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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

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]

from the 30 feet surrounding the house greatly reduces the risk that ¯re will come in direct contact with the structure, thereby reducing risk of ¯re damage to the house. Beyond 30 feet, trimming trees, removing dead underbrush, and creating ¯re breaks will also greatly reduce risk of ¯re damage to the house.[5]

Despite the bene¯ts 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 di®erentiated 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 wild¯re risk and perceptions of who is responsible for reducing risk. Many homeowners expressed the opinion that wild¯re 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 e®ective in conjunction with public risk reducing activities.

This paper extends the wild¯re literature by considering the spillover loads in the area cause ¯res to gain speed and intensity and quickly burn everything in the area. The e®ect 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

2 The Wild¯re Problem

Prior to the 20th century, many dry forests in the West featuring ponderosa pine and Douglas ¯r experienced low severity ¯res as frequently as every 4 to 25 years (Graham et al. [15]). These ¯res cleared out surface fuels and ladder fuels, leaving a vertical gap between the ground and the canopy above. The e®ect was to reduce the probability of crown ¯res which burn across tree tops. By having frequent small surface ¯res, the chance of a large high intensity crown ¯re is reduced.

As humans began to develop in forests, the policy of ¯re suppression led to a decrease in the number of ¯res. The e®ect of ¯re 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 ¯res today are much more likely to turn into crown ¯res than in the past. The ¯res in 2000, 2002, and 2003 in Arizona, California, and Colorado are examples of large high intensity crown ¯res 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 ¯res are the biggest threat to houses and other man-made structures in the forest. Crown ¯res spread faster and burn with a higher intensity than surface ¯res and are therefore a bigger threat for igniting houses. Once a wild¯re reaches a certain intensity (about 500 Btu/ft/sec) ¯re departments are unable to defend houses against the ¯re (NFPA [1]). The increased probability of crown ¯res in recent years combined with the

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 wild¯re destroys their house. According to Cohen [8], in most ¯res 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 wild¯re destroys an agent's house is r. The probability that a wild¯re starts in the vicinity of a house is assumed to be exogenous; none of the agents are responsible for starting the ¯re. For example, the ¯re may be started by lightning, camping ¯res, or cigarettes carelessly discarded by motorists.

Conditional on a ¯re starting, let $q(n$

likely that a wild¯re 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 e®ect 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 bene¯ts of mitigation do not have to be strictly increasing or decreasing as more people mitigate.

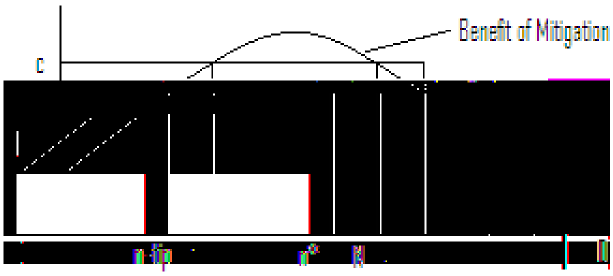

Figure 1: Two Equilibria

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 bene¯t 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 payo® dominance should guide equilibrium selection. Agents should coordinate on the equilibrium, if it exists, which has the highest payo®s for everyone. In this model, the equilibrium where some agents choose S always payo® 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 payo®s. 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 payo® dominant equilibrium, it is more risky since the resulting payo® 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 payo®s 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]).

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 $i = 1, \ldots, N$. Without loss of generality, let $c_1 \leq c_2 \leq \ldots \leq c_N$.

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 $min(c_n) > max[PB(n($

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 satis¯es the conditions above. There is always at least one equilibrium, but there could

4.1 The Data

The source of the data is the Wild¯re Hazard Identi¯cation and Mitigation System (WHIMS)[13], a Boulder County, CO project which originated in 1992 as a division of the Boulder County Wild¯re Mitigation Group. The purpose of the project was to assess wild¯re 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 ¯re districts.

To assess the risk at a particular site, both neighborhood speci¯c hazards and site speci¯c 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 ¯re will be, how fast the ¯re will spread, and crown ¯re 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-speci¯c data was measured using a questionnaire. Volunteer ¯re ¯ghters 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 wild¯re 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 ¯fth 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 ¯re departments to reach the site during a ¯re. FIRE-PROT evaluated the speed with which the ¯re 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 identi¯cation of the e®ect of risk externalities, what Manski [21] calls the re°ection problem. Manski [21] de¯nes three di®erent kinds of social e®ects which may in practice be di±cult to identify. First, endogenous e®ects are present when one neighbor's choice depends on the average choice of other neighbors. The risk externality model has an endogenous e®ect; the defensible space outcomes of neighboring sites in°uence a homeowner's risk, which in turn in°uences the homeowner's defensible space choice.

Contextual e®ects, the second type of social e®ect, 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 ¯re and this may in turn a®ect the homeowner's choice about defensible space.

The third type of social e®ect is known as a correlated e®ect. Correlated e®ects 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 organizv8 elike c257re mdstirit or2601escrwners arsocia
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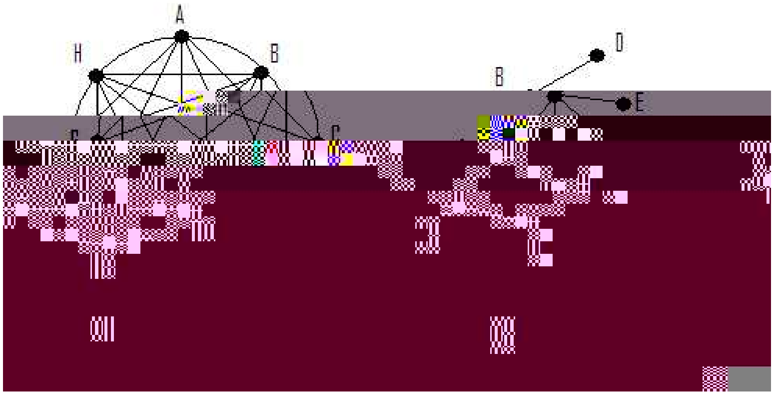

Figure 2:

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

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

This is a first order spatial autoregressive model with spatial autocorrelation (see Anselin [4]).

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 ϵ 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 ϵ (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 ϵ. 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 whicproach consist.Tf22.070TD[(.)Ites 8[(exofules)86s-339(87,)-476(not)86selemen87,4-181.27T

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 ϵ 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 de¯ned as 1 for houses with 30 feet or more defensible space and 0 otherwise. The model 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. Iible93(prely6(wnm6.)-4232e)1ntO

Table 5: Results without contextual e®ects

	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
* signi¯cant at 10%; ** signi¯cant at 5%; *** signi¯cant 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			

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 $I < L$. 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 I. Then, $PBI(n) = [(1 - p(n)]q(n)r(L - I)$.

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 $\pi_0 = q(0)rI$, 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

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 bene¯t 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 bene¯t to mitigation as the game without insurance, but they face less risk. As x increases, the discount o®ered by insurance companies decreases until x is so high that no discount is o®ered.

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 o®er 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 o®er the same di®erentiated premiums as in the case with homogenous costs. When this does not hold, there may be other di®erentiated premiums which they could o®er which would induce some fraction of the homeowners to invest in defensible space, or they may o®er only the π_0 option.

In practice, it may be di±cult 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 o®er 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 di±culty in measuring the e®ect of defensible space on wild¯re risk for each individual site, most insurance companies have instead opted not to o®er any kind of discount to properties with defensible space.

6 Policy Implications

The model developed in Section 3 gives insight into the potential e®ectiveness 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 bene¯cial 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 wild¯re 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 e®ective 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 speci¯c homeowners may be a viable option. Conditional cash transfers are money provided once speci¯c actions are undertaken. The model suggests that conditional cash transfers need not be made available to all homeowners, though it may be di±cult to discriminate or identify how many homeowners need to be o®ered this option in order to tip the community into a more socially bene¯cial 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.

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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 igation measures. Although this was uncommon in the past, the devastation caused by recent ¯res has prompted insurance companies to rethink their approach to wild¯re. 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 wild¯re risk. While it was once acceptable for homeowners to ignore the threat of wild¯re, the buildup of fuel in forests has made proper wild¯re risk mitigation essential. This paper has shown that the problem of managing wild¯re risk can be solved through the cooperation of policy makers, insurance companies, and homeowners living in the WUI.

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