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Risk Externalities and the Problem of Wildfire Risk

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Abstract

Homeowners living in the wildland-urban interface must decide whether or not to create a defensible space around their house in order to mitigate the risk of a wildfire destroying their home. Risk externalities complicate this decision; the risk that one homeowner faces depends on the risk mitigation decisions of neighboring homeowners. This paper models the problem as a game played between neighbors in a wildland-urban interface. The model predicts that one of two outcomes is likely: most or all homeowners have a defensible space or no homeowners have one. Data from Boulder County, Colorado confirm that a household's defensible space decision depends on the defensible space outcomes at neighboring sites. The model provides insights into the likely effectiveness of programs designed to encourage households to create defensible space as well as the prospects for insurance to provide incentives for economically efficient mitigation.

Key Words: wildfire, risk, externalities, coordination games, spatial interactions

JEL Classification: Q23, Q54, C72, D81, C21

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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 emphasizes 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, provide 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

[2] "Fires in the Wildland Urban Interface," U.S. Fire Administration Topical Fire Research Series, Vol. 2, Issue 16, March, 2002.

[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.[5]

Despite the benefits that homeowners face from creating a defensible space, many homeowners living in the WUI choose not to do so. Currently, most 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 recently begun an inspection program under which policies may be dropped if homeowners do not comply with the defensible space requirements within 18 to 24 months following an inspection.[6] Other insurance companies are considering similar programs.

Several papers have estimated individual willingness to pay for various private and public risk reduction options including defensible space (Fried et al. [14], McKee et al. [22], Talberth et al. [27]). The results suggest that individuals have a positive willingness to pay for risk reduction even when insured. However, the presence of public risk-reduction programs may reduce demand for private risk reducing activities like defensible space. Winter and Fried [30] 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. Brenkert et al. [5] 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 neighboring properties, including adjacent public lands. This is true since heavy fuel

[5] Institute For Business and Home Safety, "Is Your Home Protected From Wildfire Disaster? A Homeowner's Guide To Wildfire Retrofit"

[6] USDA Forest Service Fire and Aviation Management Briefing Paper, 8/20/2003

loads in the area cause fires to gain speed and intensity and quickly burn everything in the area. The effect of these risk interdependencies is to create a coordination game between neighbors which suggests new approaches to policy aimed at encouraging risk mitigation.

Spillovers from defensive expenditures have been discussed in the context of the control of gypsy moths. Jakus [18] 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 [20] and Heal and Kunreuther [17], who refer to the problem of risk externalities as interdependent security. Their leading example is airline security. If airlines can only screen bags that they check and not bags which are transferred from other airlines, then they face some risk of a bomb getting on a plane from the lack of security on the part of other airlines. The wildfire mitigation problem is similar to this example since the actions of other agents impact the risk that one agent faces.

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 that one of two outcomes is likely: most or all homeowners mitigate or no homeowners mitigate. The model provides insights into the likely effectiveness of programs designed to encourage households to mitigate as well as the prospects for insurance to provide incentives for economically efficient mitigation.

Data from Boulder County, Colorado support the predictions of the model and confirm the presence of spatial interactions. The defensible space decisions from neighboring homes are a significant determinant of a house's defensible space outcome. An instrumental variable approach is used to control for the simultaneity of defensible space decisions as well as unobserved spatial autocorrelation.

The remainder of the paper is organized as follows. Section 2 provides some background on the science of wildfire and wildfire risk mitigation. Section 3 presents the basic model and discusses social welfare. Section 4 empirically tests for spatial interactions in defensible space decisions. Section 5 discusses the possibility for insurance companies to induce mitigation. Section 6 summarizes 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. [15]). 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 which burn across tree tops. By having frequent small surface 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 man-made structures in the forest. Crown fires spread faster and burn with a 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 30 feet 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, 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 and Fried [30]). The Structural Ignition Assessment Model (SIAM) predicts that intense crown fires could ignite houses up to 40 meters away under certain conditions (Cohen [8]). In five experiments conducted by Cohen [8] 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 [15]). 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.

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 reaching neighboring properties. So, as more homeowners create a defensible space, neighboring 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.

The objective of this paper 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

Assume that there are N identical agents who all face the same probabilities and costs. Each agent has income Y and faces a risk of loss L if a wildfire destroys their house. According to Cohen [8], in most fires a house either survives undamaged or is destroyed; partial losses are uncommon. So, I assume the loss is either 0 or L. The baseline probability that a wildfire destroys an agent's house is r. The probability that a wildfire starts in the vicinity of a house is assumed to be exogenous; 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.

Conditional on a fire starting, let $q(n)$ be the probability that the fire reaches an agent's property, where n is the number of other agents who have defensible space. Assume that $q(n)$ is a decreasing function of n. As more neighbors invest in defensible space, a buffer is created around the property which decreases the chance that a wildfire reaches the property.

Conditional on a fire reaching the property, let $p(n)$ be the probability that defensible space fails to protect the structure. Assume that $p(n)$ is a decreasing function of n. 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. I assume that structures without defensible space are always destroyed when a wildfire reaches the property[7].

Agents choose between two strategies: S, to invest in defensible space, and N, not to invest. Investing in defensible space incurs a cost of c and reduces the probability of a wildfire destroying the house by $p(n)$. The probability that a house is destroyed by wildfire is $p(n)q(n)rL$ for agents choosing S and $q(n)rL$ for agents choosing 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 equilibria will depend on the specific form of $p(n)$ and $q(n)$.

If a homeowners creates defensible space, his or her neighbors benefit in two ways. First, the defensible space acts as a buffer which makes it is less

[7]Homeowners can alter the probability that their house is destroyed (regardless of having defensible space) by investing in structural mitigation. Including another term for the conditional probability that a structure is destroyed given that the fire reaches the structure would make the model more realistic. This term would be independent of n and would therefore have no effect on the results presented here.

likely that a wildfire reaches neighboring homes ($q(n)$ decreases). Second, the defensible space reduces crowning potential in the neighborhood by reducing ladder fuels and by protecting a house which could act as a ladder fuel ($p(n)$ decreases). This second effect makes defensible space more valuable for neighboring homes because it increases the probability that defensible space will successfully protect a home. As a result of the two types of risk reduction spillovers, the benefits of mitigation do not have to be strictly increasing or decreasing as more people mitigate.

This contrasts with previous examples of interdependent security. At issue is the strategic complementarity and substitutability of wildfire mitigation decisions (see Bulow, Geanakoplos, and Klemperer [7] and Cooper and John [10]). The examples of Kunreuther and Heal [20] fall into the category of either strategic complements (airline security) or strategic substitutes (vaccination). In contrast, other agent's wildfire mitigation decisions can be both strategic complements and substitutes depending on how many other agents have chosen to mitigate.[8]

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. When very few people are creating a defensible space, crown fires are likely and so defensible space is not very effective. As more people create a defensible space, the likelihood of crown fires decreases and the benefit of defensible space increases. When the number of homes with a defensible space gets very large, the likelihood that a fire reaches the property decreases and so the benefit of defensible space decreases. Assume also that $PB(N-1) > PB(0)$. This says that the declining benefit of defensible space when it is widespread does not completely undo the benefits the defensible space.

The relative value of the costs and benefits of mitigation will determine the equilibria of the game. If costs are high enough, then the only equilibrium will be for everyone to choose N. This is true if $c > PB(n)$ for all n. In this case, everyone choosing N is a dominant strategy equilibrium.

Similarly, if costs are low enough, then the only equilibrium will be for everyone to choose S. This is true if $c < PB(n)$ for all n. In this case, everyone choosing S is a dominant strategy equilibrium.

When $c > PB(0)$ and $c < max[PB(n)]$, two equilibria exist. One equilibrium is for no one to mitigate. If $c < PB(N-1)$, then the second equi-

[8] For other examples where choices change between strategic complements and substitutes, see Schelling [23], pp. 239-41.

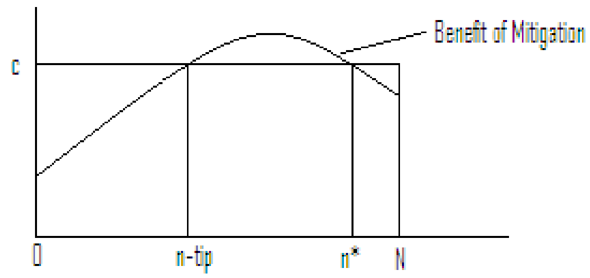

Figure 1: Two Equilibria

librium is for everyone to mitigate. If $c > PB(N-1)$, then define n^* such that $PB(n^*) < c < PB(n^*-1)$. The second equilibrium is for n^* agents to choose S and $N - n^*$ to choose N. The latter case is illustrated in Figure 1 for continuous n.

When two equilibria exist, it is possible that outcomes at the Pareto-inferior equilibrium will occur. The next section identifies the social optimal level of mitigation and compares the equilibria to the social optimum. Then, the question of equilibrium selection is addressed.

3.1 Social Welfare

Define the social marginal benefit as the total benefit to all agents from one agent choosing S. This can be expressed as a function of how many other agents are choosing S.

$SMB(n) = [1 - p(n)]q(n)rL + nrL[p(n-1)q(n-1) - p(n)q(n)] + (N - n - 1)rL[q(n) - q(n+1)]$

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 3.1 *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.*

When one equilibrium is for n^* agents to choose S, note that $n^s > n^*$. In other words, both equilibria are sub-optimal. This is because the agents deciding to mitigate do not experience the full social benefit from mitigating due to the positive externality. An interesting question is which equilibrium is preferable: the one where n^* agents mitigate or the one where no one mitigates. The following corollary addresses this question.

Corollary 3.2 *If there are two equilibria, the equilibrium where some agents choose S Pareto-dominates the equilibrium where no one chooses S.*

When two equilibria exist, the possibility for under-investment in mitigation is now clear. When no one else invests in mitigation, there is no incentive for an agent to choose to invest despite the fact that the optimal amount of mitigation is for most or all agents to mitigate. Furthermore, the other equilibrium, while not always optimal, is always preferable. The next section discusses a feature of the model which provides insight into which equilibria will be observed and how policy can be designed to induce agents to the preferred equilibrium.

3.2 Tipping

When two equilibria exist, the game is a coordination game[9]. 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 [16] 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. [9]; Straub [26]; Schmidt et al. [24]). Risk dominance captures the notion that some strategies are more 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 1 (taken from Harsanyi and Selten [16], p.89). Although (U_1, U_2) is the payoff dominant equilibrium, it is more risky since the resulting payoff for each player could be either 0 or 9, depending on the other player's choice. 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 $U(1)$.

[9]See Cooper and John [10]).

Table 1: A Stag Hunt Game

	U_2	V_2
U_1	9,9	0,8
V_1	8,0	8,8

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 believe that this outcome is more likely than other outcomes. In this case, choosing S is more risky.

Another equilibrium selection criteria, called security by van Huyck et al. [28], 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 $Y - q(0)rL$. When two equilibria are present, it must be true that $Y - q(0)rL > Y - c - p(0)q(0)rL$. 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, effective 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.[10] In order to overcome the coordination failure, a small group of agents must coordinate rather than the entire community.

In experiments, van Huyck et al. [29] show that the outcome of games is

[10]Similar examples of tipping a game to a new equilibrium are explained in Heal and Kunreuther [17], Schelling [23], and Dixit [11].

sensitive to initial conditions. If agents begin on one side of a threshold, they converge to one equilibrium; if they begin on the other side of the threshold, they converge to the other equilibrium.

Define the tipping point, n^{tip}, such that $PB(n^{tip} - 1) < c < PB(n^{tip})$. The tipping point is the same kind of threshold studied in van Huyck et al. [29]. If a coalition of n^{tip} agents commit to choosing S, then the only Nash equilibrium is the equilibrium where some or all agents mitigate. Play will converge to the preferred equilibrium. On the other hand, if agents believe that fewer than n^{tip} agents will choose S, then agents will coordinate on the inferior equilibrium where no one mitigates. The goal of policy, therefore, is to form coalitions of homeowners to create defensible space together rather than having agents act alone.

The next section allows for heterogeneity in mitigation costs and shows that the fundamental results do not change.

3.3 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.[11] 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 $c_1 \leq c_2 \leq ... \leq c_N$.

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

[11]See Fried et al. [14]

dominant strategy equilibrium. If $max(c_n) < min[PB(n)]$, then everyone choosing S is a dominant strategy equilibrium.

There could be zero, one, or more than one value of n^* that satisfies the conditions above. There is always at least one equilibrium, but there could be more. When two equilibria exist, a coordination game exists just as with homogeneous costs.

When there is a mixed equilibria where some choose N and some choose S, 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 n^i choose S to the equilibrium where n^{i+1} choose S.

Another possibility with heterogeneous costs is cascading. [12] Suppose there are two equilibria. Suppose if one person unilaterally 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.

4 Data and Empirical Results

In practice, there is a great amount of heterogeneity among homeowners living in the WUI, due in part to differences in preferences and risk. The objective of this section is to demonstrate that houses are more likely to have a defensible space when their neighbors do, controlling for both observed and unobserved heterogeneity.

[12] See Dixit [11]

4.1 The Data

The source of the data is the Wildfire Hazard Identification and Mitigation System (WHIMS)[13], a Boulder County, CO project which originated in 1992 as a division of the Boulder County Wildfire Mitigation Group. The purpose of the project was to assess wildfire risk on a house by house basis, educate homeowners about that risk, and encourage homeowners to voluntarily mitigate the risk. Altogether, there are 1474 observations from six fire districts.

To assess the risk at a particular site, both neighborhood specific hazards and site specific hazards were measured. To measure hazards at the neighborhood level, the WHIMS project collected spatial data on fuel types in the county and combined this with existing topographical data into a GIS database. This data was then used to measure the hazard that any site faced as a result of the neighborhood in which it was located. Hazards were assessed on a scale of 0 to 10, 10 being most at risk. The Fire Behavior Index (FBI) evaluates how intense a fire will be, how fast the fire will spread, and crown fire potential in the neighborhood of a site. The Dangerous Topography Index (DTI) evaluates how close a site is to dangerous topographical features such as steep slopes and V-shaped canyons. Summary statistics for these and other WHIMS variables are found in Table 2.

Site-specific data was measured using a questionnaire. Volunteer fire fighters visited homes over the course of several months and answered 24 questions about the site. Because the data were collected over time, observations for one site may not correspond to the same time as observations for another site. The length of time is relatively short, so this should not be a major problem.

The questionnaire divided defensible space outcomes into four categories: less than 20 feet, more than 20 but less than 30 feet, more than 30 but less than 60 feet, and more than 60 but less than 100 feet[14]. Table 3 shows the distribution of defensible space outcomes.

The questionnaire covered many aspects of wildfire risk in addition to defensible space. From these questions, several hazard indices were generated for each site. Like the neighborhood hazard ratings, these hazards were rated

[13] A detailed description of how the data was collected is provided in the WHIMS Manual [2].

[14] A fifth category, more than 100 feet, was available as an option, but no observations in the data had more than 100 feet of defensible space.

Table 2: Summary Statistics

Variable	Observations	Mean	S.D.
FBI	1474	5.81	1.91
DTI	1474	4.71	2.25
ACCESS	1474	4.74	1.99
FIRE-PROT	1474	1.59	1.58
WATER	1474	5.71	1.97
Area	1474	181,442	349,609
Structure Value	1474	204,449	141,146
Land Value	1474	147,964	74,605

Table 3: Distribution of Defensible Space Outcomes

Amount of D.S.				
More than	Less than	Frequency	Percent	Cumulative %
0 ft.	20 ft.	544	36.91	36.91
20 ft.	30 ft.	484	32.84	69.74
30 ft.	60 ft.	269	18.25	87.99
60 ft.	100 ft.	177	12.01	100.00
Total		1474	100.00	

on a scale of 0 to 10, 10 being the highest risk. ACCESS evaluated the ability of fire departments to reach the site during a fire. FIRE-PROT evaluated the speed with which the fire department could reach the site. WATER evaluated the availability of water near the site.

Other information that is available for each site is the area, perimeter, land value, structure value, age of structure, square footage, number of bedrooms, and number of bathrooms. Lot size may be important for two reasons. First, small lots may not be able to have defensible space without working directly with neighboring lots. Second, houses in neighborhoods with small lots and a high density of structures are more susceptible to ignition from the neighboring structures.

4.2 Econometric Issues

In this section, I discuss the estimation strategy given the available data. First, I address the identification of the effect of risk externalities, what Manski [21] calls the reflection problem. Manski [21] defines three different kinds of social effects which may in practice be difficult to identify. First, endogenous effects are present when one neighbor's choice depends on the average choice of other neighbors. The risk externality model has an endogenous effect; the defensible space outcomes of neighboring sites influence a homeowner's risk, which in turn influences the homeowner's defensible space choice.

Contextual effects, the second type of social effect, are present when one neighbor's choice depends on the average exogenous characteristics of the other neighbors. For example, if a homeowner's neighbors all face very high risk due to the topography around their homes, the homeowner may fear that their neighbors' homes will act as a ladder to start a crown fire and this may in turn affect the homeowner's choice about defensible space.

The third type of social effect is known as a correlated effect. Correlated effects occur when homeowners' choices depend on unobserved characteristics which are spatially correlated. For example, homeowners may experience varying levels of education regarding the importance of defensible space. Because this education may come from local organizations like fire district offices or homeowners associations, it is plausible that knowledge about defensible space is spatially clustered. The possibility that homeowners may spread this information among their friends who may also be their neighbors offers further support to this idea.

The purpose of this section is to estimate the effect of risk externalities, a type of endogenous effect. The identification of endogenous effects is important because the tipping phenomenon discussed in section 3.2 only occurs in the presence of endogenous effects. As a result, policies aimed at inducing tipping will be ineffective if only contextual and correlated effects exist.

Manski [21] shows that identification of endogenous effects is not possible when neighborhoods are defined such that everyone in a neighborhood is a neighbor of everyone else. This is appropriate for examples like school performance where students at a school may influence the performance of other students at the school. For the current example, I expect a homeowner's decision to be influenced by their immediate neighbors. Their immediate neighbors may in turn have neighbors which are not the immediate neighbor of the homeowner. This fact makes it possible to identify endogenous effects.

To make this clear, consider the linear model shown below. Y is an nx1 vector of observed defensible space outcomes. W is an nxn matrix of neighborhood connections; $W_{ij} = 0$ if i and j are not immediate neighbors and $W_{ij} = \frac{1}{n_i}$ if i and j are immediate neighbors, where n_i is the number of immediate neighbors that i has.

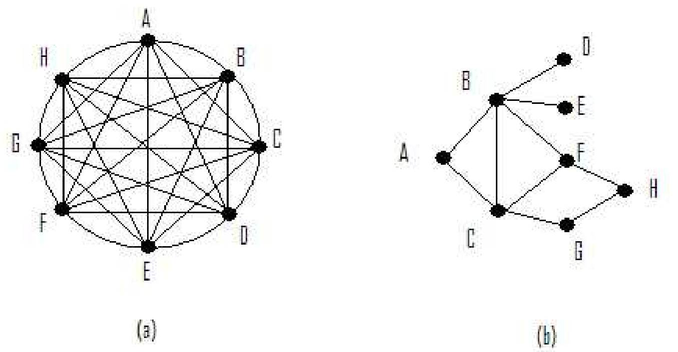

Figure 2:

$$Y = \alpha + \beta WY + WX\gamma + X\delta + \mu \tag{1}$$

$$\mu = \eta M\mu + \epsilon \tag{2}$$

This is a first order spatial autoregressive model with spatial autocorrelation (see Anselin [4]). β represents the endogenous effect - the effect of neighbors' defensible space outcomes on a homeowner's outcome. X is an nxk matrix of exogenous characteristics where k is the number of characteristics. The characteristics in X are the site characteristics available from the WHIMS data, including the WHIMS hazard ratings (FBI, DTI, FIREPROT, WATER, and ACCESS) as well as the lot size, structure value, and land value. γ is a kx1 vector of parameters which represent the contextual effects. δ is a kx1 vector of parameters which represent the effect of a house's own characteristics on its owner's defensible space choice. Finally, μ is a spatially correlated error term (M may or may not equal W) and ϵ is random noise. η represents the correlated effect.

The Manski [21] case is shown in Figure 2 (a). Each house has every other house as a neighbor. So, the W matrix will only have zeroes on the diagonal. This means each element of WY will be a linear combination of X. Similarly, each element of WX will also be a linear combination of X. As a result, β and γ cannot be separately identified.

In contrast, consider the graph in Figure 2 (b). House A has two neighbors, B and C. B and C, in addition to having A and each other as neighbors, also have D, E, F, and G as neighbors. Now, the Ath row of WX is a linear combination of the rows of X corresponding to A's neighbors, B and C. On the other hand, the Ath row of WY is a linear combination of all rows of X. As a result, β and γ are identified.

Because Y appears on the right hand side of equation 1, an endogeneity problem exists. WY is correlated with μ which implies that OLS estimates will not be consistent. An instrumental variable approach is used to deal with this issue. Previous work in public economics has used WX, the neighbors' exogenous characteristics, as instruments for WY, assuming no contextual effects (see Figlio et al. [12] and Fredriksson et al.[13]). In order to allow for the possibility of contextual effects, I instead use neighbors' neighbors' exogenous characteristics (eliminating common neighbors) as an instrument for WY. As explained in the previous paragraph, these should be correlated with WY. If they are in fact exogenous, they should be uncorrelated with the error terms and therefore make a suitable instrument. Because the predicted value of WY used in the second stage is determined entirely from the exogenous instruments, the 2SLS approach estimates β consistently even in the presence of spatial correlation of the error term μ (see Brueckner [6] and Kelejian and Prucha [19]).

To further deal with the issue of unobserved variables which may be spatially correlated, I include fire district and community fixed effects. This allows houses that are relatively close to each other to have correlated μ. By defining M to include all houses in a community, not just immediate neighbors, the fixed effect will capture the common element in the error term among neighbors, leaving just the well-behaved ϵ. The implicit assumption is that the unobserved variable affects the entire community while the effect of risk externalities will be primarily from a homeowner's immediate neighbors. When this assumption does not hold, I rely on the instrumental variable approach described in the previous paragraph to yield consistent estimates. It is still useful to include fixed effects because there is reason to believe that some unobserved variables may impact an entire neighborhood, homeowners association, or fire district. For example, some fire district managers may actively educate homeowners and encourage mitigation. Communities with active homeowners associations also may actively encourage mitigation, and state and federal grants to promote mitigation also operate at the community-wide level.

In constructing the community fixed effects discussed in the previous paragraph, I consider two possible definitions of a community: the tax area and the block. There are 32 tax areas which vary in size from 1 to 403 sites.

The mean size of a tax area is 62 sites and the median is 21. There are 122 blocks which vary in size from 1 to 115 sites, with a mean of 19 sites and a median of 10.

Another potential problem is the endogeneity of site choice. I consider two situations where this could cause estimation problems. First, suppose that an individual's unobserved taste for trees is an important determinant of the individual's defensible space decision as well as who they live near. Individuals with a strong preference for trees may choose to live near other people who feel the same way. This could lead to false evidence that an individual's defensible space choice depends on their neighbors' choices when in fact it depends on their preference for trees. This would bias estimates of β upward. However, since I am instrumenting neighbors' defensible space decisions with neighbors' X, estimates will not be biased as long as neighbors' X are uncorrelated with the error term.

Second, it is possible that homeowners attitudes toward wildfire cause them to choose where to live based on certain risk factors included in X. These same attitudes could also influence their defensible space choice. In this case, X will be correlated with μ and estimates of the coefficients on X will be biased. This problem alone will not affect estimates of β, which is the primary goal of this section. However, this problem is confounded by the significant spatial autocorrelation of X. Since a site's X are correlated with neighboring sites' X, the proposed instrument for WY will be correlated with the error term. In other words, spatial correlation of X combined with endogenous site choice leads to sorting based on unobserved characteristics and invalidates the proposed instrument. If X were only correlated with immediate neighbors, it would be difficult to control for the sorting effect. However, since the X are highly correlated over a larger geographic area, I can control for this effect with community fixed effects. The community fixed effect should capture the effect of the unobserved variable which is driving the sorting. If the fixed effect captures the part of the error term which is correlated with X, then the remaining error term should be uncorrelated with X and so the instrument should be valid and estimates should be consistent.

The last econometric issue I discuss is how to define defensible space. The simplest approach is to assume a linear model where the dependent variable Y is the amount of defensible space a homeowner has. In this case, Y is defined as the median of each interval. This allows us to use two-stage least squares, which is recommended over non-linear models by Angrist and Krueger [3] to reduce the risk of specification error when instrumental variables are used.

However, homeowners may not view defensible space as a continuous variable. Most of the educational literature which homeowners would have access to suggests that homeowners have at least 30 feet of defensible space[15]. As a result, homeowners may view their defensible space choice as a binary choice: having less than 30 feet or having more. In this case, Y is defined as 1 for houses with 30 feet or more defensible space and 0 otherwise. The model becomes a probit model if the error is assumed to be normally distributed.

In the next section, I report results using a linear model as well as a probit. In all cases, I expect β, the coefficient on the right-hand side Y term, to be positive, indicating that a house is more likely to have (more) defensible space when their neighbors have more defensible space.

4.3 Results

Table 4 shows the results when the amount of defensible space Y is defined as the median of the interval and contextual effects are included as regressors. For each model, the results are presented with no community fixed effects, with tax area fixed effects, and with block level fixed effects. All estimations include fire district fixed effects. For comparison, the first three columns show OLS results. The second three columns show the results of two-stage least squares (2SLS) using as instruments the average values of FBI, FIRE-PROT, and lot size for the houses which are neighbors' neighbors but not direct neighbors. In the 2SLS estimations, it does not appear that contextual effects are present.

Table 5 shows the results when contextual effects are removed as regressors. The variable Y is still defined as the median of the interval. For the first three columns, the instruments used are the same as before, the average values of FBI, FIRE-PROT, and lot size for neighbors' neighbors. Since the neighbor averages should not be included in the second stage, they can now be considered as instruments for the neighbor defensible space average. In the last three columns of Table 5, the instruments used are the average values of FBI, FIRE-PROT, and lot size for neighbors' houses (spatially lagged once instead of twice).

In all cases, the instruments pass the Sargan over-identification test. The null hypothesis that the instruments are uncorrelated with the error term

[15]For example, see Institute For Business and Home Safety, "Is Your Home Protected From Wildfire Disaster? A Homeowner's Guide To Wildfire Retrofit".

cannot be rejected. Furthermore, the instruments all pass the Anderson under-identification test, rejecting the null hypothesis that the equation is under-identified. To test for weak instruments, I report the Cragg-Donald statistic suggested by Stock and Yogo [25]. The small values reported in Table 4 indicate that these instruments may be weak and estimates may be biased. However, the first order lags used in the last three columns of Table 5 are much stronger instruments. Based on the tables in Stock and Yogo [25], these estimates should be biased less than 5%.

Looking at both tables, the coefficient on neighbors' average defensible space is significant in all but one specification and highly significant in many of the specifications. It is positive, indicating that a homeowner creates more defensible space when their neighbors have more defensible space. The results from the last three columns of Table 5 imply that when neighbors have an average of 10 feet more defensible space, a house will have between 4 and 5 more feet of defensible space. These estimates are significant at the 1% level for two of the estimations and at the 5% level for the third estimation.

Table 6 shows the results of a two-stage probit where Y is defined as a binary variable: 1 if the site has at least 30 feet of defensible space and 0 otherwise. The neighbor % defensible space variable is therefore the percentage of neighboring sites which have at least 30 feet of defensible space. The results imply that a site where all neighbors have a defensible space is between 50% and 70% more likely to have a defensible space compared to a site where no neighbors have a defensible space.

The results of all of the estimations presented here confirm that the defensible space outcomes of neighbors play a significant role in homeowners' own defensible space decisions. These results offer support to the risk externality model. The next two sections discuss how to provide incentives for homeowners to invest in defensible space in communities where it is not common.

5 Insurance

One reason that many homeowners may choose not to invest in defensible space is insurance. 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. In fact, if individuals were fully insured,

Table 4: Results including contextual effects as regressors

	OLS			2SLS		
	(1)	(2)	(3)	(4)	(5)	(6)
Neighbor DS Avg	0.293***	0.234***	0.193***	0.674**	0.525	0.619**
	(0.030)	(0.032)	(0.034)	(0.337)	(0.396)	(0.299)
FBI	-0.994*	-0.770	-0.935*	-0.538	-0.590	-0.557
	(0.525)	(0.526)	(0.539)	(0.731)	(0.660)	(0.675)
DTI	-1.302***	-1.364***	-1.376***	-1.465***	-1.431***	-1.470***
	(0.381)	(0.380)	(0.389)	(0.420)	(0.401)	(0.415)
ACCESS	-0.868**	-0.793*	-0.869**	-0.977**	-0.835*	-1.052**
	(0.422)	(0.423)	(0.428)	(0.469)	(0.450)	(0.461)
FIRE-PROT	1.186**	1.266**	1.191**	1.005*	1.058*	0.972
	(0.544)	(0.543)	(0.561)	(0.590)	(0.615)	(0.594)
WATER	1.964**	1.744**	1.853**	2.073**	1.984**	1.972**
	(0.865)	(0.885)	(0.884)	(0.933)	(0.960)	(0.932)
Area	0.000	0.000*	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Structure Value	0.000*	0.000*	0.000*	0.000	0.000*	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Land Value	-0.000	-0.000	-0.000	-0.000**	-0.000**	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Neighbor FBI Avg	-1.238*	-0.770	-1.281*	-0.442	-0.354	-0.428
	(0.633)	(0.668)	(0.713)	(0.850)	(0.784)	(0.980)
Neighbor DTI Avg	0.551	0.054	0.284	1.059	0.645	0.800
	(0.495)	(0.508)	(0.539)	(0.679)	(0.864)	(0.641)
Neighbor ACCESS Avg	0.223	0.191	0.350	0.619	0.547	0.730
	(0.513)	(0.526)	(0.562)	(0.648)	(0.685)	(0.674)
Neighbor FIRE-PROT Avg	-0.271	0.066	-0.074	-0.767	-0.351	-0.687
	(0.650)	(0.665)	(0.740)	(0.833)	(0.956)	(0.912)
Neighbor WATER Avg	-0.982	-1.656*	-1.036	-1.344	-1.789*	-1.654
	(0.950)	(0.997)	(1.015)	(1.093)	(1.067)	(1.125)
Neighbor Area Avg	-0.000	0.000	0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Fire District FE	Yes	Yes	Yes	Yes	Yes	Yes
Community FE	None	Tax	Block	None	Tax	Block
Instruments				Neighbors' Neighbors' Avg of FBI, FIRE-PROT and Area		
Sargan over-ID				0.105	0.134	0.541
(p-value)				(0.9490)	(0.9352)	(0.7630)
Anderson under-ID				13.917	10.819	21.903
(p-value)				(0.0030)	(0.0127)	(0.0001)
Stock-Yogo Cragg-Donald				4.58	3.51	6.93
Observations	1399	1399	1399	1291	1291	1291

Standard errors in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%

Table 5: Results without contextual effects

	2SLS			2SLS		
	(1)	(2)	(3)	(4)	(5)	(6)
Neighbor DS Avg	0.561***	0.447*	0.559***	0.449***	0.406**	0.409***
	(0.210)	(0.233)	(0.206)	(0.159)	(0.166)	(0.157)
FBI	-0.983	-0.804	-0.766	-1.256**	-0.829	-0.929
	(0.637)	(0.576)	(0.658)	(0.583)	(0.525)	(0.592)
DTI	-1.119***	-1.271***	-1.299***	-1.112***	-1.298***	-1.354***
	(0.350)	(0.368)	(0.375)	(0.328)	(0.342)	(0.351)
ACCESS	-0.587*	-0.568*	-0.716*	-0.629**	-0.637**	-0.648*
	(0.324)	(0.344)	(0.366)	(0.305)	(0.324)	(0.340)
FIRE-PROT	0.738	1.007*	0.831	0.884**	1.084**	0.966*
	(0.478)	(0.555)	(0.530)	(0.441)	(0.481)	(0.500)
WATER	1.173**	0.896	0.920	1.079**	0.768	0.944
	(0.548)	(0.676)	(0.660)	(0.515)	(0.627)	(0.635)
Area	0.000	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Structure Value	0.000	0.000*	0.000*	0.000*	0.000*	0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Land Value	-0.000**	-0.000**	-0.000*	-0.000	-0.000*	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Fire District FE	Yes	Yes	Yes	Yes	Yes	Yes
Community FE	None	Tax	Block	None	Tax	Block
Instruments	Neighbors' Neighbors' Avg of FBI, FIRE-PROT and Area			Neighbors' Avg of FBI, FIRE-PROT and Area		
Sargan over-ID	0.979	0.514	1.032	2.027	0.981	1.489
(p-value)	(0.6128)	(0.7732)	(0.5968)	(0.3629)	(0.6123)	(0.4750)
Anderson under-ID	33.300	29.210	43.360	49.360	50.255	62.156
(p-value)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Stock-Yogo Cragg-Donald	11.10	9.58	13.90	16.54	16.59	20.08
Observations	1291	1291	1291	1399	1399	1399

Standard errors in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%

Table 6: Results of Two-Stage Probit

	Two-Stage Probit		
	(1)	(2)	(3)
Neighbor % Def Space	0.545*	0.623*	0.698*
	(0.281)	(0.348)	(0.360)
FBI	-0.022	-0.019	-0.017
	(0.013)	(0.012)	(0.013)
DTI	-0.025***	-0.028***	-0.029***
	(0.008)	(0.009)	(0.010)
ACCESS	-0.008	-0.009	-0.014
	(0.007)	(0.008)	(0.009)
FIRE-PROT	0.014	0.013	0.014
	(0.010)	(0.012)	(0.012)
WATER	0.018	0.008	0.009
	(0.012)	(0.015)	(0.016)
Area	0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)
Structure Value	0.000*	0.000*	0.000*
	(0.000)	(0.000)	(0.000)
Land Value	-0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)
Fire District FE	Yes	Yes	Yes
Community FE	None	Tax	Block
Instruments	Neighbors' Avg of FBI, FIRE-PROT and Area		
Observations	1399	1387	1363

Reported values are the marginal effects from a change in the variable.
Standard errors in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%

it is likely that no one would choose to invest in defensible space.

In practice, individuals cannot insure themselves for the total loss because of non-market aspects to losing a house such as losing family heirlooms.[16] As a result, individuals receive some benefits from mitigation even when insured, albeit much less than without insurance. This explains why many homeowners choose to have defensible space even though almost all are insured.

Because a large portion of the benefits of defensible space accrue to insurance companies, they may be able to offer discounted premiums for those who invest in defensible space as a way of encouraging homeowners to invest. Depending on the cost of verifying mitigation, this kind of policy may or may not be feasible. This section establishes conditions under which competitive insurance companies will be able to offer these kinds of discounted premiums.

Assume that homeowners can insure their house for at most $l < L$. Assume that insurance markets are competitive, and let $x \geq 0$ be the cost of verifying that one house has defensible space. Risk averse individuals will purchase the maximum possible insurance if priced competitively. Risk neutral individuals will be indifferent between any amount of competitively priced insurance. I 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 individuals mitigate in equilibrium. 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 $\pi_0 = q(0)rl$, the expected payout when no one mitigates.

Depending on x, insurance companies may be able to offer premium discounts to homeowners who mitigate. Let π_S be the premium for homeowners who mitigate and let π_N be the premium for those who do not. Define the premium discount as $d = \pi_N - \pi_S$. The effect of this discount is to reduce the cost of defensible space to $c - d$. If $c - d \leq PBI(0)$, then it becomes a dominant strategy for all homeowners to choose to mitigate. If this condition is not met, then the discount will not be effective at inducing any homeowners to mitigate if starting from the equilibrium where no one has defensible space. So, the only discount which will induce any mitigation will induce all homeowners to mitigate.

[16] Fried et al. [14] and McKee et al. [22] provide evidence that supports this claim.

It therefore must be the case that π_S and π_N earn zero profits when all homeowners mitigate. It also must be the case that all homeowners choose π_S over π_N. The zero-profit conditions when all homeowners invest in defensible space are:

$$\pi_S = p(N-1)q(N-1)rl + x \tag{3}$$

and

$$\pi_N = q(N-1)rl \tag{4}$$

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

$$d = [1 - p(N-1)]q(N-1)rl - x \tag{5}$$

If $d > c$, then the premium discount offered by insurance companies is greater than the cost of mitigation. This discount will always induce all homeowners to invest in defensible space. Even when $d < c$, the discount can effectively induce mitigation if $c - d \leq PBI(0)$. This is true because of the uninsurable loss. For the discount to actually induce mitigation, the following condition must hold:

$$x \leq PBI(0) + [1 - p(N-1)]q(N-1)rl - c \tag{6}$$

If this condition is not met, then individuals would choose π_N and insurance companies cannot profitably offer a premium discount. In this case, competitive insurance companies will offer contracts with a premium of π_0 to all homeowners regardless of whether they invest in mitigation. If an insurance company were to try to offer the differentiated contract, it could not guarantee that it would induce anyone to mitigate and it would therefore not be profitable. If c is large enough, this condition may not be met even when $x = 0$.

If the condition in equation 6 is met, then insurance companies will offer contracts with a premium of π_S or π_N depending on mitigation. All homeowners will choose to invest in defensible space. Since all agents choose π_S over π_N and $\pi_N < \pi_0$, competitive insurance companies cannot offer π_0 to everyone when equation 6 is satisfied.

To summarize, let $d = [1 - p(N-1)]q(N-1)rl - x$. If $x \leq [1 - p(N-1)]q(N-1)rL - [PB(N-1) - PB(0)] - c$, then competitive insurance companies will 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.

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.

The results so far depend on the assumption of homogenous individuals. When the model is generalized to allow for heterogeneity in costs, the ability of insurance companies to offer premium discounts depends on the distribution of costs. If $c_n \leq PBI(n) + [1 - p(N-1)]q(N-1)rl - x$ for all n, then competitive insurance companies will offer the same differentiated premiums as in the case with homogenous costs. When this does not hold, there may be other differentiated premiums which they could offer which would induce some fraction of the homeowners to invest in defensible space, or they may offer only the π_0 option.

In practice, it may be difficult for insurance companies to observe the costs for all homeowners. In order to set premiums without this information, insurance companies would need to verify fuel loads on all adjacent properties, a much costlier task. The presence of nearby, untreated public lands further confounds the problem.

This section has shown that if the cost of verifying mitigation is low enough, insurance companies can offer premium discounts which encourage everyone to invest in defensible space. If a homeowner's loss is not fully insurable, the premium discount need not fully re-imburse homeowners for the cost of mitigation. However, even if the cost of verifying fuel loads at one site is low enough, substantial heterogeneity among homeowners living in the WUI would force insurance companies to verify fuel load management on adjacent properties as well. Given the difficulty in measuring the effect of defensible space on wildfire risk for each individual site, most insurance companies have instead opted not to offer any kind of discount to properties with defensible space.

6 Policy Implications

The model developed in Section 3 gives insight into the potential effectiveness of policies aimed at encouraging homeowners to undertake mitigation measures. The model suggests that policies aimed at forming coalitions of homeowners within a community can solve the coordination problem and lead to the socially beneficial equilibrium. The members of a coalition who collectively agree to create defensible space can provide the incentive for others to follow.

These coalitions may be informal groups of neighbors who work together to create defensible space, as mentioned in Brenkert et al. [5]. Alternatively, formal community organizations can play a large role in wildfire management decisions. 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. The 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.

For many communities, adjacent public lands are the largest neighbor to homeowners. If these lands are dense, untreated forest, they place the homeowners at great risk. Given the high risk, these homeowners may view defensible space as a futile measure. In this case, thinning on public lands that are adjacent to private communities can promote mitigation among homeowners in the WUI. In a sense, mitigation of this one large publicly-owned neighbor may induce the neighboring privately-owned lands to invest in defensible space. Several homeowners interviewed by Brenkert et al. [5] allude to this point.

Insurance companies are another viable option through which homeowners may be convinced to invest in defensible space. As explained in Section 5, insurance companies may be able to offer premium discounts to homeowners who have defensible space. However, risk externalities pose a problem for insurers wanting to offer premium discounts when there is substantial heterogeneity among homeowners. The costs of verifying fuel loads on all adjacent properties may be prohibitively expensive. While this information problem presents a problem, it is 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. Homeowners' decisions about whether to invest in defensible space depend on their neighbors' decisions. Communities may get stuck at the equilibrium where no one has a defensible space since no one has incentive to unilaterally create a defensible space. Data from Boulder County, CO confirm that households are more likely to have defensible space when their neighbors do.

Providing grants which make defensible space cheaper should induce homeowners to create defensible space. The presence of risk externalities suggest two additional strategies to promote investment in defensible space. First, in order to form community coalitions, policies should work at the community-wide level instead of targeting individual homeowners. This can be accomplished by contacting homeowners and encouraging them to contact their neighbors, by making equipment available to a group of neighbors at once, and by scheduling public meetings to inform homeowners in a community about the wildfire problem. Second, thinning public lands remains an integral part of any strategy to reduce wildfire risk in the WUI. In addition to the direct risk reduction, risk externalities may lead nearby homeowners to invest in defensible space and other risk mitigating measures in response to public thinning projects.

Insurance companies also have the potential to promote investment in defensible space by offering lower premiums to homeowners with defensible space or to communities which have collectively invested in wildfire risk mitigation measures. Although this was uncommon in the past, the devastation caused by recent fires has prompted insurance companies to rethink their approach to wildfire. State Farm has recently instituted a program to inspect properties and make defensible space a condition for policy renewal, and other insurance companies are considering similar programs.

Increasing development in the WUI requires new approaches to managing wildfire risk. While it was once acceptable for homeowners to ignore the threat of wildfire, the buildup of fuel in forests has made proper wildfire risk mitigation essential. This paper has shown that the problem of managing wildfire risk can be solved through the cooperation of policy makers, insurance companies, and homeowners living in the WUI.

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