Risk Externalities and the Problem of Wildfire Risk

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Abstract
Homeowners living in the wildland urban interface face a decision of whether or not to create a defensible space around their house in order to reduce the risk of a wildfire destroying their home. Risk externalities complicate this decision; the risk that one homeowner faces depends on the mitigation decisions of neighboring homeowners. This paper models the problem as a game played between neighbors in a wildland urban interface. Multiple Nash equilibria may exist, some of which are sub-optimal. The model predicts outcomes that are consistent with mitigation outcomes in many communities: in some communities just about everyone mitigates while in other communities almost no one mitigates. The model provides insights into the likely effectiveness of current programs designed to encourage households to mitigate as well as the prospects for insurance to provide incentives for economically efficient mitigation.

Key Words: risk, externalities, forest, coordination games, Nash equilibrium, tipping
JEL Classification: Q23, C72, D81, Q58

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1 Introduction

In the period 1960 - 2003, the average number of wildfires per year in the U.S. was over 133,000. The average number of acres burned per year over this period was over 4 million while the average annual cost of suppression was over $824 million.\(^1\) While living with wildfire has always been a fact of life in much of the U.S., development in the wildland urban interface (WUI) is growing rapidly. As noted in a recent U.S. Fire Administration paper\(^2\), “In the Western U.S. alone, 38% of new home construction is adjacent to or intermixed with the WUI.” Growth in the WUI implies increased risk of property loss and increased costs of defending structures against wildfires when threatened. In the 2003 fire season, 2,381 structures were lost to wildfire, 835 of these primary residences.\(^3\) The frequency of fires, particularly in times of drought, combined with increased exposure to wildfire risk has created what many politicians view as a considerable management problem. For example, the problem of wildfire management was used to justify passage of the Healthy Forests Restoration Act of 2003.

While much of the wildfire legislation and directives emphasize managing public lands, particularly with regards to reducing fuel loads and coordinating suppression across agencies, a fair amount of emphasis has also been placed on encouraging private property owners to protect themselves against wildfire risks. Programs such as Firewise which is sponsored by the National Wildfire Coordinating Group, target information to individual homeowners while communities are targeted through the Firewise Communities program.\(^4\)

Through proper mitigation, homeowners can greatly reduce the fire risk of property loss. Building a house with a fire-resistant roof and walls is an important part of protecting a house from wildfires. Similarly, managing fuel loads around the house by creating a defensible space will also help to protect the house. Removing trees, bushes, firewood, and other flammable material

\(^1\)Data for these calculations was obtained from National Interagency Fire Center, http://www.nifc.gov/stats/wildlandfirestats.html


\(^3\)http://www.usfa.fema.gov/statistics/wildfire/

\(^4\)According to the firewise website (http://www.firewise.org), members of the NWCG are responsible for wildland fire management in the United States. They represent the USDA-Forest Service, the Department of Interior, the National Association of State Foresters, the U.S. Fire Administration and the National Fire Protection Association. The NWCG’s Wildland/Urban Interface Working Team directs the Firewise program.
from the 30 feet surrounding the house greatly reduces the risk that fire will come in direct contact with the structure, thereby reducing risk of fire damage to the house. Beyond 30 feet, trimming trees, removing dead underbrush, and creating fire breaks will also greatly reduce risk of fire damage to the house.⁹

Despite the benefits that homeowners face from creating a defensible space, many homeowners living in the WUI choose not to do so. Currently, insurance companies do not provide any incentives in the form of lower premiums for homeowners who create defensible space, though premiums are differentiated according to building materials. In the Rocky Mountain region, State Farm Insurance has unilaterally announced it is considering requiring defensible space as a condition of insurance which is essentially a penalty for not creating defensible space.

Several papers have estimated individual willingness to pay for various private and public risk reduction options including defensible space (Fried et al. [8], McKee et al. [14], Talberth et al. [18]). The results suggest that individuals have a positive willingness to pay even when insured, but that some public programs could reduce private expenditures on risk reducing activities. Winter and Fried [21] conducted focus groups to gauge homeowners’ attitudes towards wildfire risk and perceptions of who is responsible for reducing risk. Many homeowners expressed the opinion that wildfire risk reduction is a shared responsibility between homeowners and public agencies. They accepted the notion that they are responsible for protecting their own house by creating defensible space, but they also believe that defensible space is only effective in conjunction with public risk reducing activities.

This paper extends the wildfire literature by considering the spillover effect that one agent’s mitigation has on other agents’ risk. In a recent working paper, Brenkert, Champ, and Flores [2] report the results of a series of qualitative in-person interviews with WUI households. When asked why they have not created a defensible space or undertaken other mitigation measures, some WUI homeowners noted that their own mitigation actions are of little value given fuel loads on their neighbor’s property, including adjacent public lands. This is true since other houses in the area can act as fuel for the fire, causing it to gain speed and intensity and quickly burn everything in the area. The effect of these spillovers is to create a coordination game between

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⁹Institute For Business and Home Safety, "Is Your Home Protected From Wildfire Disaster? A Homeowner’s Guide To Wildfire Retrofit"
neighbors which suggests several policy directions not yet considered in the literature.

Spillovers from defensive expenditures have been discussed in the context of the control of gypsy moths. Jakus [12] presents a model where one agent’s averting behavior benefits other agents’ utility as well as influencing the price of averting behavior for everyone. However, Jakus’s model does not examine risk reduction spillovers, only utility and price spillovers.

The approach of this paper is closest to that of Kunreuther and Heal [13] and Heal and Kunreuther [11], who refer to the problem of risk externalities as interdependent security. Their leading example is airline security. If airlines can only carefully screen bags that they check and not bags which are transferred from other airlines, then they face some risk of a bomb getting on the plane from the lack of security on the part of other airlines. In their model, if few airlines are screening bags, the benefit of screening bags is small because it is likely that a bomb could get on the plane from other airlines. As more airlines choose to screen bags, the benefit of screening bags increases.

The wildfire mitigation problem is similar to this example since the actions of other agents impact the risk that one agent faces. However, there are several important differences. First, the way one agent’s actions interact with the actions of other agents is different. Instead of adding the probabilities of several independent events occurring, everyone’s actions impact the probability of a single event occurring. Second, the actions of other agents can impact an agent’s risk in two ways - directly reducing the risk and indirectly affecting risk by increasing the effectiveness of mitigation. In the Kunreuther and Heal papers, other agents can only directly reduce risk, they cannot impact the effectiveness of mitigation. Finally, unlike the example above, the benefits of mitigation do not have to be strictly increasing as more people mitigate. Rather, the benefits increase at first, then decrease.

Following on the work of Kunreuther and Heal, this paper presents a model of interdependent security where private benefits of risk reducing measures are increasing when the first few other agents undertake risk reducing measures, but then begin to decrease once a sufficient number of other agents have undertaken the measures. The model describes wildfire risk mitigation decisions and predicts outcomes that are consistent with mitigation outcomes in many communities: in some communities just about everyone mitigates while in other communities almost no one mitigates. The model provides insights into the likely effectiveness of current programs designed to encourage households to mitigate as well as the prospects for insurance to provide
incentives for economically efficient mitigation. The remainder of the paper is organized as follows. The next section provides some background on the science of wildfires and wildfire risk mitigation. Section 3 presents the basic model and discusses social welfare. Section 4 adds insurance to the model. Section 5 considers the case of heterogeneous mitigation costs. Section 6 discusses the policy implications of the model. Section 7 concludes.

2 The Wildfire Problem

Prior to the 20th century, many dry forests in the West featuring ponderosa pine and Douglas fir experienced low severity fires as frequently as every 4 to 25 years (Graham et al. [9]). These fires cleared out surface fuels and ladder fuels, leaving a vertical gap between the ground and the canopy above. The effect was to reduce the probability of crown fires. By having frequent small fires, the chance of a large high intensity crown fire is reduced. As humans began to develop in forests, the policy of fire suppression led to a decrease in the number of fires. The effect of fire suppression has been to increase the amount of surface fuels and ladder fuels and decrease the vertical gap between these fuels and the canopy. As a result, surface fires today are much more likely to turn into crown fires than in the past. The fires in 2000, 2002, and 2003 in Arizona, California, and Colorado are examples of large high intensity crown fires that occurred as a result of the buildup of surface and ladder fuels. This change in the forest structure over the last hundred years is important because crown fires are the biggest threat to houses and other manmade structures in the forest. Crown fires spread faster and have higher intensity than surface fires and are therefore a bigger threat for igniting houses. Once a wildfire reaches a certain intensity (about 500 Btu/ft/sec) fire departments are unable to defend houses against the fire (NFPA [1]). The increased probability of crown fires in recent years combined with the inability to protect houses from intense crown fires presents an important policy issue.

Homeowners are advised to create a defensible space of 10 meters around their house and use fire-safe materials when constructing the house in order to protect the house from wildfires (NFPA [1]). However, for intense crown fires under extreme weather conditions such as those described above, this may not be enough. For example, in the Stephan Bridge Road Fire in 1990, some houses burned which had created 300 feet of defensible space (Winter
The Structural Ignition Assessment Model (SIAM) predicts that intense crown fires could ignite houses up to 40 meters away under certain conditions (Cohen [4]). In five experiments conducted by Cohen [4] with houses at a distance of 10 meters, two of the houses ignited.

To protect a house from crown fires, either a larger fire break must be created or the structure of the forest must be changed in the vicinity of the house. The process of thinning reduces the likelihood of crown fires by removing ladder fuels, reducing surface fuels, and decreasing crown density. Thinning must be horizontal as well as vertical. That is, a vertical fuel gap between the ground and the canopy must be created as well as spreading the fuel horizontally along the ground. While thinning an entire forest by mechanical means (as opposed to prescribed burnings) is not feasible, thinning in strategic places can have a significant impact on fire behavior (Graham [9]). Even thinning in random places has some impact, especially in the local area. In other words, random thinning in a wildland urban interface, while not preventing the spread of large crown fires, may redirect the fire away from the WUI or reduce the intensity of the fire in the WUI.

The act of creating a defensible space is similar to thinning: surface fuels, ladder fuels, and crown fuels are removed within a 30 foot radius of a house. So, as more homeowners in the WUI create a defensible space around their homes, the structure of the forest will be equivalent to a forest which has been thinned in a random manner. As described above, this could have a significant impact on the intensity of the fire in the WUI and may prevent crown fires which approach the WUI from spreading through the WUI. The more homeowners which create the defensible space, the stronger this effect will be.

In short, homeowners who create a defensible space alone will protect their homes from surface fires but unless their defensible space is large in size (20 meters or more), crown fires will still be a threat. Creating a defensible space has a spillover effect which decreases the chance of crown fires in the WUI. So, as more homeowners create a defensible space, all homes in the WUI become protected from crown fires. Creating defensible space is a private good for surface fire protection but a public good for crown fire protection. Furthermore, collective action on the part of residents of the WUI to thin the public lands adjacent to the WUI will further reduce the threat of crown fires destroying their community.

Our objective is to model defensible space as a good which has private benefits as well as public spillover effects. If the cost of defensible space
is high enough that the private benefits alone do not warrant creating the space, then the optimal decision about whether to create defensible space depends on neighboring homeowners’ decisions.

3 The Model

The next section describes a basic two player model. Then, a more general model is presented with more than two players, and social welfare is discussed. The solution to the model suggests that a coordination failure is possible. The final part of this section discusses the coordination failure as well as the possibility of tipping to correct it.

3.1 Two Agent Model

Assume that each agent has income $Y$ and faces a risk of loss $L$ if a wildfire destroys their house. According to (need to get reference), in most fires a house either survives undamaged or is destroyed, but partial losses are uncommon. So, we assume the loss is either $0$ or $L$. The baseline probability that a wildfire destroys an agent’s house is $r$. The baseline probability is assumed to be exogenous in the sense that none of the agents are responsible for starting the fire. For example, the fire may be started by lightning, camping fires, or cigarettes carelessly discarded by motorists. There are two ways that the actual probability an agent faces can be less than $r$. First, the agent can invest in mitigation by creating a defensible space around their home. This incurs a cost of $c$ but reduces the probability by $p$ where $0 < p < 1$. Second, the agent benefits from the mitigation of his or her neighbor. This reduces the probability by $q$ where $0 < q < 1$. The agent chooses whether or not to invest in mitigation in order to maximize his or her expected wealth. The agent chooses between two strategies: $S$, to invest in mitigation, and $N$, not to invest. The agents’ payoffs are shown in Table I.

If $c < qrL(1-p)$, then (S,S) is a dominant strategy equilibrium because the cost of clearing trees is less than the expected benefit regardless of what the other player does. If $qrL(1-p) < c < rL(1-p)$, then (S,N) and (N,S) are both Nash equilibria. In this case, if you can free ride on the other player’s choice of S, you are better off choosing N but if the other player is choosing N then choosing S becomes worthwhile. If $c > rL(1-p)$, then (N,N) is a dominant strategy equilibrium because the cost of clearing trees is greater
Table 1: Payoffs in two-player game

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>$Y - qrL, Y - c - prL$</td>
<td>$Y - rL, Y - rL$</td>
</tr>
</tbody>
</table>

than the expected benefit.

### 3.2 Multiple Agent Model

Now suppose there are $N$ identical agents who all face the same probabilities and costs. An agent affects his or her neighbor’s risk in two ways. There is a direct effect that as more people invest in mitigation, it becomes less likely that a wildfire will reach an agent’s property. Let $q(n)$ be the effect of other people mitigating on the probability of a wildfire reaching an agent’s property; $q(n)$ is a decreasing function of $n$, the number of other people who invest in mitigation. In the extreme case where everyone mitigates, $q(n)$ approaches zero. This is like a house completely surrounded by neighbors who have all created a defensible space. So, all of the neighbors actions work in place of someone doing it themselves. This effect is similar to the problem of vaccinations described by Kunreuther and Heal [?].

The second effect is indirect - as more people invest in mitigation, the effectiveness of mitigation increases. As more people mitigate, the fire will be less intense when it reaches the property and therefore defensible space is more likely to successfully protect the house. Let $p(n)$ be the effect of an agent mitigating on the probability of a wildfire destroying his or her house; $p(n)$ is a decreasing function of $n$.

The expected payoff for an agent choosing $S$ is $Y - c - p(n)q(n)rL$ and the payoff for someone choosing $N$ is $Y - q(n)rL$. An agent will choose $S$ if $c < PB(n)$ where $PB(n) = [1 - p(n)]q(n)rL$. The resulting equilibrium will depend on the specific form of $p(n)$ and $q(n)$.

When very few people are creating a defensible space, the benefit of doing so is very small since a fire will have so much speed and intensity upon reaching the property that clearing trees is ineffective at protecting the house. Only when enough people are clearing trees will mitigation have a decent chance at saving the house. When the number of people clearing trees gets
very large, it becomes unlikely that a fire will reach the property and so the choice to clear trees is less beneficial. So, the benefits of mitigation increase at first and then decline.

At issue is the strategic complementarity and substitutability of wildfire mitigation decisions (see Bulow, Geanakoplos, and Klemperer [3] and Cooper and John [6]). The examples of Kunreuther and Heal fall into the category of either strategic complements (airline security) or strategic substitutes (vaccination). In contrast, other agent’s wildfire mitigation decisions can be either strategic complements or substitutes depending on how many other agents have chosen to mitigate.6

Assume that \( p'(n)q(n) > q'(n)p(n) \) for small \( n \) and the opposite is true for large \( n \). Then the benefit function will increase at first, then decrease. The following proposition states the equilibria which are possible in this scenario.

**Proposition 3.1** Define \( n^* \) such that \( PB(n^*) < c < PB(n^* - 1) \). If \( n^* \) exists, it is a Nash equilibrium for \( n^* \) agents to choose \( S \) and \( N - n^* \) to choose \( N \). If \( c < PB(N - 1) \), then it is a Nash equilibrium for everyone to choose \( S \). If \( c > PB(0) \), then it is a Nash equilibrium for everyone to choose \( N \). Furthermore, if \( c > \max[PB(n)] \), then everyone choosing \( N \) is a dominant strategy equilibrium for all players. If \( c < \min[PB(n)] \), then everyone choosing \( S \) is a dominant strategy equilibrium for all players.

There are five cases that come from this proposition:

1. The only equilibrium is everyone choosing \( N \).
2. The only equilibrium is everyone choosing \( S \).
3. There are two equilibria: one where everyone chooses \( N \) and one where \( n^* \) agents choose \( S \) and \( N - n^* \) choose \( N \).
4. There are two equilibria: one where everyone chooses \( N \) and one where everyone chooses \( S \).
5. The only equilibrium is for \( n^* \) agents to choose \( S \) and \( N - n^* \) to choose \( N \).

Figure [1] illustrates the five cases for continuous \( n \).

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6For other examples where choices change between strategic complements and substitutes, see Schelling [15], pp. 239-41.
Figure 1: Equilibria
3.3 Social Welfare

Define the social marginal benefit as the total benefit to all agents from one agent choosing S. This can be expressed as function of how many other agents are choosing S. Then, \( SMB(n) = [1 - p(n)]q(n)rL + nrL[p(n - 1)q(n - 1) - p(n)q(n)] + (N - n - 1)rL[q(n) - q(n + 1)] \). Assume that \( SMB(n) \) has the same form as \( PB(n) \), increasing then decreasing in \( n \). Define \( n^s \) such that \( SMB(n^s + 1) < c < SMB(n^s) \). If no such \( n^s \) exists, then let \( n^s = N \). The following proposition identifies the Pareto optimal situation.

**Proposition 3.2** If the only equilibrium is for everyone to choose N and if \( \sum_{n=0}^{n^s-1} SMB(n) < cn^s \), then it is socially optimal for everyone to choose N. For all other cases, it is socially optimal for \( n^s \) agents to choose S.

For cases 3 and 5, where one equilibrium was for \( n^s \) agents to choose S, note that \( n^s > n^s^* \). In other words, it is socially optimal for more agents to mitigate than will in equilibrium. This is because the agents deciding to mitigate do not experience the full social benefit from mitigating due to the positive externality.

For case 3 where it is optimal for \( n^s \) agents to mitigate, an interesting question is whether it is preferable for \( n^s^* \) to mitigate or no one to mitigate. The following corollary addresses this question.

**Corollary 3.3** If there are two equilibria, the equilibrium where some agents choose S Pareto-dominates the equilibrium where no one chooses S.

3.4 Tipping

Cases 3 and 4 are examples of coordination games with multiple Pareto-ranked equilibria (see Cooper and John [6]). There are two kinds of coordination failure that can occur. It is possible that no equilibrium is reached or that the Pareto-dominated equilibrium is reached. Harsanyi and Selten [10] argue that payoff dominance should guide equilibrium selection. Agents should coordinate on the equilibrium, if it exists, which has the highest payoffs for everyone. In this model, the equilibrium where some agents choose S always payoff dominates the equilibrium where everyone chooses N.

However, experimental evidence has shown that agents often focus on the risk dominant equilibrium (Cooper et al. [5]; Straub [17]; Schmidt et al. [16]). Risk dominance captures the notion that some strategies are more
Table 2: A Stag Hunt Game

<table>
<thead>
<tr>
<th></th>
<th>( U_1 )</th>
<th>( V_1 )</th>
</tr>
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<tbody>
<tr>
<td>( U_2 )</td>
<td>9,9</td>
<td>0,8</td>
</tr>
<tr>
<td>( V_2 )</td>
<td>8,0</td>
<td>8,8</td>
</tr>
</tbody>
</table>

risky than others because if an agent follows the strategy for one equilibrium and others do not, that agent faces much lower payoffs. For example, consider the two player game in Table \( \text{2} \) (taken from Harsanyi and Selten \[\text{10}\], p.89). Although \((U_1, U_2)\) is the payoff dominant equilibrium, it is more risky since the resulting payoff could be either 0 or 9. The equilibrium \((V_1, V_2)\) is risk dominant because both agents guarantee themselves payoffs of 8, thereby reducing (in fact, eliminating) the strategic uncertainty. Formally, \( V \) risk dominates \( U \) because the Nash product of \( V \) (64) is greater than the Nash product of \( U \) (1).

If an agent believes that any outcome is equally likely, then choosing \( N \) is risk dominant if the sum of the benefits to choosing \( N \) when it is the preferred choice outweigh sum of the benefits of choosing \( S \) when \( S \) is the preferred choice. However, since the initial state of the world is unmitigated, agents may interpret this as a signal that other agents will not mitigate. In this case, agents believe that everyone or most agents choosing \( N \) is more likely than other outcomes. In this case, choosing \( S \) is more risky. So, the equilibrium where everyone chooses \( N \) is risk dominant if agents have beliefs that other will not mitigate.

Another equilibrium selection criteria, called security by van Huyck et al. \[\text{19}\], is that agents want to avoid big losses associated with the worst-case scenario. The maximin approach avoids this problem by choosing the strategy that has the largest worst-case payoff. For players choosing \( S \), the worst-case payoff occurs when no one else chooses \( S \), yielding a payoff of \( Y - c - p(0)q(0)rL \). For players choosing \( N \), the worst-case payoff also occurs when no one chooses \( S \), yielding \( Y - q(0)rL \). By assumption, in cases 3 and 4, \( Y - q(0)rL > Y - c - p(0)q(0)rL \). This implies agents following a maximin strategy would always choose \( N \). So, if agents care about security, the observed outcome will be the equilibrium where everyone choose \( N \).

Despite the fact that the initial state of the world is unmitigated and agents may hesitate to be the first and only homeowners to mitigate, effec-
tive policy should be able to overcome the coordination failure and lead to the preferred outcome. Policy should take advantage of the possibility for tipping to occur. There exists a tipping point such that, below the tipping point, no one has incentive to unilaterally mitigate, but once the point is reached, it becomes in the interest of other agents to follow until the preferred equilibrium is reached. In order to overcome the coordination failure, a small group of agents must coordinate rather than the entire community.

Define the tipping point, \( n_{\text{tip}} \), such that \( PB(n_{\text{tip}} - 1) < c < PB(n_{\text{tip}}) \). Figure 1 shows \( n_{\text{tip}} \) for the relevant cases. If a coalition of \( n_{\text{tip}} \) agents commit to choosing S, then the only Nash equilibrium is the equilibrium where some or all agents mitigate. It is no longer a Nash equilibrium for everyone to choose N. Alternatively, if all agents believe that at least \( n_{\text{tip}} \) agents will choose S, then agents will coordinate on the preferred equilibrium.

In experiments, van Huyck et al. [20] show that the outcome of games is sensitive to initial conditions. If agents begin on one side of the tipping point, they converge on one equilibrium; if they begin on the other side of the tipping point, they converge on the other equilibrium. The goal of policy, therefore, is to change the structure of the game so that the initial state has or appears to have at least \( n_{\text{tip}} \) agents mitigating.

### 4 Insurance

In practice, homeowners purchase a positive amount of insurance due to lender requirements as well as their own risk preferences. If mitigation information is not used to set premiums, insurance may discourage mitigation. This is the moral hazard problem. If mitigation information is used to set premiums, insurance may overcome the coordination problem and induce mitigation in situations where it would not occur without insurance. Moreover, the cost to the insurance company may be less than the cost of mitigation. This result depends on the cost of verifying mitigation.

Assume that individuals cannot insure themselves for the total loss because of non-market aspects to losing a house such as losing family heirlooms. As a result, homeowners can insure their house for at most \( l < L \). Assume that insurance markets are competitive, and let \( x >= 0 \) be the cost

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7Similar examples of tipping a game to a new equilibrium are explained in Heal and Kunreuther [11], Schelling [15], and Dixit [7].

8Fried et al. [8] and McKee et al. [14] provide evidence that supports this assumption.
of verifying that one house has mitigated. Risk averse agents will purchase the maximum possible insurance if priced competitively. Risk neutral agents will be indifferent between any amount of competitively priced insurance. We assume that they also purchase the maximum possible insurance. Define $PBI$ as the marginal private benefit to mitigating when insured for a loss of $l$. Then, $PBI(n) = [(1 - p(n))q(n)r(L - l)]$.

If insurance companies do not use mitigation information to set premiums, they will set premiums equal to their expected payout. Their expected payout depends on how many agents mitigate in equilibrium. We assume that when $c > PBI(0)$, insurance companies will price insurance based on the equilibrium where no one mitigates. So, if $c > PBI(0)$, premiums are set at $q(0)rl$, the expected payout when no one mitigates.

Insurance companies may be able to offer premium discounts to homeowners who mitigate. Let $\pi_S$ be the premium for homeowners who mitigate and let $\pi_N$ be the premium for those who do not. If $PBI(N - 1) > PBI(0)$, the only discount which will induce any mitigation will induce all agents to mitigate. The zero-profit conditions are:

\[
\pi_S = p(N - 1)q(N - 1)rl + x
\]

and

\[
\pi_N = q(N - 1)rl
\]

The discount $d$ for mitigating is $\pi_N - \pi_S$:

\[
d = [1 - p(N - 1)]q(N - 1)rl - x
\]

If $d > c$, then the premium discount offered by insurance companies is greater than the cost of mitigation. This discount will always induce mitigation. Even when $d < c$, the discount can effectively induce mitigation because of the uninsurable loss. The effect of the premium discount is to lower the cost of mitigation to $c - d$. For the discount to actually induce mitigation, the following condition must hold:

\[
c - d \leq PBI(0)
\]

Substituting for $d$ in the previous equation,

\[
x \leq PBI(0) + [1 - p(N - 1)]q(N - 1)rl - c
\]
If this condition is not met, then the largest premium which insurance companies can profitably offer is not enough to induce any homeowners to mitigate. If \(c\) is large enough, this condition may not be met even when \(x = 0\).

When \(x=0\), insurance companies discount premiums by the expected insured loss. Homeowners’ total benefit to mitigation will be the decreased expected uninsurable loss and the decreased premium. At equilibrium, this will equal the total expected loss. That is, at equilibrium, homeowners’ get the same benefit to mitigation as the game without insurance, but they face less risk.

As \(x\) increases, the discount offered by insurance companies decreases until \(x\) is so high that no discount is offered.

These results are summarized in the following proposition:

**Proposition 4.1** Let \(d = [1 - p(N - 1)]q(N - 1)r - x\). If \(x <= [1 - p(N - 1)]q(N - 1)rL - [PB(N - 1) - PB(0)] - c\), then competitive insurance companies can induce all homeowners to mitigate by offering premium discounts of \(d\) in return for mitigation. Otherwise, insurance companies cannot profitably use premium discounts to induce any mitigation.

## 5 Heterogeneous Costs

There are two ways to interpret heterogeneity in mitigation costs. First, houses have variation in the initial level of fuel load found on the property. This causes the cost of reducing the fuel load to differ among homeowners. A second interpretation is that the cost parameter captures variation in taste for trees. Some homeowners who live in a wildland urban interface specifically choose to do so because they want to live in the forest.\(^9\) The cost of clearing the forest around their house is therefore made up of two parts: the physical cost of clearing and the utility cost. Homeowners who prefer to live in the trees in general will have a higher cost of creating a defensible space than those who don’t care.

With heterogeneous costs, there are many more possible equilibria. Let \(c_i\) be the cost of mitigation for the \(i^{th}\) homeowner for \(i = 1, ..., N\). Without loss of generality, let \(c_1 <= c_2 <= ... <= c_N\). Then, the following proposition defines all equilibria.

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\(^9\)See Fried et al. [8]
Proposition 5.1 Consider all values of \( n^* \) such that \( c_{n^*+1} > PB(n^*) \) and \( c_{n^*} < PB(n^* - 1) \). For every \( n^* \), it is a Nash equilibrium for \( n^* \) agents to choose \( S \) and \( N - n^* \) to choose \( N \). If \( c^N < PB(N - 1) \), then it is also a Nash equilibrium for everyone to choose \( S \). If \( c_1 > PB(0) \), then it is also a Nash equilibrium for everyone to choose \( N \). Furthermore, if \( \min(c_n) > \max(PB(n)) \), then everyone choosing \( N \) is a dominant strategy equilibrium for all players. If \( \max(c_n) < \min(PB(n)) \), then everyone choosing \( S \) is a dominant strategy equilibrium for all players.

There could be zero, one, or more than one value of \( n^* \) that satisfies the condition in the proposition. There is always at least one equilibrium, but there could be more. The five cases discussed in Section 3.2 are still possibilities. However, there are additional cases from this proposition, and there could be more than two equilibria.

For cases 3 and 5 from Section 3.2, when there are equilibria where some choose \( N \) and some choose \( S \), a few more comments can be made. It is possible for a member of the group choosing \( S \) to have higher mitigation costs than a member from the group choosing \( N \). However, the general trend should be that the group choosing \( S \) has lower mitigation costs than the group choosing \( N \). In other words, homeowners with more fuel load on their property or who have strong preferences for trees are more likely to free ride on the mitigation of other homeowners.

When there are multiple equilibria, for every pair of equilibria, \( n^i \) and \( n^{i+1} \), there must be a value of \( n \), denoted \( n^{i-tip} \), such that \( c_{n^{i-tip}} > PB(n^{i-tip} - 1) \) and \( c_{n^{i-tip} + 1} < PB(n^{i-tip}) \). A coalition of \( n^{i-tip} \) agents who all choose \( S \) is enough to tip the game from the equilibrium where everyone chooses \( N \) to the other equilibrium.

Suppose there are a small group of agents with very low mitigation costs and the rest of the agents have higher costs. It is possible that the existence of the agents with low costs tips the game from case 3 to case 5. In other words, the equilibrium where everyone chooses \( N \) is eliminated because some agents have mitigation costs low enough that they will always do it. Knowing that these agents will always choose \( S \) then makes it in the interest of even more agents to choose \( S \). The result is that the only equilibrium is for \( n^* \) to choose \( S \) and the equilibrium where everyone chooses \( N \) is eliminated.

Another possibility with heterogeneous costs is cascading.\(^{10}\) Suppose we are in a case where there are two equilibria. Suppose if one person unilaterally

\(^{10}\)See Dixit \cite{Dixit}
decided to choose S it would make a second person’s best strategy switch from N to S. The second person changing from N to S then makes a third person’s best strategy switch from N to S. The process can continue in this manner until the preferred equilibrium is reached.

6 Policy Implications

The model developed above gives insight into the potential effectiveness of policies aimed at encouraging homeowners to undertake mitigation measures. First, the model suggests an interaction between mitigation costs and risk externalities. Lowering costs, of even just a few homeowners, can provide the impetus for tipping to a more socially beneficial equilibrium. In Colorado, counties administer Federal funds to provide grants for communities to rent equipment such as wood chippers that make it easier for homeowners to reduce fuel loads. These chippers are typically available for a month or so and their limited time availability often provides the impetus for homeowners to undertake mitigation. Grants of this nature can be quite effective in communities for which there is a coordinating institution such as a homeowners association or road association.

In some instances there are no grant-coordinating community institutions available or willing to take the lead, though there are still substantial risk externalities. In these cases, conditional cash transfers aimed at specific homeowners may be a viable option. Conditional cash transfers are money provided once specific actions are undertaken. Our model suggests that conditional cash transfers need not be made available to all homeowners, though it may be difficult to discriminate or identify how many homeowners need to be offered this option in order to tip the community into a more socially beneficial level of mitigation. A conditional cash transfer program could easily result in a situation where once mitigation begins for some of the homeowners, others also begin to mitigate and perhaps coalesce into a group that may then be able to coordinate as a group.

Risk externalities pose a problem for insurers wanting to offer premium discounts as a means of encouraging mitigation. In particular, an insurer may have difficulty verifying mitigation and fuel load management by policyholders. In order to obtain a socially optimal outcome, an insurer would also need information on mitigation and fuel load management for properties adjacent to policyholders, a seemingly impossible task. While these informa-
tion problems present a problem, they are not intractable. The Firewise Communities Program certifies communities as firewise once the community has satisfied certain management and planning criteria. Communities must continually satisfy these criteria in order to maintain certification. Firewise certification for a community effectively breaks the information impasse for insurers. Insurers could efficiently set premiums with this information.

7 Conclusions

This paper explains the problem of wildfire risk mitigation as a coordination problem. Communities are likely to get stuck at the equilibrium where no one mitigates since no one has incentive to unilaterally change their strategy. However, it may be possible to tip the game to the socially preferable outcome with a relatively small number of homeowners. Furthermore, when verifying mitigation is not too costly, insurance companies can induce mitigation by lowering premiums for homeowners or communities that mitigate.

The model suggests that effective policy should work at the community-wide level and that public information about mitigation has value. The presence of coordinating institutions like homeowners associations can provide the driving force in communities where mitigation is common. In communities where mitigation is not common, conditional cash transfers are a viable option. Further research should address the effectiveness of policies that induce tipping and the role that insurance companies can play at inducing mitigation.

References


