_{-i}^{VA}\right) = \begin{cases} C_i\left(q_i^{VA}\right) + D_i\left(q_i^{VA}, Q_{-i}^{VA}\right) & \text{if a VA is reached} \\ EC_i\left(q_i^{BL}\middle|Q_{-i}^{BL}\right) + \Delta_i & \text{otherwise} \end{cases} \tag{8}$$

where $\Delta_i > 0$ denotes the additional forest patrol assessment the landowner must pay if an agreement is not reached.

The policymaker is assumed to maximize expected social welfare from fire risk mitigation. The payoffs in the absence of an agreement correspond to those of the baseline scenario plus benefits from the additional forest patrol assessment $W(\sum \Delta_i)$. Hence, the policymaker's expected social welfare from landowner *i*'s risk-averting effort equals $EW^0 \equiv \sum_i EW_i\left(q_i^{BL}\middle|Q_{-i}^{BL}\right) + W(\sum \Delta_i)$ without a VA and equals $EW_i\left(q_i^{VA}\middle|Q_{-i}^{VA}\right)$ with a VA.

We use Nash bargaining to model the negotiation process underlying a VA. Specifically, the equilibrium outcome $\{q_i^{VA}, i = 1, \ldots, n\}$ is determined by the simultaneous solutions to the following *n* Nash programs:

$$\max_{q_i^{VA}} \left[\sum_{i=1}^{n} EW_i\left(q_i^{VA} \middle| Q_{-i}^{VA}\right) - EW^0\right]^{\alpha_i}\left[EC_i^0 - EC_i^{VA}\left(q_i^{VA} \middle| Q_{-i}^{VA}\right)\right]^{1-\alpha_i}, i=1, \ldots, n \tag{9}$$

where α_i is the policymaker's bargaining power (Fleckinger and Glachant 2011), which reflects the weight placed on the policymaker's net gains in the bargaining process. In this context, bargaining power could be derived from the fact that fire suppression and fighting are publicly supplied and threat of requiring landowners to pay more to cover such costs through, *e.g.,* a higher rate of forest patrol assessment, will lead landowners to carry out more mitigation effort. EW^0 and $EC_i^0 = EC_i(q_i^{BL} | Q_{-i}^{BL}) + \Delta_i$ are disagreement outcomes for the policymaker and the landowner, respectively. These *n* programs are, in general, not independent; the solution to one program may depend on the solutions to the other *n*-1 programs.

The equilibrium outcomes under VA are summarized in the following proposition.

Proposition 2. *The policymaker and landowner i always reach a VA, for all i. In equilibrium,* $q_i^{VA} > q_i^{BL}$ *for all i and* $Q^{VA} > Q^{BL}$ *for any value of* $\bar{Q}$.

This result indicates that, regardless of the risk-mitigation threshold, a VA yields a higher risk-mitigation effort level than the baseline. This implies that a VA can potentially overturn a no-mitigation outcome resulting from a high threshold in the baseline scenario. There are two main reasons for this. First, with a VA, landowners face lower expected costs because no additional forest patrol assessment will be imposed. Landowners are willing to provide higher risk-mitigation effort in exchange for certainty of no additional assessment that comes with a VA. Second, the negotiation process ensures that the policymaker, who prefers higher risk-mitigation effort, has a say about the effort level provided. For this reason, the risk-mitigation effort level will be positive even in the case of a high threshold.

Risk-Mitigation Effort and Welfare Comparisons

Thus far, we have compared landowners' risk-averting effort under each incentive program to the baseline. It is also relevant to ask whether we can learn something about the relative risk-averting effort levels that result from these programs, and how this depends on the risk-averting effort threshold. The results of these comparisons are summarized in the following proposition. When comparing a negligence standard with a strict liability rule, we assume the due standard of care is set at the efficient level if it is no higher than $\tilde{q}_i$; otherwise, it is set at $\tilde{q}_i$ (see corollary 3).

Proposition 3.

i. *If* $\bar{Q} > Q_{min}^{NS}$, $Q^{VA} > Q^{NS} = Q^{SL} = Q^{BL} = 0$.

ii. *If* $\bar{Q} \leq q_{max}^{SL}$ *and* α^i *is sufficiently large for all i,* $Q^{VA} \geq Q^{NS} > Q^{BL} \geq Q^{SL} > 0$.

iii. *If* $q_{max}^{SL} < \bar{Q} \leq Q_{min}^{NS}$, *and* α^i *is sufficiently large for all i, there exist an equilibrium for each incentive scheme such that* $Q^{VA} \geq Q^{NS} > Q^{BL} \geq Q^{SL}$.

iv. *For all* $\bar{Q}$, Q^{CS} *can vary from* Q^{VA} *to* Q^{BL} *as the deadweight loss of government cost sharing* δ *varies from zero to a high level.*

These results suggest that, when the threshold is sufficiently high, a voluntary agreement can always generate a positive level of risk-mitigation effort. Cost sharing can also generate a positive level of risk-mitigation effort when the deadweight loss of government payments is relatively low.

When the threshold is relatively low, all incentive schemes generate positive risk mitigation effort above the threshold. Cost sharing generates the highest level of risk mitigation when the deadweight loss of government payments is low and the percentage of costs shared is sufficiently high. Among the rest of the programs, voluntary agreements generate the highest level of risk mitigation if the policymaker's bargaining power is high enough. This makes sense given that the policymaker's objective function includes benefits that increase in mitigation effort. Hence, he prefers higher effort than landowners, who want to minimize expected costs.

For intermediate levels of the threshold, there is always an equilibrium with positive risk mitigation effort for each of the incentives. The same results and intuition apply to these levels of mitigation effort.

Given that risk-averting effort is costly, it is also relevant to compare the expected welfare levels corresponding to each equilibrium risk-averting effort level. This comparison yields the following result.

Proposition 4:

i. *If $\bar{Q} > Q_{min}^{NS}$, α^i is large enough for all i, $EW^{VA} > EW^{NS} = EW^{SL} = EW^{BL}$.*

ii. *If $\bar{Q} \leq q_{max}^{SL}$ and α^i is large enough for all i, $EW^{VA} \geq EW^{NS} > EW^{BL} \geq EW^{SL}$.*

iii. *If $q_{max}^{SL} < \bar{Q} \leq Q_{min}^{NS}$ and α^i is large enough for all i, there exist equilibria for each incentive scheme such that $EW^{VA} \geq EW^{NS} > EW^{SL} \geq EW^{BL}$.*

iv. *For all $\bar{Q}$, EW^{CS} can vary from EW^{VA} to EW^{BL} as the deadweight loss of government cost sharing δ varies from zero to a high level.*

With a high threshold, a negligence standard, strict liability, and immunity (baseline) yield the same expected welfare because these incentives are ineffective in increasing risk mitigation effort relative to the baseline. A voluntary agreement yields higher expected welfare than these incentive policies because it yields positive risk mitigation as long as the regulator's bargaining power is not too low. If the regulator has relatively little bargaining power, he will not be able to elicit mitigation effort from the landowner, and hence the corresponding expected welfare would be no higher than that resulting from other incentive policies.

Cost sharing can increase the level of individual landowners' mitigation efforts, reducing the expected wildfire damage. However, given the deadweight loss associated with government expenditure, cost sharing improves social welfare only for relatively low levels of deadweight loss, and the optimal level of cost sharing is defined by:

$$\gamma^* = argmax_{\gamma}\{\sum_{i=1}^{n} EW_i\big(q_i^c(\gamma,0)|Q_{-i}^c(\gamma,0)\big)\}. \qquad (10)$$

If the deadweight loss of government payments is sufficiently low, cost sharing yields the highest expected welfare.

When the threshold is low or in the intermediate range, all incentive policies except for a strict liability rule can result in higher expected welfare than the baseline. Among the programs, voluntary agreements yield the highest expected welfare when the regulator's bargaining power is sufficiently high. In addition, when fire risk mitigation does not generate a substantial amount of environmental benefits and the expected cost increases slowly as the mitigation level increases, a negligence standard can also be used to achieve the efficient outcome if the due standard of care is set at the optimal level. Results in Propositions 3 and 4 are summarized in Table 1.

Policy Implications

In the preceding sections we compared the risk-mitigation effort and welfare effects of a variety of incentives for eliciting wildfire risk mitigation behavior. Our results provide insights into the effectiveness of liability rules and voluntary mitigation agreements relative to cost-sharing and an immunity baseline.

First, our results suggest that the magnitude of the risk-mitigation effort threshold plays an important role in determining the effectiveness and welfare impacts of different incentives. The threshold determines whether or not landowners are motivated to exert mitigation effort, and thereby affects both the equilibrium in the baseline and the relative effectiveness of the different incentives. The choice of incentive policy should take the level of the threshold into account. In practice, it is likely not feasible to accurately measure the threshold level, so policymakers must estimate if it is relatively high or low on the basis of underlying landscape characteristics such as weather, compatibility of fire mitigation with tree growth, and mitigation on public lands. The effectiveness of the policies may be limited by errors in this estimation. Another caveat is that the mitigation levels are likely to vary widely across heterogeneous landowners. This could create a sense of inequality that might diminish the effectiveness of incentive programs.

Second, a strict liability rule is ineffective and can even be counterproductive at increasing mitigation effort. When mitigation has a larger local effect, each landowner is better at reducing others' liabilities than his own liability. As a result, each landowner's expected marginal net benefit from mitigation is lower under a strict liability rule than in the baseline. In contrast, a negligence standard can increase mitigation and expected welfare above the baseline when the threshold is relatively low. In addition, when fire risk mitigation does not generate a substantial amount of environmental benefits and the expected cost increases slowly with the mitigation level, a negligence standard will result in the efficient outcome if the due standard of care is set at the optimal level.

Third, voluntary mitigation agreements are effective at eliciting mitigation effort regardless of the relative level of the threshold. In particular, voluntary agreements will generate positive mitigation effort even when the threshold is relatively high and liability rules are ineffective. Additionally, voluntary agreements yield higher (at least not lower) mitigation effort and expected welfare than liability rules for any level of the threshold as long as the regulator has enough bargaining power relative to each of the landowners.

Fourth, the effectiveness and welfare effects of cost-sharing depend on the deadweight loss from raising the necessary funds. This implies that there is a tradeoff for this policy. Higher levels of cost sharing increase the effectiveness of the incentive, but they raise the deadweight loss and thereby reduce expected welfare.

Fifth, when the threshold is sufficiently low, preemptive risk-mitigation effort incentives exist, which lead landowners to engage in mitigation activities even in the absence of incentives. Such voluntary risk-mitigation efforts may not be enough; otherwise, the problem of insufficient risk mitigation would not exist in the first place. In this situation, incentives such as cost-sharing, voluntary agreements, and negligence standards can all increase landowners' mitigation effort.

Finally, it is important to recognize that landscape features, such as population density, topographical characteristics, weather, and underlying vegetation can affect the relative efficiency of different incentive programs. The mitigation threshold is likely lower in relatively densely developed settings where concentrated fuel management might be effective, in diverse and fragmented landscapes providing natural fire breaks, and in locations with higher humidity and lower temperatures and wind speed. In these landscapes, all the incentive schemes except strict liability rules can generate positive risk mitigation effort above the baseline. Conversely, the mitigation threshold is probably higher when population is scattered over a large area, the landscape is flat and has few natural fire breaks, and in areas characterized by low humidity, high temperatures, and high wind speeds. In such landscapes, the policymaker can rely on voluntary agreements or cost sharing to generate positive risk-mitigation effort. Hence, recognition of landscape conditions, and how they interact with weather characteristics, is critical when developing mitigation policy prescriptions (Calkin et al. 2014).

Conclusions

In recent years, U.S. wildfire policy has shifted from focusing on fire suppression to an approach that integrates fire suppression with risk mitigation through fuel reduction. For example, the former governor of California has called for doubling the amount of land treated to prevent fires in the state by 2023, and the current governor has declared a state of emergency to accelerate forest thinning projects and other programs. The state legislature has earmarked $1 billion over five years for such efforts (Schoonover 2019). In this context the forest management decisions of private non-industrial forest owners are particularly important, and incentives to elicit management activities that mitigate fire risk are highly relevant, because landowners may not carry out sufficient fire risk mitigation on their own.

In this paper we examine the effectiveness and welfare implications of several incentive policies. In particular, we examine two novel approaches, which have not been studied extensively in the context of wildfire management: liability rules and voluntary agreements. We also assess the effectiveness of cost sharing, a more frequently studied approach. Our analysis uses a threshold model of public good provision, which specifically allows for the possibility that each landowner's mitigation choices depend on the total amount of mitigation provided in the landscape. This modeling approach has not been used in the fire risk management literature before, but aligns well with empirical evidence and survey data suggesting that landowners' risk mitigation decisions are influenced by those of their neighbors.

Our results suggest that cost sharing can be the most effective incentive for eliciting risk mitigation effort as long as the percentage of costs shared is sufficiently high. However, if the deadweight loss of raising funds for relatively large cost sharing proportions is high, cost sharing will not necessarily be welfare enhancing. Additionally, if the government's ability to offer cost sharing is further limited by budget constraints, additional or alternative incentive policies may be called for.

One important insight gained from this analysis is that the risk mitigation threshold is critical in determining the effectiveness and welfare effects of different incentive programs. In practice, the landscape in the western United States is characterized by increasingly dry and hot fire seasons, significant amounts of public land where little treatment has taken place, high mitigation costs, and budget constraints. These conditions imply that the mitigation threshold is likely to be relatively high. Our results indicate that, in such a scenario, voluntary risk mitigation agreements could be a viable option, as they can increase mitigation effort and welfare regardless of the mitigation threshold, as long as the regulator has bargaining power with landowners. Finally, we find that the use of negligence standards can also be effective and welfare enhancing, but only when the mitigation threshold is sufficiently low.

This analysis assumes landowners make fully rational cost-minimizing decisions. However, behavioral economics principles suggest that bounded rationality can be important in contexts characterized by uncertainty and limited information, where feedback about the effects of individual actions is poor, and where social norms shape decisions. All these characteristics are present in the choices modeled here. This may imply that the effectiveness of policies that rely on voluntary participation, such as cost-sharing or voluntary agreements, could be negatively affected by low enrollment driven by factors such as preference for default management choices or framing of the additional effort required by participation. Explicit modeling of these bounded rationality considerations is an important topic for future research.

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Table 1. Summary of Results

	Mitigation Effort			Expected Welfare		
Policy	$\bar{Q} > Q_{min}^{NS}$	$q_{max}^{SL} < \bar{Q} \leq Q_{min}^{NS}$	$\bar{Q} \leq q_{max}^{SL}$	$\bar{Q} > Q_{min}^{NS}$	$q_{max}^{SL} < \bar{Q} \leq Q_{min}^{NS}$	$\bar{Q} \leq q_{max}^{SL}$
Baseline (BL)	$Q^{BL} = 0$	Q^{BL}	$Q^{BL} > 0$	EW^{BL}	EW^{BL}	EW^{BL}
Strict Liability (SL)	$Q^{SL} = 0$	$Q^{BL} \geq Q^{SL}$	$Q^{BL} \geq Q^{SL} > 0$	$EW^{SL} = EW^{BL}$	$EW^{BL} \geq EW^{SL}$	$EW^{BL} \geq EW^{SL}$
Negligence Standard (NS)	$Q^{NS} = 0$	$Q^{NS} > Q^{BL} \geq Q^{SL}$	$Q^{NS} > Q^{BL} \geq Q^{SL} > 0$	$EW^{NS} = EW^{SL} = EW^{BL}$	$EW^{NS} > EW^{BL} \geq EW^{SL}$	$EW^{NS} > EW^{BL} \geq EW^{SL}$
Voluntary Agreements (VA)	$Q^{VA} > 0$	$Q^{VA} \geq Q^{NS} > Q^{BL} \geq Q^{SL}$	$Q^{VA} \geq Q^{NS} > Q^{BL} \geq Q^{SL} > 0$	$EW^{VA} > EW^{NS} = EW^{BL} = EW^{SL}$	$EW^{VA} \geq EW^{NS} > EW^{BL} \geq EW^{SL}$	$EW^{VA} \geq EW^{NS} > EW^{BL} \geq EW^{SL}$
Cost Sharing (CS)	$Q^{CS} \geq Q^{VA}$ to $Q^{CS} = 0$ as δ increases	$Q^{CS} \geq Q^{VA}$ to $Q^{CS} = Q^{BL}$ as δ increases	$Q^{CS} \geq Q^{VA}$ to $Q^{CS} = Q^{BL} > 0$ as δ increases	$EW^{CS} \geq EW^{VA}$ to $EW^{CS} = EW^{BL}$ as δ increases	$EW^{CS} \geq EW^{VA}$ to $EW^{CS} = EW^{BL}$ as δ increases	$EW^{CS} \geq EW^{VA}$ to $EW^{CS} = EW^{BL}$ as δ increases

Notes: Q = total amount of effort for all landowners. $\overline{Q}$ = mitigation threshold. EW = expected social welfare. δ = deadweight loss of raising tax revenue. Q_{min}= minimum total mitigation effort that would result given that all other landowners take cost-minimizing effort level. q_{max} = maximum mitigation level that a single landowner is willing to exert given that all other landowners take no effort.

Footnotes

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[1] Wildfire fuel refers to all combustible biomass on the landscape, from grasses, tree needles and leaves to shrubs, downed trees, and logs.

[2] While in practice a policy maker could conceivably implement combinations of these policies, for our purposes of comparison between them it is necessary to examine their impacts separately.

[3] Landowners refer to any owners of real estate properties on the landscape, including residential, commercial, private and corporate landowners. The distinction of different types of landowners does not affect the analysis as long as they face the same liability rules and incentives.

[4] $B_i(\cdot)$ includes benefits other than fire damages avoided, such as wildlife habitat improvements. It is possible that these benefits also depend on the total mitigation effort Q, but to keep the model tractable we assume that $B_i(\cdot)$ represents benefits generated by landowner i's mitigation effort only.

[5] Alternatively, the policymaker's expected social welfare from landowner i's risk-averting effort can be defined as the sum of the net benefit from the mitigation effort plus the expected fire damages avoided. This would lead to the same results below because the social welfare functions under the two specification differ by only a constant.

[6] This assumption is justified by a marginal interpretation of the Hand rule, commonly used by American courts to decide questions of negligence. The Hand rule states that negligence is attributed to the injuring party when the cost of precaution is less than the expected cost of harm.

[7] Although any agreement reached is induced by the threat of the assessment, we follow the literature by referring to such agreements as "voluntary agreements".

Figure 1. The maximum level of effort a landowner is willing to exert to ensure that mitigation is effective

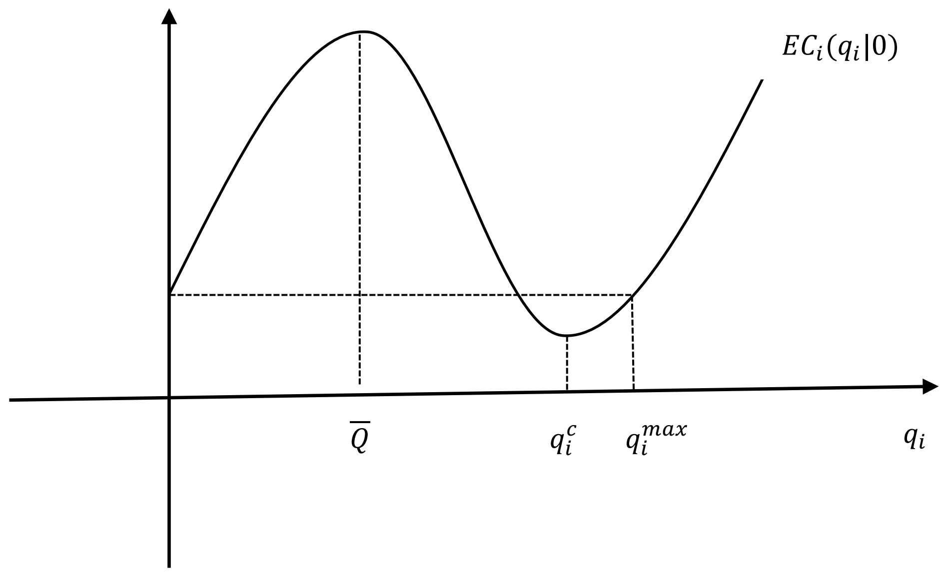


Figure 2. Reaction functions and three possible equilibrium outcomes (*n* = 2)

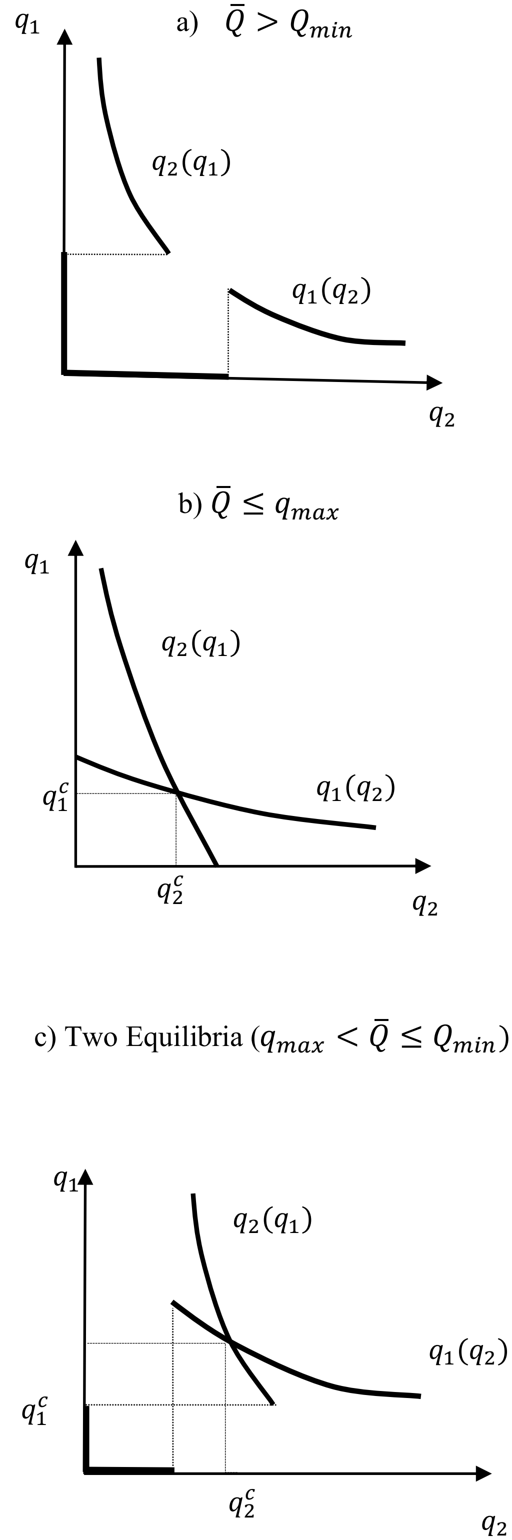
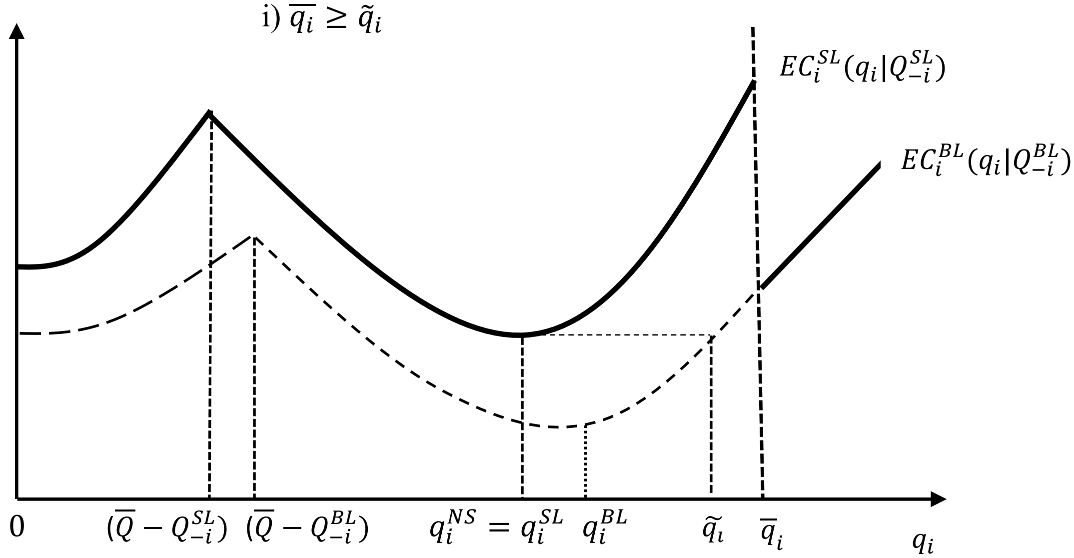


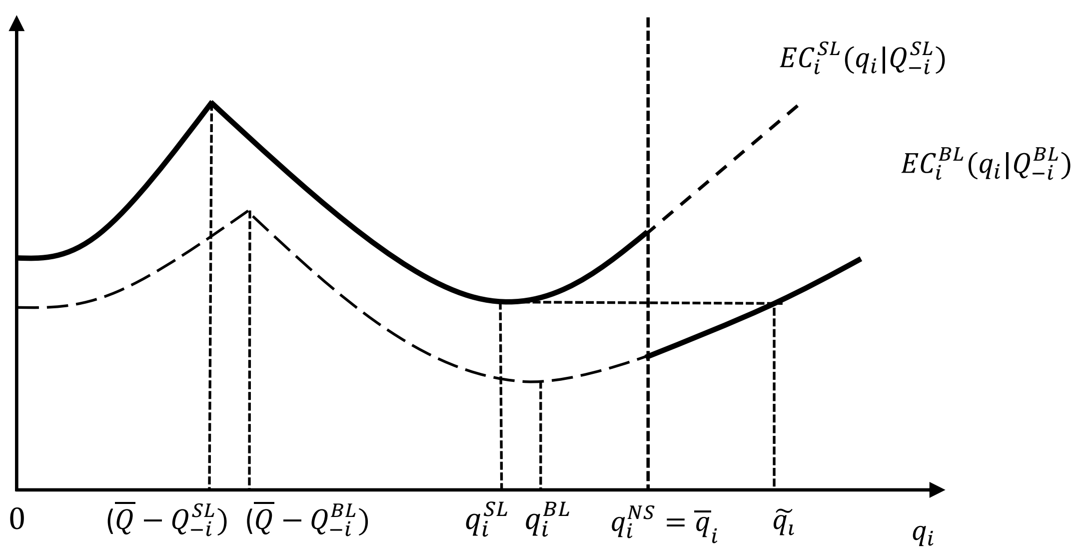
Figure 3. Equilibrium outcome for negligence standard

i) $\overline{q_i} \geq \tilde{q}_i$



Denotes the effective cost function under the negligence standard

ii) $\overline{q_i} < \tilde{q}_i$



Denotes the effective cost function under the negligence standard

ONLINE APPENDIX

Langpap, Christian, and JunJie Wu. Preemptive Incentives and Liability Rules for Wildfire Risk Management. *American Journal of Agriculture Economics.*

Proof of Lemma 1

We start by showing that the response function defined by equation (4) is decreasing in Q_{-i}. The first-order condition that defines the response function $q_i = q_i(Q_{-i})$ is

$$\frac{\partial EC_i(q_i|Q_{-i})}{\partial q_i} = (1-\gamma)C_i'(q_i) + \frac{\partial D_i(q_i,Q_{-i})}{\partial q_i} - \frac{\partial ER_{-i}(q_i|Q_{-i})}{\partial q_i} + \frac{\partial ED_{-i}(q_i|Q_{-i})}{\partial q_i} = 0 \qquad \text{(A1)}$$

where

$$\frac{\partial ER_{-i}(q_i|Q_{-i})}{\partial q_i} = \sum_{k\neq i} \frac{\partial[\theta_k(q_k)p_{ki}^F(q_k,q_i,Q)D_i^F(q_i,Q_{-i})]}{\partial q_i}$$

$$\frac{\partial ED_{-i}(q_i|Q_{-i})}{\partial q_i} = \sum_{k\neq i} \frac{\partial[\theta_i(q_i)p_{ik}^F(q_i,q_k,Q)D_k^F(q_k,Q_{-k})]}{\partial q_i}.$$

Differentiating (A1) with respect to Q_{-i} and rearranging gives

$$\frac{\partial q_i}{\partial Q_{-i}} = -\frac{\frac{\partial^2 EC_i(q_i|Q_{-i})}{\partial q_i \partial Q_{-i}}}{\frac{\partial^2 EC_i(q_i|Q_{-i})}{\partial {q_i}^2}} \qquad \text{(A2)}$$

where the numerator and the denominator are obtained by differentiating (A1) with respect to Q_{-i} and q_i:

$$\frac{\partial^2 EC_i(q_i|Q_{-i})}{\partial q_i \partial Q_{-i}} = \frac{\partial^2 (p_{ii}^F D_i^F)}{\partial q_i \partial Q_{-i}} + \sum_{k\neq i} \frac{(1-\theta_k(q_k))\partial^2[p_{ki}^F(q_k,q_i,Q)D_i^F(q_i,Q_{-i})]}{\partial q_i \partial Q_{-i}} + \frac{\partial^2 ED_{-i}}{\partial q_i \partial Q_{-i}}$$

$$\frac{\partial^2 EC_i(q_i|Q_{-i})}{\partial {q_i}^2} = (1-\gamma)C_i''(q_i) + \frac{\partial^2 (p_{ii}^F D_i^F)}{\partial q_i^2} + \sum_{k\neq i} \frac{(1-\theta_k(q_k))\partial^2[p_{ki}^F(q_k,q_i,Q)D_i^F(q_i,Q_{-i})]}{\partial q_i^2} + \frac{\partial^2 ED_{-i}}{\partial q_i^2}$$

The diminishing marginal effect of mitigation effort implies that $\frac{\partial^2 (p_{ki}^F D_i^F)}{\partial q_i^2} > 0$ and $\frac{\partial^2 (p_{ik}^F D_k^F)}{\partial q_i^2} > 0$, while the complementarity assumption of individual landowners' mitigation efforts implies $\frac{\partial^2 (p_{ki}^F D_i^F)}{\partial q_i \partial q_k} \leq 0$ and $\frac{\partial^2 (p_{ik}^F D_k^F)}{\partial q_i \partial q_k} \leq 0$ for any $k \neq i$. Using these properties, we can show that both the denominator and the numerator of (A2) are positive and the denominator is greater than the numerator. Thus, $-1 < \frac{\partial q_i}{\partial Q_{-i}} < 0$ for $i = 1, \ldots, n$. Because $q_i = q_i(Q_{-i})$ for $i = 1, \ldots, n$ are continuous functions mapping the compact convex set $W = \{(q_1, \dots, q_n) | 0 \leq q_i \leq q_i^M, i = 1, \dots, n\}$ to itself, where q_i^M is an exogenously given maximum feasible effort level for landowner i, by Brouwer's Fixed Point Theorem there exists a fixed point $(q_1^*, \dots, q_n^*)$ such that $q_1^* = q_i(Q_{-i}^*)$ for i = 1, …, n. By definition, $(q_1^*, \dots, q_n^*)$ is a Nash equilibrium.

Now we prove the uniqueness of the equilibrium. Suppose there is an additional Nash equilibrium $Q^{*\prime}$ and assume without loss of generality that $Q^{*\prime} \leq Q^*$. Then there exists at least one i such that $q_i^{*\prime} \leq q_i^*$. Since q_i^* is decreasing in Q_{-i}^*, it must be that $Q_{-i}^{*\prime} \geq Q_{-i}^*$. Since $\frac{\partial Q}{\partial Q_{-i}} = \frac{\partial q_i}{Q_{-i}} + 1 > 0$, Q is increasing in Q_{-i}, which, together with $Q_{-i}^{*\prime} \geq Q_{-i}^*$, implies that $Q^{*\prime} \geq Q^*$. It follows that $Q^{*\prime} = Q^*$. Given this, we can prove that $q_i^{*\prime} = q_i^*$ for $\forall i$. Suppose $q_i^{*\prime} > q_i^*$ for landowner i, then there must be a landowner j such that $q_j^{*\prime} < q_j^*$ because $Q^{*\prime} = Q^*$. $q_i^{*\prime} > q_i^*$ implies that $Q_{-i}^{*\prime} < Q_{-i}^*$, which, together with $\frac{\partial Q}{\partial Q_{-i}} = \frac{\partial q_i}{Q_{-i}} + 1 > 0$, implies $Q^{*\prime} < Q^*$. Likewise, $q_j^{*\prime} < q_j^*$ implies that $Q_{-j}^{*\prime} > Q_{-j}^*$, which, together with $\frac{\partial Q}{\partial Q_{-j}} = \frac{\partial q_j}{Q_{-j}} + 1 > 0$, implies $Q^{*\prime} > Q^*$, a contradiction with $Q^{*\prime} < Q^*$. Thus, $q_i^{*\prime} = q_i^*$ for $\forall i$. This proves the uniqueness of the equilibrium.

To prove (i), suppose $q_i^* > 0$ for any i. $\overline{Q} = +\infty$ implies $Q < \overline{Q}$. This implies that $\frac{\partial D_i(q_i, Q_{-i})}{\partial q_i} = \frac{\partial ER_{-i}(q_i|Q_{-i})}{\partial q_i} = \frac{\partial ED_{-i}(q_i|Q_{-i})}{\partial q_i} = 0$. Evaluating the first order condition (A1) at $q_i^* > 0$, we obtain $\frac{\partial EC_i(q_i|Q_{-i})}{\partial q_i} = (1-\gamma)C_i'(q_i) > 0$ for any θ_i. Therefore, $q_i^* > 0$ is not a best response when $\overline{Q} = +\infty$.

Similarly, to prove (ii) suppose $q_i^* = q_i^c = 0$ for any i. Note that $\overline{Q} = 0$ implies that $\frac{\partial D_i(0, Q_{-i})}{\partial q_i} < 0$. This, together with the assumption $C_i'(0) = 0$, implies that $\frac{\partial EC_i(0|Q_{-i})}{\partial q_i} = \frac{\partial ED_i(0|Q_{-i})}{\partial q_i} + \frac{\partial ED_{-i}(0|Q_{-i})}{\partial q_i} < 0$ for any Q_{-i}. Because an increase in q_i will reduce landowner i*'s* expected cost, $q_i^c = 0$ is not a best response. This leaves $q_i^c > 0 \; \forall i$.

Proof of Proposition 1

(i) We first prove that if $\bar{Q} > Q_{min}(\gamma, \theta)$, $(q_1^*, \dots, q_n^*) = (0, \dots, 0)$ is the only equilibrium. To this end, we first prove that $q_i^* = 0 \; \forall \; i$ is an equilibrium. The condition that $\bar{Q} > Q_{min}(\gamma, \theta) > q_{max}(\gamma, \theta)$ implies that

$\bar{Q} > q_i^{max}$ $\forall$ i. Because $EC_i(q_i|0)$ increases in q_i for $q_i < \bar{Q}$, $q_i^{max} = 0$ $\forall$ i. This implies $EC_i(q_i|0) > EC^i(0|0)$ for any $q_i > 0$ $\forall$ i. Given that no landowner can achieve lower expected cost by deviating, q_i^* = 0 $\forall$ i must be an equilibrium.

To prove q_i^* = 0 $\forall$ i is the only equilibrium, note first that any $0 < Q < \bar{Q}$ cannot be an equilibrium; otherwise, it would have been available as a Nash equilibrium in the special case $\bar{Q}$= +∞. Also, any $Q \neq Q_c$ and $Q > \bar{Q}$ cannot be an equilibrium; otherwise, it would have been available as a Nash equilibrium in the special case $\bar{Q} = 0$. Additionally, $Q = Q_c$ cannot be an equilibrium because $\bar{Q} > Q_{min}(\gamma, \theta)$ implies that for at least one landowner *k*, $\bar{Q} > q_k^{min} + Q_{-k}^c$. By the definition of q_k^{min} and noticing that $EC_k(q_k|Q_{-k}^c)$ increases in q_k when $q_k < \bar{Q} - Q_{-k}^c$, we have $EC_k(0|Q_{-k}^c) < EC_k\left(q_k^{min}\middle|Q_{-k}^c\right) \leq EC_k(q_k^c|Q_{-k}^c)$, which means that landowner *k* has incentives to deviate given Q_c^{-k}. Thus, $q^i = q_c^i$ $\forall$ i cannot be an equilibrium.

Finally, to prove that $(q_1^0, \dots, q_n^0), \sum_i q_i^0 = \bar{Q}$ is not an equilibrium, we use contradiction. Suppose $(q_1^0, \dots, q_n^0)$ is an equilibrium, then $q_i^0 = \text{argmin}_{q_i}\{EC_i\left(q_i\middle|Q_{-i}^0\right)\}$, we can write $q_i^0 = f_i\left(Q_{-i}^0\right) - Q_{-i}^0$, where $f_i\left(Q_{-i}^0\right) = \text{argmin}_{q_i}\{EC_i\left(q_i\middle|Q_{-i}^0\right)\}+Q_{-i}^0$. From the proof of Lemma 1, $0 < f_i'\left(Q_{-i}^0\right) + 1$. Note that $\bar{Q} = q_i^0 + Q_{-i}^0 = f_i\left(Q_{-i}^0\right)$. Also, because q_i^* = 0 $\forall$ i is an equilibrium, $f_i(0) = \underset{q^i}{\text{argmin}}\, q^i(q^i|\, 0) = 0$.

Since $0 < \bar{Q}$ by construction, $f_i(0) < f_i\left(Q_{-i}^0\right)$. Given that $0 < f_i'\left(Q_{-i}^0\right)$, it follows that $0 < Q_{-i}^0$ $\forall i$. Further, $f_i'\left(Q_{-i}^0\right) - 1 < 0$, which implies that $f_i\left(Q_{-i}^0\right) - Q_{-i}^0$ is decreasing, and therefore $q_i^0 = f_i\left(Q_{-i}^0\right) - Q_{-i}^0 < f_i\left(0^{-i}\right) - 0 = 0$ $\forall i$, which implies that $\bar{Q} = \sum q_i^0 < 0$, a contradiction.

So far, we have proved that if $\bar{Q} > Q_{min}(\gamma, \theta)$, any $Q > 0$ cannot be an equilibrium. Therefore, $(q_1^*, \dots, q_n^*) = (0, \dots, 0)$ is the only equilibrium.

(ii) Next, we prove that if $\bar{Q} \leq q_{max}(\gamma, \theta)$, $q_i^* = q_i^c(\gamma, \theta) > 0$ for all i is the only Nash equilibrium by using the same logic as in *(i)*. We first show that that $q_i^* = q_i^c(\gamma, \theta) \forall i$ is an equilibrium. The condition that $\bar{Q} \leq q_{max}(\gamma, \theta) < Q_{min}(\gamma, \theta)$ implies that $\bar{Q} \leq q_i^{min} + Q_{-i}^c$ $\forall$ i. This implies that $EC_i(q_i|Q_{-i}^c) > EC_i(q_i^c|Q_{-i}^c)$ for any $q_i < \bar{Q} - Q_{-i}^c$. Also, by definition, $q_i^c = \underset{q_i}{\text{argmin}} EC_i(q_i|Q_{-i}^c)$ if $q_i >$

$\bar{Q} - Q_c^{-i}$. Therefore, $EC_i(q_i|Q_{-i}^c) \geq EC_i(q_i^c|Q_{-i}^c)$ for any $q_i \geq 0 \ \forall \ i$. Given that no landowner can achieve lower expected cost by deviating, $q_i = q_i^c \ \forall \ i$ must be an equilibrium.

To prove $q_i^* = q_i^c(\gamma, \theta) \ \forall \ i$ is the only equilibrium, note first that any $0 < Q < \bar{Q}$ cannot be an equilibrium; otherwise, it would have been available as a Nash equilibrium in the special case $\bar{Q}= +\infty$. Also, any $Q \neq Q^c$ and $Q > \bar{Q}$ cannot be an equilibrium; otherwise, it would have been available as a Nash equilibrium in the special case $\bar{Q} = 0$. Additionally, $Q = 0$ cannot be an equilibrium because $\bar{Q} \leq q_{max}(\gamma, \theta)$ implies that for at least one landowner *k*, $\bar{Q} \leq q_k^{max}$, which implies that $EC_k(0|0) \geq EC_k(q_k^{max}|0)$. Thus, landowner *k* has incentive to deviate, and $q^i = 0 \ \forall \ i$ cannot be an equilibrium.

Finally, to prove that $(q_1^0, \dots, q_n^0), \sum_i q_i^0 = \bar{Q}$ is not an equilibrium, we use contradiction. Suppose $(q_1^0, \dots, q_n^0)$ is an equilibrium. As in part (i), $0 < f_i'(Q_{-i}^0) < 1$ and $\bar{Q} = q_i^0 + Q_{-i}^0 = f_i(Q_{-i}^0)$. Also, because $q_i^* = q_i^c \ \forall \ i$ is an equilibrium, $q_i^c = f_i(Q_{-i}^0) - Q_{-i}^0$, which implies that $Q^c = f_i(Q_{-i}^0)$. Since $Q^c < \bar{Q}$, $f_i(Q_{-i}^c) < f_i(Q_{-i}^0)$. Given that $0 < f_i'(Q_{-i}^0)$, it follows that $Q_{-i}^c < Q_{-i}^0 \ \forall i$. Because $f_i'(Q_{-i}^0) - 1 < 0$, which implies that $f_i(Q_{-i}^0) - Q_{-i}^0$ is decreasing, and therefore $q_i^0 = f_i(Q_{-i}^0) - Q_{-i}^0 < f_i(Q_{-i}^c) - Q_{-i}^c = q_i^c \ \forall i$, which implies that $\bar{Q} = \sum q_i^0 < Q_c$, a contradiction. So far we have proved that any $Q \neq Q^c$ cannot be an equilibrium. Therefore, $q_i^* = q_i^c(\gamma, \theta) \ \forall \ i$ is the only equilibrium when $\bar{Q} \leq q_{max}(\gamma, \theta)$.

(iii) Finally, we prove that if $q_{max}(\gamma, \theta) < \bar{Q} \leq Q_{min}(\gamma, \theta)$, both $q_i^* = q_i^c(\gamma, \theta) > 0$ for all *i* and $q_i^* = 0$ for all *i* are equilibria. Condition $q_{max}(\gamma, \theta) < \bar{Q}$ implies that $q_i^{max} < \bar{Q} \ \forall \ i$, which implies that $EC^i(0|0) < EC^i(q_i|0)$ for any $q_i > 0$. Given that no landowner has incentive to deviate from $q_i^* = 0 \ \forall \ i$, $q_i^* = 0 \ \forall \ i$ must be an equilibrium. Also, condition $\bar{Q} \leq Q_{min}(\gamma, \theta)$ implies that $\bar{Q} \leq q_i^{min} + Q_{-i}^c \ \forall \ i$, which implies that $q_i^{min} = q_i^c$ and $EC_i(q_i|Q_{-i}^c) \geq EC_i(q_i^c|Q_{-i}^c)$ for any q_i. By definition $q_i^* = q_i^c(\gamma, \theta) \ \forall \ i$ is an equilibrium.

To prove that $q_i^* = q_i^c(\gamma, \theta) \ \forall \ i$ and $q_i^* = 0 \ \forall \ i$ are the only equilibria, note first that any $0 < Q < \bar{Q}$ cannot be an equilibrium; otherwise, it would have been available as a Nash equilibrium in the special case $\bar{Q}= +\infty$. Also, any $Q \neq Q_c$ and $Q > \bar{Q}$ cannot be an equilibrium; otherwise, it would have been available as a Nash equilibrium in the special case $\bar{Q} = 0$. Thus, all we need to prove is that $Q = \bar{Q}$ cannot be an equilibrium by following the same logic in (i). Suppose $(q_1^0, \dots, q_n^0)$ is an equilibriu. As in part (i), $0 < f_i'(Q_{-i}^0) < 1$ and $\bar{Q} = q_i^0 + Q_{-i}^0 = f_i(Q_{-i}^0)$. Also, because $q_i^* = 0\ \forall\ i$ is an equilibrium, $f_i(0) = \underset{q^i}{\operatorname{argmin}}\, q^i(q^i | 0) = 0$. Since $0 <\ \bar{Q}$ by construction, $f_i(0) < f_i(Q_{-i}^0)$. Given that $0 < f_i'(Q_{-i}^0)$, it follows that $0 < Q_{-i}^0\ \forall i$. Further, $f_i'(Q_{-i}^0) - 1 < 0$, which implies that $f_i(Q_{-i}^0) - Q_{-i}^0$ is decreasing, and therefore $q_i^0 = f_i(Q_{-i}^0) - Q_{-i}^0 < f_i(0^{-i}) - 0 = 0\ \forall i$, which implies that $\bar{Q} = \sum q_i^0 < 0$, a contradiction.

Proof of Lemma 2

Differentiating the first-order condition that defines $q_i^c(\gamma, 0)$, we obtain

$$\frac{\partial q_i^c(\gamma,0)}{\partial \gamma} = \frac{C_i{}'(q_i^c)}{\frac{\partial^2 EC_i(q_i^c | Q_{-i}^c)}{\partial {q_i}^2}} > 0$$

Also, by the definition of $q_i^{max}(\gamma, 0)$, if $q_i^{max}(\gamma, 0) > 0$, we must have $\frac{\partial EC_i(q_i^{max} | 0)}{\partial q_i} > 0$. Otherwise, there would be larger q_i satisfying (5), contradicting the definition that $q_i^{max}(\gamma, 0)$ is the largest q_i satisfying (5). Differentiating (5) with respect to γ, we obtain:

$$\frac{\partial q_i^{max}(\gamma,0)}{\partial \gamma} = \frac{C_i(q_i^{max})}{\frac{\partial EC_i(q_i^{max}|0)}{\partial q_i}} > 0 \text{ if } q_i^{max}(\gamma, 0) > 0.$$

Finally, by the definition of $q_i^{min}(\gamma, \theta)$, if it is positive, then $q_i^{min}(\gamma, \theta) = q_i^c(\gamma, 0)$. Therefore,

$$\frac{\partial q_i^{min}(\gamma,0)}{\partial \gamma} > 0 \text{ if } q_i^{min}(\gamma, 0) > 0$$

The result then follows from the definitions of $q_{max}(\gamma, \theta)$ and $Q_{min}(\gamma, \theta)$.

Proof of Corollary 1

i) The results follow directly from proposition 1, $q_{max}^{CS} > q_{max}^{BL}$, $Q_{min}^{CS} > Q_{min}^{BL}$ and $\frac{\partial q_i^c(\gamma,0)}{\partial \gamma} > 0$.

ii) Because $q_i^{max}(\gamma, 0)$ increases with γ for any *i*, there exists a $\overline{\gamma}$ such that when $\geq \overline{\gamma}$ $q_{max}^{CS} =$

$\max\{q_i^{max}(\gamma,0), i=1,\dots,n\} \geq \overline{Q}$. Then, from part (ii) of proposition 1, $q_i^* = q_i^c(\gamma,0) > 0$ for all i is the only Nash equilibrium when $\gamma \geq \overline{\gamma}$.

Proof of Lemma 3

Note that $\theta_i(q_i) = \theta$, which equals 1 under the strict liability rule and 0 in the baseline (no liability). If $q_i^{max}(0,\theta) = 0$, $\frac{\partial q_i^{max}(0,\theta)}{\partial \theta_i} = 0$. If $q_i^{max}(0,\theta) > 0$, then $q_i^{max}(0,\theta) > \overline{Q}$ and $\frac{\partial EC_i(q_i^{max}|0)}{\partial q_i} > 0$. In this case, (5) holds with equality. Differentiating (5) with respect to θ for $\gamma = 0$, we obtain

$$\frac{\partial q_i^{max}(0,\theta)}{\partial \theta} = \frac{\frac{\partial EC_i(0|0)}{\partial \theta} - \frac{\partial EC_i(q_i^{max}|0)}{\partial \theta}}{\frac{\partial EC_i(q_i^{max}|0)}{\partial q_i}} \tag{A3}$$

Although the denominator in (A3) is positive, the numerator is negative. To show this, note that

$$\begin{aligned}\frac{\partial EC_i(0|0)}{\partial \theta} - \frac{\partial EC_i(q_i^{max}|0)}{\partial \theta} &= [ER_{-i}(q_i^{max}|0) - ER_{-i}(0|0)] - [ED_{-i}(q_i^{max}|0) - ED_{-i}(0|0)] \\ &= \textstyle\sum_{k\neq i}\{[p_{ki}^F(0,q_i^{max})D_i^F(q_i^{max},0)] - [p_{ki}^F(0,0)D_i^F(0,0)]\} \\ &\quad - \textstyle\sum_{k\neq i}\{[p_{ik}^F(q_i^{max},0)D_k^F(q_i^{max},0)] - [p_{ik}^F(0,0)D_k^F(0,0)]\} < 0\end{aligned}$$

which is negative because the difference in the first parenthesis is smaller (more negative) than the difference in the second parenthesis due to the assumption that risk-mitigation effort has a larger marginal effect on expected damages locally. Given that the denominator of (A3) is positive while the numerator is non-positive, we have

$$\frac{\partial q_i^{max}(0,\theta)}{\partial \theta} < 0.$$

By definition, $q_i^{min}(0,\theta) \leq q_i^c(0,\theta)$. If $q_i^{min}(0,\theta) < q_i^c(0,\theta)$, then $q_i^{min}(0,\theta) = 0$ and $\frac{\partial q_i^{min}(0,\theta)}{\partial \theta_i} = 0$. If $q_i^{min}(0,\theta) = q_i^c(0,\theta)$, we can derive $\frac{\partial q_i^c(0,\theta)}{\partial \theta_i}$ by differentiating the first-order condition that defines $q_i^c(0,\theta)$ to obtain

$$\frac{\partial q_i^c(0,\theta)}{\partial \theta} = -\frac{\sum_{k\neq i}\left[\frac{\partial\left[p_{ik}^F(q_i,q_k,Q)D_k^F(q_k,Q_{-k})\right]}{\partial q_i} - \frac{\partial\left[p_{ki}^F(q_k,q_i,Q)D_i^F(q_i,Q_{-i})\right]}{\partial q_i}\right]}{\frac{\partial^2 EC_i(q_i^c|Q_{-i}^c)}{\partial {q_i}^2}} < 0$$

where the denominator is positive because EC_i minimizes at q_i^c, and the numerator is also positive because the mitigation effort has a larger marginal effect on expected damages locally. This result, together with $q_i^{min}(0,\theta) = 0$ or $q_i^c(0,\theta)$, implies that

$$\frac{\partial q_i^{min}(0,\theta)}{\partial \theta} \leq 0.$$

When $q_i^{min}(0,\theta) = q_i^c(0,\theta)$, $\frac{\partial q_i^{min}(0,\theta)}{\partial \theta}$ is strictly negative.

Proof of Corollary 2.

i) The results follow directly from proposition 1, $q_{max}^{SL} \leq q_{max}^{BL}$, and $Q_{min}^{SL} \leq Q_{min}^{BL}$.

ii) The result follows directly from $\frac{\partial q_i^c(0,\theta)}{\partial \theta} < 0$.

Proof of Lemma 4.

First, we prove if $\overline{q_i} < \tilde{q}_i \;\; \forall i$, $Q_{min}^{NS} > Q_{min}^{SL} > Q_{min}^{BL}$. By definition, $Q_{min}(0,\theta) = \min\{[q_1^{min}(0,\theta) + Q_{-1}^c(0,\theta)], \ldots, [q_n^{min}(0,\theta) + Q_{-n}^c(0,\theta)]\}$, where $q_i^{min}(0,\theta)$ is the minimum q_i that satisfies

$$EC_i\big(q_i \big| Q_{-i}^c(0,\theta)\big) \leq EC_i\big(q_i^c(0,\theta) \big| Q_{-i}^c(0,\theta)\big).$$

There are two possible cases: a) $q_i^{SL} = q_i^c(0,\theta)$, and b) $q_i^{SL} = 0$. Consider first case a), which is illustrated in Figure 3. In this case, $q_i^{SL} = q_i^{min}(0,\theta) = q_i^c(0,\theta)$. Let $\tilde{q}_i$ be the maximum q_i satisfying $EC_i\big(q_i^{SL} | Q_{-i}^{SL}\big) \geq EC_i\big(q_i | Q_{-i}^{BL}\big)$. If $\tilde{q}_i > \overline{q_i}$, q_i^{min} under the negligence standard equals $\overline{q_i} > q_i^c(0,0)$, which is greater than $q_i^{min} = q_i^{SL}$ under strict liability and $q_i^{min} \leq q_i^c(0,0)$ in the baseline. Therefore, when $\tilde{q}_i > \overline{q_i}$, $Q_{min}^{NS} > Q_{min}^{SL} > Q_{min}^{BL}$. However, if $\tilde{q}_i \leq \overline{q_i}$, q_i^{min} under the negligence standard equals $q_i^c(0,\theta)$, which is the same under strict liability, but below the q_i^{min} in the baseline if $q_i^{min} = q_i^c(0,0) > q_i^c(0,\theta)$.

Now consider the case of $q_i^{SL} = 0$, which is illustrated in Figure 3a. In this case, $q_i^{min}(0,\theta) = 0$ under the strict liability rule. If $\tilde{q}_i > \overline{q_i}$, q_i^{min} equals $\overline{q_i}$ under the negligence standard, which is greater than $q_i^{min} = 0$ under strict liability. q_i^{min} under the negligence standard is also above the q_i^{min} in the baseline because by definition, q_i^{min} in the baseline cannot be larger than $q_i^c(0{,}0)$, which is below $\overline{q_i}$. However, if $\tilde{q}_i \leq \overline{q_i}$, $q_i^{min} = 0$ under the negligence standard, which is the same as under strict liability and can be below the q_i^{min} in the baseline.

Second, we prove if $\overline{q_i} < \tilde{q}_i \; \forall i$, $q_{max}^{NS} > q_{max}^{BL} > q_{max}^{SL}$. By definition, $q_{max}(0,\theta) = \max\{q_1^{max}(0,\theta),\ldots,\ q_n^{max}(0,\theta)\}$, where $q_i^{max}(0,\theta)$ is the maximum q_i that solves $EC_i(q_i|0) \leq EC_i(0|0)$. Again, there are two possible cases: a) $q_i^{SL} = q_i^c(0,\theta)$, and b) $q_i^{SL} = 0$. In case a), $q_i^{max}(0,\theta)$ under the strict liability rule is defined by $EC_i^{SL}(0|0) = EC_i^{SL}(q_i|0)$. $q_i^{max}(0,\theta)$ under the negligence standard is defined by $EC_i^{SL}(0|0) = EC_i^{BL}(q_i|0)$, which is greater than both $q_i^{max}(0,\theta)$ under the strict liability rule and $q_i^{max}(0,\theta)$ in the baseline, the later of which is defined by $EC_i^{BL}(0|0) = EC_i^{SL}(q_i|0)$. This proves $q_{max}^{NS} > q_{max}^{BL} > q_{max}^{SL}$.

In case b) $q_i^{max}(0,\theta) = 0$ under the strict liability rule. If $\overline{q}_i < \tilde{q}_i$, $q_i^{max} = \tilde{q}_i$ under the negligence standard, which is greater $q_i^{max} = 0$ under the strict liability rule. $q_i^{max} = \tilde{q}_i$ under the negligence standard, which solves $EC_i^{SL}(0|0) = EC_i^{BL}(q_i|0)$, is also greater than the q_i^{max} in the baseline, which solves $EC_i^{BL}(0|0) = EC_i^{BL}(q_i|0)$ because $EC_i^{SL}(0|0) > EC_i^{BL}(0|0)$. Therefore, if $\overline{q_i} < \tilde{q}_i \; \forall i$, $q_{max}^{NS} \geq q_{max}^{BL} \geq q_{max}^{SL}$. However, if $\overline{q}_i > \tilde{q}_i$ $q_i^{max} = 0$ under the negligence standard, which is exactly the same as under the strict liability, which can be below the q_i^{max} in the baseline.

Proof of Corollary 3.

i) The results follow directly from proposition 1 and $q_{max}^{NS} \geq q_{max}^{BL} \geq q_{max}^{SL}$, $Q_{min}^{NS} > Q_{min}^{SL} > Q_{min}^{BL}$.

ii) There are two possible cases: a) $q_i^{SL} = q_i^c(0,\theta)$, and b) a) $q_i^{SL} = 0$. In case a), $q_i^{SL} = q_i^{min}(0,\theta) = q_i^c(0,\theta)$. If $\tilde{q}_i < \overline{q_i}$, $q_i^{NS} = argmin\{EC_i(q_i|Q_{-i})\} = q_i^c(0,\theta)$, which is the same under strict liability. If $\tilde{q}_i \geq \overline{q_i}$, $q_i^{NS} = argmin\{EC_i(q_i|Q_{-i})\} = \overline{q_i} > q_i^{BL}$, which is greater than q_i^{SL}. In case b), $q_i^{min}(0,\theta) = 0$ under the strict liability rule. If $\tilde{q}_i < \overline{q_i}$, $q_i^{min} = 0$ under the negligence standard, $q_i^{NS} =$

$argmin\{EC_i(q_i|Q_{-i})\} = 0$, which is the same as under strict liability. However, if $\tilde{q}_i \geq \overline{q_i}$, $q_i^{NS} = argmin\{EC_i(q_i|Q_{-i})\} = \overline{q_i}$ under the negligence standard, which is greater than $q_i^{SL} = q_i^{BL} = 0$.

Proof of Proposition 2

Given the concavity of $EW_i(q_i^{VA}|Q_{-i}^{VA})$ and the convexity of $C_i(q_i^{VA})$, the Nash program (9) is concave and therefore has a solution q_i^{VA}. This implies that the policymaker and landowner *i* always reach a VA.

To prove that $q_i^{VA} > q_i^{BL}$ for any *i*, we show that any $(q_1^{VA}, \ldots, q_n^{VA})$ with $q_k^{VA} \leq q_k^{BL}$ for some *k* cannot be an equilibrium because the policymaker would have incentives to deviate. Note that under a VA, the landowner will not face any additional forest patrol assessment, and there exits $\overline{q}_k^{VA}$>q_k^{BL} such that $EC_i^{VA}(\overline{q}_i^{VA}|Q_{-i}^{VA}) = EC_i(q_i^{BL}|Q_{-i}^{BL}) + \Delta_i$. To prove this, note that $EC_i^{VA}(q_i^{NI}|Q_{-i}^{VA}) > EC_i(q_i^{BL}|Q_{-i}^{BL}) + \Delta_i$. Otherwise, we must have $EC_k^{VA}(q_k^{BL}|Q_{-k}^{VA}) = EC_k(q_k^{BL}|Q_{-k}^{BL}) + \Delta_i$, which means $Q_{-k}^{VA} < Q_{-k}^{BL}$. This, together with $q_k^{VA} \leq q_k^{BL}$, implies $EW_k(q_k^{VA}|Q_{-k}^{VA})$<$EW_k(q_k^{BL}|Q_{-k}^{BL}) + W(\sum \Delta_i)$, which contradicts the assumption that $(q_1^{VA}, \ldots, q_n^{VA})$ is an equilibrium. Therefore, there exits $\overline{q}_k^{VA}$>q_k^{BL} such that $EC_i^{VA}(\overline{q}_i^{VA}|Q_{-i}^{VA}) = EC_i(q_i^{BL}|Q_{-i}^{BL}) + \Delta_i$. This implies that the policymaker would be better off if he requests a mitigation level between $\overline{q}_k^{VA}$and q_k^{BL} and the landowner would accept it. This proves that that $q_i^{VA} > q_i^{BL}$ for any *i*.

Proof of Proposition 3

i) From lemma 4, $q_{max}^{NS} > q_{max}^{BL} \geq q_{max}^{SL}$. Thus, when $\bar{Q} > Q_{min}^{NS}$, $\bar{Q} >, q_{max}^{NS} > q_{max}^{BL} \geq q_{max}^{SL}$, $Q^{NS} = Q^{SL} = Q^{BL} = 0$. The result $Q^{VA} > Q^{NS} = 0$ follows directly from proposition 2.

ii) From lemma 4, $q_{max}^{NS} > q_{max}^{BL} \geq q_{max}^{SL}$. Thus, when $\bar{Q} \leq q_{max}^{SL}$, $\overline{Q} \leq q_{max}^{SL} \leq q_{max}^{BL} < q_{max}^{NS}$. $Q^{NS} > Q^{BL} \geq Q^{SL} > 0$. To show that $q_i^{VA} \geq q_i^{NS}$ for sufficiently large α^i, it suffices to show that $q_i^{VA} \rightarrow \overline{q}_i^*$ as $\alpha^i \rightarrow 1$ because $q_i^{NS} = \overline{q_i} \leq \overline{q}_i^*$, where $(\overline{q}_1^*, \ldots, \overline{q}_N^*)$ denote the levels of effort that maximize the aggregate social welfare. To prove $q_i^{VA} \rightarrow \overline{q}_i^*$ as $\alpha^i \rightarrow 1$, note that the first-order condition that defines

$(\overline{q}_1^*, \ldots, \overline{q}_N^*)$ is:

$$\frac{\partial EW_i}{\partial q_i} = 0,\ i = 1, \ldots, n \tag{A3}$$

The first-order condition that defines $(q_1^{VA}, \ldots, q_n^{VA})$:

$$\alpha_i[\textstyle\sum_{i=1}^{n} EW_i(q_i|Q_{-i}) \ - EW^0]^{\alpha_i-1} \frac{\partial EW_i}{\partial q_i} \left[EC_i^0 - C_i\left(q_i^{VA}\right)\right]^{1-\alpha_i}$$

$$+[\textstyle\sum_{i=1}^{n} EW_i(q_i|Q_{-i}) \ - EW^0]^{\alpha_i}(1-\alpha_i)\left[EC_i^0 - C_i(q_i)\right]^{-\alpha_i}\left(-\frac{\partial C_i(q_i)}{\partial q_i}\right) = 0, i \ = \ 1, \ldots, n \tag{A4}$$

As $\alpha_i \to 1$, (A4)→(A3), which implies that $q_i^{VA} \to \overline{q}_i^*$ as $\alpha^i \to 1$. Therefore, for sufficiently large α_i, $q_i^{VA} \geq q_i^{NS}$.

iii) The result that $Q^{NS} > Q^{BL} \geq Q^{SL}$ follows directly from lemma 3. Also, as shown in ii), as $\alpha_i \to 1$, $q_i^{VA} \geq q_i^{NS}$. Therefore, when α^i is sufficiently large for all *i*, $Q^{VA} \geq Q^{NS}$.

iv) These results follow directly from the result that as the level of cost sharing γ varies from zero to one, $q_i^c(\gamma, 0)$ varies from the level without any regulation, $q_i^c(0,0)$, to the maximum mitigation level possible.

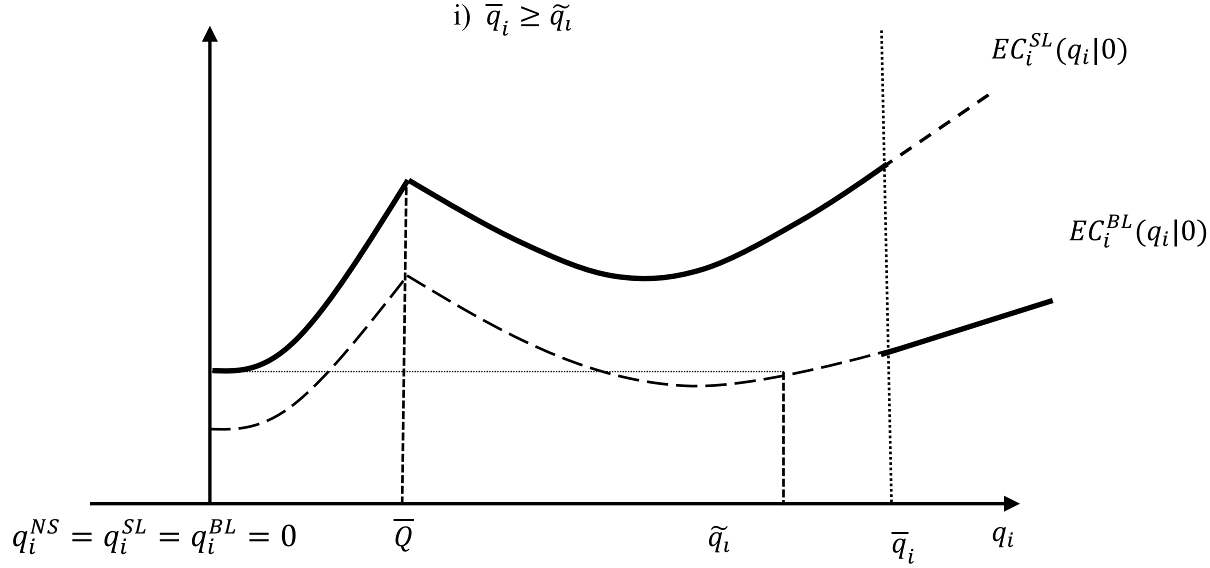
Proof of Proposition 4

Result (i) follows directly from (i) of proposition 3. To prove (ii) and (iii), note from propositions 3 that $q_i^* \geq q_i^{VA} \geq q_i^{NS} > q_i^{BL} \geq q_i^{SL}\ \forall i$. Since $q_i^* = \arg\max EW^i\left(q^i\right)$, expected welfare is increasing in this range of q, and it follows that $EW^{VA} \geq EW^{NS} > EW^{BL} \geq EW^{SL}$.

(iv) From the first-order condition that defines the optima level of cost sharing (10), we can show that when δ is sufficiently large, the optimal level of cost sharing $\gamma^* = 0$. In this case, the expected welfare under the cost sharing program EW^{CS} equals EW^{BL}. However, when $\delta = 0$, $\gamma^* = argmax_\gamma\left\{EW_i\left(q_i^c(\gamma, 0)|Q_{-i}^c(\gamma, 0)\right)\right\}$, and $q_i^{CS} = q_i^* \geq q_i^{VA}\ \forall i$, which implies that $Q^{CS} \geq Q^{VA}$.

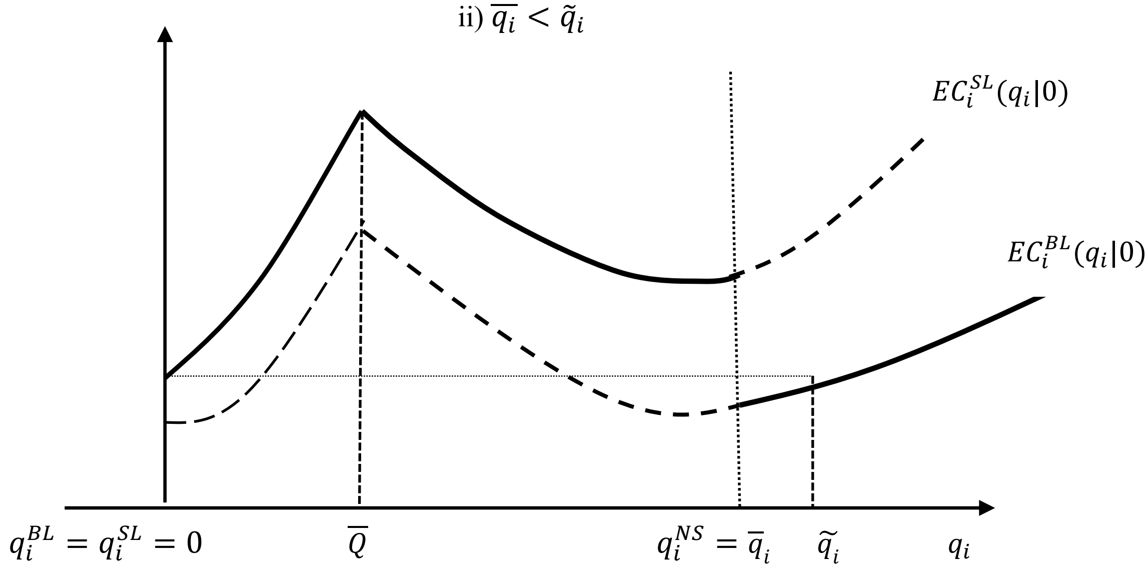
Figure 3a. Equilibrium outcome for negligence standard with no mitigation in the baseline

i) $\overline{q}_i \geq \tilde{q}_i$



Denotes the effective cost function under the negligence standard

ii) $\overline{q_i} < \tilde{q}_i$



Denotes the effective cost function under the negligence standard