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Externalities in the Wildland - Urban Interface: Private Decisions, Collective Action, and Results from Wildfire Simulation Models for California

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## ABSTRACT

Much of the property damage from wildfires occurs when fires spread into built up areas, the wildland urban interface. Fire spread within such areas occurs from house to house, as embers from one burning structure ignite neighboring ones. Actions can be taken to mitigate the chances that a given house will ignite. This size and configuration of this external benefit depends on the assumed process of fire spread. In this paper we use a simulation model based on plausible parameters to illustrate likely patterns of marginal benefit from mitigation as a function of building density and effectiveness of mitigation. The model indicates that a common pattern is for marginal benefit to unmitigated neighbors to be low at low levels of community mitigation, rise to a maximum, and then fall quickly to a low level. This maximum marginal benefit (known as "herd immunity") helps to indicate the optimal pattern of mitigation in a community. However individual owners in Nash equilibrium will not take the spillover benefits into account. We use the distribution of house values in a California community relative to an assumed cost of mitigation to illustrate in the model the level of mitigation owners will undertake when they make independent investment decisions, and the corrective actions that can lead to the social optimum. We discuss the use of rules or subsidies for insurance premium adjustments based on mitigation activities. Because it will rarely be optimal to mitigate all homes, the optimal solution may involve unequal treatment and raise equity issues.

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# EXTERNALITIES IN THE WILDLAND- URBAN INTERFACE: PRIVATE DECISIONS, COLLECTIVE ACTION, AND RESULTS FROM WILDFIRE SIMULATION MODELS FOR CALIFORNIA

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## Introduction

Recent wildfires in California have created the prospect of major losses for homeowners, insurers, and local communities. The fires are caused by climate-change induced heat waves and droughts combined with the urban and suburban development of areas traditionally at wildfire risk. In 2020 nearly 10,000 fires burned over 4.2 million acres across California, more than 4% of the state's total land area, and more than three times as many acres burned in 2021.The Camp Fire in November 2018 was the most destructive wildfire in California history to that date, damaging or destroying over 18,800 structures worth about $16.5 billion, of which $12.5 billion was covered by payouts from insurers. Not surprisingly, there has been extensive discussion of whether collective action, especially on land use zoning and insurance coverage, should be taken to reduce or control future damages. (California Department of Insurance, 2018).

This paper outlines the social and private goals for mitigation and insurance for wildfire damages to homes in high risk areas in California and demonstrates the possibility of gains from moving towards more efficient levels of each. We also consider the role of insurance in providing incentives for mitigation. The model incorporates the cost, the private benefits, and the total benefits from mitigation. Then we illustrate properties of this model with a simulation exercise linked to real world parameters to describe improved combinations of homeowner behavior, insurance firm policies in terms of coverage, premiums, and premium discounts for mitigation, state regulation of insurance coverage and premiums, and community regulation of mitigation and building density.

We show how different levels of mitigation can reduce expected fire damage, given a model of how fire spreads in a congested area, and solve for the optimal pattern of mitigation under risk neutrality, the level at which the marginal benefit from increased mitigation just equals the marginal cost of increased investment in mitigation. We turn to the behavioral issue of what levels of mitigation and insurance coverage risk averse property owners will choose compared to the socially optimal levels. We show how pricing of insurance can induce owners to mitigate even when owners do not have or respond to information on wildfire threats. Insurance can actually correct some common behavioral biases and bring expected outcomes closer to the optimum. Regulation of either homeowner behavior (through laws, building codes, and zoning rules) or insurer discounts for various kinds of mitigation can close remaining

gaps and improve matters yet further. Intervention to improve efficiency, we show, focuses on the mitigation choices of owners of houses. We also show that the optimal solution requires a mix of unmitigated and mitigated house.

Our main conceptual contributions are to show that the pattern of marginal benefits to neighbors from a given homeowner' wildfire mitigation has special features that are different from the general economic model of external diseconomies and imply different policy responses. We find that variation in the effectiveness of mitigation (given the cost of mitigation) generally affects outcomes much more than variation in the cost of mitigation. We also show that insurance premium reductions for mitigation can lead to an optimal solution even if owners are uncertain about loss probabilities or the effectiveness of mitigation, and that subsidization of such premium discounts may lead to efficiency.

The theory of externality, modified and adapted.

It is useful to think of the property and life damage from wildfire threat as being generated in two phases. Usually, the initial point of ignition for the fire is in an unpopulous area (forest, grasslands) and the initial spread of the fire primarily consumes vegetation. However, when a fire reaches a community, its character changes. Houses are ignited not just (or even primarily) from adjacent burning forests and other vegetation but from embers of one burning house blown to other vulnerable structures, sometimes skipping in unpredictable pattern from one structure to another. This often leaves most houses destroyed but some untouched in its wake. This phenomenon implies that any action a homeowner can take to reduce or mitigate the chances of his house igniting can also provide benefit to neighbors as a lower threat to their houses especially if they are unmitigated. Mitigation in the form of brush clearing, fireproof construction or retrofitting, and roof sprinklers can be very effective as long as wind speed is not too high. interactive or spillover benefit is an example of the concepts of externalities, in which the action by one agent provides both private benefit (his or her home is protected) but also benefits to others, and yet that benefit to others may well not be considered in the decision making of the agent.

Externalities have long been recognized by economists as potentially leading to failure of individual interactive or market behavior to achieve a mutually beneficial outcome (Buchanan and Stubblebine, 1962; Dasgupta and Ehrlich, 2013). The phenomenon of possible spread within a built up area is a special form of externality, one labeled "reciprocal" or "interdependent externality" (as distinguished from one way or unidirectional externality) because in this setting all agents engage in behaviors that affect each other. (Davis and Whinston, 1962; Heal and Kunreuther, 2007).

Given its cost and effectiveness, property owners may privately decide to invest in mitigation. In doing so they will evaluate the current level of fire risk their homes face which is determined in part by how many neighboring homes have already mitigated, but they will not take into account any benefits to their

neighbors from their decision to mitigate. This wedge between the private benefit of mitigation to the owner's property alone and the benefit to neighbors is a classic case of external effects, and implies that a Nash equilibrium (if one exists) may fall short of the social optimum.

In this paper we develop and elaborate on a theoretical model of wildfire spread as a function of the proportion and locations of mitigated buildings relative to an individual's own home. We show that this setting is best modelled as a special case of the general theory of externality. In this special case, the marginal benefit from a mitigation intervention of a given cost and effectiveness begins at a low level, rises to a peak, and then declines rapidly; it is not monotonic. The pattern for variation of marginal benefit with extent of mitigation is similar to (but somewhat different from) that of contagious disease spread and immunization  There is a level of mitigation where marginal benefit peaks ("herd immunity" in the disease case), and then declines rapidly once a proportion of exposures protected reaches a crucial level. What implications would such a pattern have for policy directed at wildfire damage?

We illustrate the application to wildfires with a simulation model for a hypothetical neighborhood that is potentially threatened from an external wildfire that, once it strikes, can spread from house to house as unmitigated structures provide wind driven embers and fuel for intensification of the fire. We use this model both to define the optimal pattern of mitigation (of a given cost and effectiveness) and to contrast that optimum with a Nash equilibrium model in which homeowners choose mitigation or not consistent with the level of mitigation chosen by their neighbors. The independent adjustment equilibrium falls short of the social or community optimum, and we discuss several options for increasing efficiency.

To our knowledge the development of this model of spread is novel, and it does yield some predictions about how corrective actions may vary with parameters such as the cost of mitigation, its effectiveness, and the distribution of house locations and values in the community.  The model also finds that optimal mitigation is less than 100% of all structures at risk, so a policy to select treated and untreated sites will have to be developed. Finally, if competitive insurance is available to cover losses at premiums that depend on risk, premium reductions for mitigation can provide incentives for optimal behavior.

Marginal benefit in externality reduction.

A key difference in the pattern of externality mitigation for wildfires from the general case of external diseconomy reduction is the expected path of marginal benefit from reducing the externality generating activity or risk beginning at zero modification of a typical scenario.  In the textbook treatment of externality the pattern is one of decreasing marginal benefit from mitigation.  For example, in the case of air pollution, beginning with a high level of pollution, it is assumed that the first decrements in pollution generated by mitigation efforts have high marginal benefit, which then decreases as efforts are increased. (See Costello et al, 2017, for an example.) If there is a constant marginal cost to externality reduction

efforts, the optimal outcome can be simply described as that at which the declining marginal benefit equals the constant marginal cost.

In contrast, the simulation model will illustrate that, with reciprocal or interdependent externality and plausible parameter values, the marginal benefit from mitigation will not be monotonic or continuously decreasing. Instead, if structures are close together (say, within 30 meters) and mitigation is effective in decreasing the probability of ignition of a home, the marginal external benefit to other unmitigated neighboring homes at risk begins at a given positive level with zero mitigation, but increases up to a point as the proportion of homes mitigated increases, reaches a maximum, and then declines rapidly thereafter, reaching near zero at proportions mitigated well less than 100 percent. This pattern has been illustrated for contagious disease (Skene et al 2014); our simulations show that it also important in a models of wildfire spread and mitigation.

The intuition behind this pattern is that, at first, reducing the risk of fire transfer from a mitigating house to its neighbors provides relatively modest benefit because those houses remain at risk from a larger number of other unmitigated neighbors. There are many paths by which a given house can be ignited; only one ignition is required for destruction, and so eliminating one path provides relatively little external benefit in addition to the private benefit to the owner of the mitigated house. However, as mitigation spreads the number of paths shrinks to a point where one further action to mitigate breaks the path and substantially lowers the likelihood of fire for a given neighboring unmitigated house.

There are some important differences between our model of wildfire spread in a community in which houses occupy fixed predetermined locations and the contagious disease model in which a person who is contagious may move around and potentially interact with all community members. The primary effect of this difference is that exposures to wildfires may have different risks depending on their locations whereas in the contagious disease model where all agents are equally likely to interact no specific exposure is more beneficial to mitigate than any other, but in a model where some infected people have above average rates of interaction and so are “super spreaders,” one can obtain the same heterogeneity of risk and marginal benefit as in the wildfire model with fixed locations.

## Simulation models

There have been several simulation models developed to predict the risk of wildfire spread and related losses to owners or insurers of structures. Many are proprietary, but some are publicly available. Insurance regulators in California have been frustrated by their inability to examine and understand the workings of such models, and homeowners have complained that such models do not adequately account for mitigation efforts they do make. The simple and transparent model we have developed is focused on

predicting the pattern of fire spread and losses in the built up areas in the urban wildfire interface, and on how that pattern is affected by mitigation in the community.

Many existing models primarily predict the pattern of wildfire spread from an initial source of ignition in open space (forest or grassland) and treat buildings as "unburnable." The evidence of spread of fire from building to building suggests that this assumption is implausible. Models that do look at the spread of fire among buildings are typically descriptive based on past experiences with such fires and/or expert opinion on likely consequences. For example, the open source "First Street Foundation" (2022) model generates estimates of community damage from mean values of historical data on 549 fires in built up areas. However, these models typically do not include measures of the extent of mitigation or its impact. Baylis and Boomhower (2021) do study the impact of building codes on fire damage but not the other measures of mitigation; they provide an estimate of the total mitigation benefit of building code adherence (compared to its absence) but do not estimate how marginal benefit varies with proportion mitigated. Our model in contrast deals with mitigation of all types and focusses on its effect as a function of the proportion and pattern of buildings mitigated.

We also consider owner behavior in choosing to invest in mitigation as a function both of the cost of mitigation and its private benefit as a function of the proportion of neighborhood homes mitigated. As more owners mitigate the probability of fire for an unmitigated structure falls and so does the expected net benefit from costly mitigation. We determine the Nash Equilibrium level of private mitigation and contrast it with the level that would be optimal for the neighborhood or community. We also consider heterogeneity of private and social benefit from mitigation as a function of their location (on the edges or the center of the neighborhood) and as a function of the replacement cost of the house. This behavioral addition is different from the behaviors in terms of forest fire fuel reduction in other simulation models.

Modeling wildfire spread in communities.

Wildfires in urban areas can be classed as an "interdependent security problem" (IDS) or a "reciprocal externality," since the risk of any house suffering damages is affected in part by the actions of other neighboring homeowners—and vice versa. Homeowners can thus either suffer damage from *primary risks* from an external source (nearby forest or grasslands) or from *secondary risks* from the fire spreading from other structures in the community. In both cases the source of transmission is firebrands (embers) that are carried by the wind from a burning fire to a previously unaffected structure and which then may ignite that structure.

Simulation model of Fire Spread:

Houses are represented with nodes characterized by information such as their location in space, their level of mitigation, their "fire state" (whether they have burned down, are on fire, or have never been on fire),

and a set of edges which are representations of the connections between houses. Their weights based on suggestions from Risk Management Solutions) represent the risk of fire transmission as a function of the distance between houses in a hypothetical grid. .For simplicity, the value of these weights or transmission probabilities is binary, positive if a house is on unit away from an ignited house and zero otherwise.

This pattern yields the formula for transmission probability (less than one) as:

$$P(Fire) = (1 - M_2)\left[0.0797 + \left(\frac{0.8228}{1 + \left(\left(\frac{D}{7.0432}\right)\text{^}3.402\right)}\right)\right]$$

Simulation Flow:

We describe a neighborhood and populate it with houses based on a set of coordinates provided beforehand. Houses (depending on their location on the grid) will be subject to the risk of catching fire from a source external to the neighborhood (this is what we call a primary fire). We input assumptions about how a fire at one house affects the others, first from the edge and then the interior.

We randomly choose a house on the edge (with some assumed probability of external fire) to begin the cycle. Then we enter the first of many steps, or replications, in which houses that have already had a chance to spread their fire burn down, and houses that are currently on fire spread their fire to neighboring houses. This process repeats for as many time steps are necessary for the fire to go out or for all houses to burn.

How the risk of a house burning varies depending on its location depends on the parameters of the model. Any fire must begin with one (among many) house on the edge but then can spread to converge on houses closer to the center of the grid. Hence a randomly selected house on the edge can have a lower or higher probability of fire compared to houses in the center depending on how easily the fire spreads toward the center. The key point however is that the risk to any one house can be different from the risk to another house even if all houses are identical and the initial incidence of fire is random.

Public and private benefits of mitigation.

There is a costly but effective mitigation action owners can take which reduces the chance that a firebrand thrown off by a neighboring home on fire will ignite the home. Such mitigation actions include fireproof roofs, non combustible siding, the presence of sprinklers, fire rated windows, or other types of fire suppression, the extent of flammable vegetation close to the home, the distance between homes, and the intensity and windspeed associated with the external fire. We therefore use the model to show how overall community damage is related to the effectiveness of mitigation in different environments such as wind and humidity.

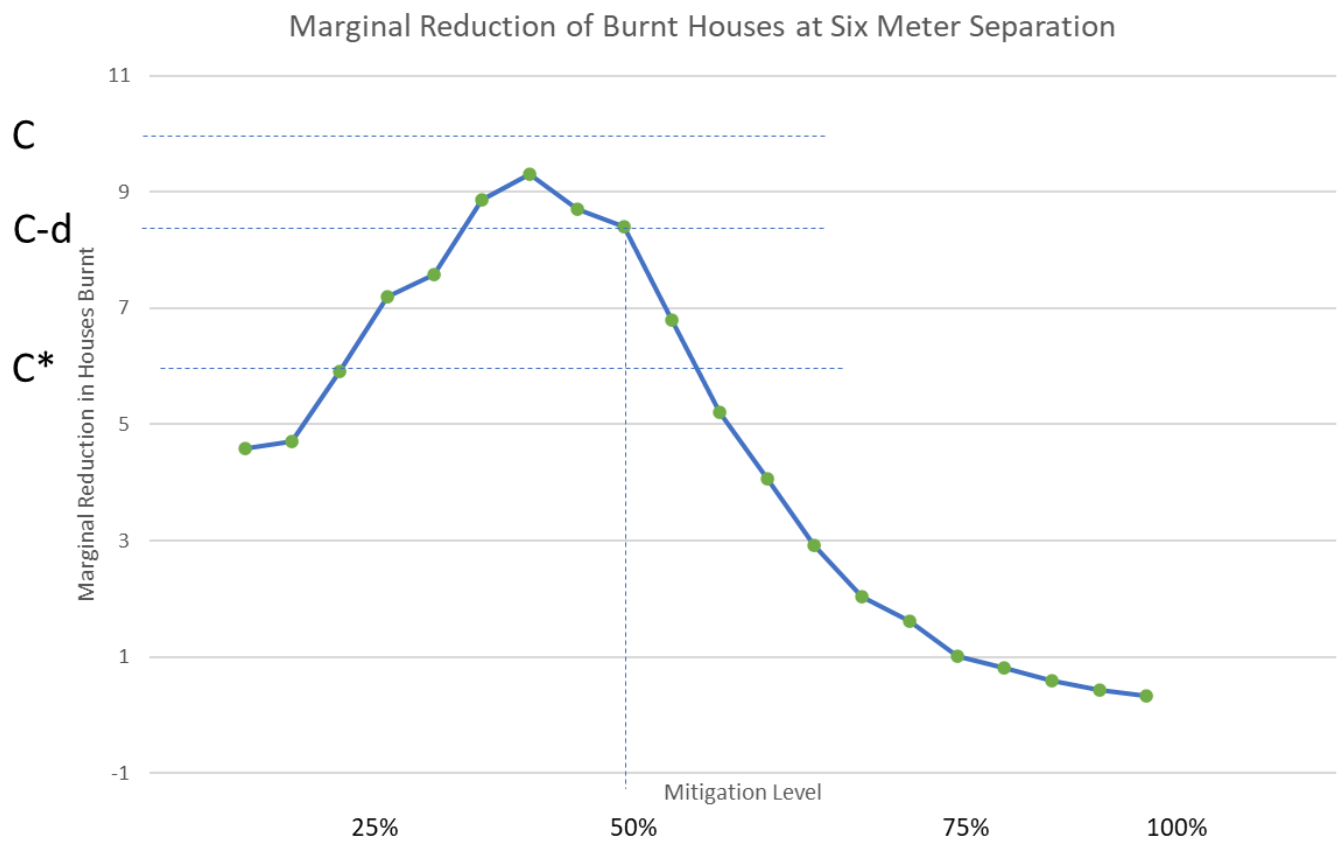
An important question is how to model the pattern of mitigation. We initially consider a heterogenous risk model in which the differences in risk from an external fire to homes on the periphery relative to those in the center is taken into account by the model. The expected number of houses that will burn when an external fire strikes the neighborhood will decrease the greater the extent of mitigation. This happens both because mitigation provides private benefits in the form of reduction of risk that a given mitigated home will burn and because, once mitigated, a home transfers less risk to other homes, especially to other unmitigated homes. There are thus private and social or neighborhood benefits from mitigation. Beginning at zero mitigation, marginal benefit begins as a positive number and falls to a level near zero when all but one home has been mitigated.

In between those two endpoints, it is likely that marginal benefit will rise at first, gradually reach a maximum, and then decline rapidly. A sample marginal benefit curve generated from the model is shown as Figure 1 and accompanying data, reflecting the pattern of marginal benefit from mitigation when 100 homes in a rectangular grid are 6 meters apart and mitigation reduces fire spread probability by 80%. The simulations in this model are run for 50,000 iterations to smooth out the estimated path of marginal benefit.

Figure 1

Panel A

Marginal Reduction of Burnt Houses at Six Meter Separation



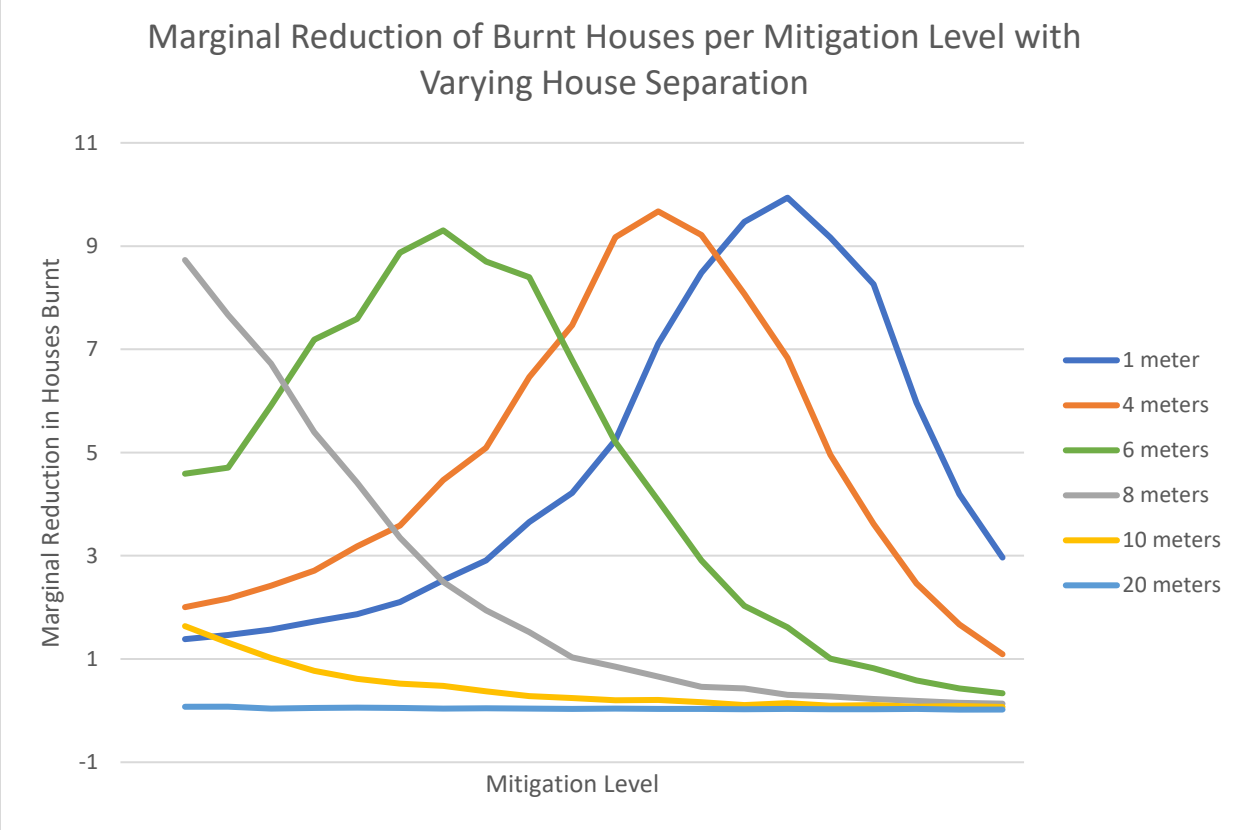
Panel B

| Percent mitigated | Mean total num burned | Marginal reduction in num burned |
|---|---|---|
| **0%** | 93.0025 | |
| **5%** | 88.41006 | 4.59244 |
| **10%** | 83.70322 | 4.70684 |
| **15%** | 77.79426 | 5.90896 |
| **20%** | 70.60638 | 7.18788 |
| **25%** | 63.01822 | 7.58816 |
| **30%** | 54.14566 | 8.87256 |
| **35%** | 44.84116 | 9.3045 |
| **40%** | 36.14086 | 8.7003 |
| **45%** | 27.74208 | 8.39878 |
| **50%** | 20.9486 | 6.79348 |
| **55%** | 15.74298 | 5.20562 |
| **60%** | 11.67108 | 4.0719 |
| **65%** | 8.759 | 2.91208 |
| **70%** | 6.72882 | 2.03018 |
| **75%** | 5.11382 | 1.615 |
| **80%** | 4.10936 | 1.00446 |
| **85%** | 3.28998 | 0.81938 |
| **90%** | 2.7038 | 0.58618 |
| **95%** | 2.27578 | 0.42802 |
| **100%** | 1.94 | 0.33578 |

When there is no mitigation, the change in the risk to unmitigated homes from the first house mitigating is small because any unmitigated house will still be hit by multiple firebrands from other neighboring houses. The maximum value for marginal benefit (at about 30% mitigation in this example) corresponds to “herd immunity.” Beyond this point further mitigation still provides some benefit to neighbors but now at much lower rates. Beyond about 70% mitigation in this example the marginal benefit from further mitigation is near zero.

Figure 2 shows a family of marginal benefit curves generated by the model. As one would expect the percentage mitigated at which the marginal benefit is maximized is larger the greater is housing density. The diagram also shows that if houses are widely spaced, marginal benefit declines continuously. One important implication of this model is that for reasonable distances between homes (4 to 6 meters) the peak of marginal benefit is in the range of 35 to 60% mitigation. Neither zero mitigation nor near complete mitigation will be appropriate to deal with spillover effects of fire within reasonably dense neighborhoods.

Figure 2: Marginal Benefit from Mitigation with Varying House Separation




What determines the optimal percentage mitigating?

These two diagrams help show how marginal benefit varies with the mitigation percentage and structure of the model. At any one of the distances between structures, the optimal mitigation percentage if the cost of mitigating a house in a community with all houses of equal value is a constant amount $C* is shown in Figure 1 by the intersection of that price line C*(the marginal cost of mitigation)

with a marginal benefit curve, at the mitigation level M*. The family of curves in Figure 2 indicates that M* is very sensitive to housing density, with high levels of mitigation needed for efficiency when structures are close together but low levels after a certain distance between houses is specified. In the model, distance and mitigation matter when houses are close together but not when they are separated.

We note first that the optimal percentage mitigated must be greater than the percentage at which marginal benefit is maximized. However, because the MB curve declines steeply from its peak, the optimal level is close to the level of maximum benefit. At high price C in figure 1 no mitigation is optimal, but if the price is a little lower at C-d it is optimal to mitigate about half of all homes. As the price falls further optimal mitigation increases but stays within a narrow range of about 40-70%regardless of the price.

This finding is important because in cases of high density, the information needed for public policy is the point of community mitigation at which MB is maximized; no matter what the level of C, the optimal percentage will be close to (though larger than) that level. On the other hand, as shown in figure 2, housing density is a key determinant of optimal mitigation.

When will rational owners invest in mitigation?

If owners knew the probability of fire hitting their structure with and without mitigation and were risk neutral, they would choose to mitigate or not depending on whether the cost of mitigation is greater or less than the change in the money value of expected fire damage to their house—which is the change in the probability of fire for that house from mitigation times the value of the house. At one extreme, owners might assume no one else will mitigate, expect the probability of fire without mitigation to be high, and then expected benefit from effective mitigation will be high as well. If all or most owners then mitigate, their initial assumption about their neighbors will turn out to be in error. At the other extreme, each owner might assume that all other neighbors will mitigate, and therefore choose to save the cost of mitigation. But if all decide not to mitigate, their initial assumption about their neighbors will also be in error. So, it is unlikely that either extreme can represent an equilibrium if there are multiple time periods.

If mitigation that provides complete protection is available at cost of C (per time period), a rational risk neutral owner will choose to mitigate if:

(1) $C < pV$

Where p is the perceived probability of fire for an unmitigated house and V is the value of the house. .

There will be a Nash equilibrium if owners follow this investment rule when the value of p based on each owner's expectation of the percentage of neighbors mitigating corresponds to the percentage of owners who satisfy equation (1) at that percentage.

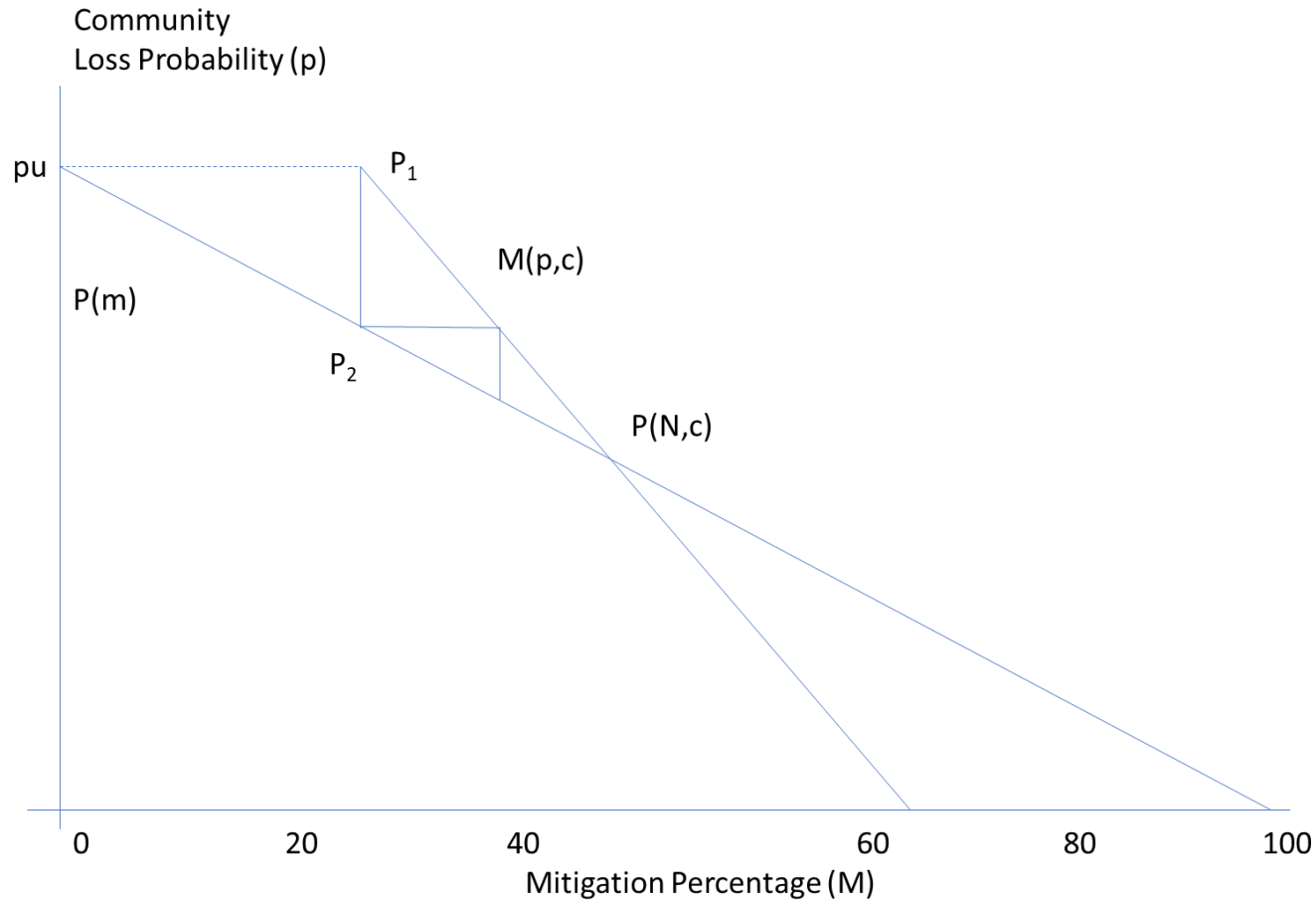
Adding variation in house value.

It is easiest to characterize this Nash equilibrium when houses have different values. We assume that houses all have the same $C cost of mitigation but different values or replacement costs. Then there can be a Nash or independent adjustment equilibrium as we now show.

Nash equilibrium

To determine the Nash equilibrium (if one exists) we first need to show the values of p (probability of fire spread) as a function of the percentage mitigated. The line p(M)) is shown in figure 3.

Figure 3




Beginning at the (high) value of p when none mitigate, we need to ask what proportion of homes would mitigate at a given mitigation cost and distribution of home values. If that number is positive at maximum p, we know that any Nash equilibrium will have a positive level of mitigation.

The pattern of percentages of homes that would choose to mitigate at various values of p at a given cost C is shown in figure 3 as M(p,C). At point P1 the percentage of homes mitigating will cause p to fall to a new combination at P2. Then the new percentage who will mitigate is at P3, and the process continues as shown until Nash equilibrium is reached at P (N, C). Lower values of C will be associated with a lower probability and higher proportion mitigating at Nash equilibrium. This curve will decline continuously from the level of C at which the most valuable homes are mitigated.

This private-benefit Nash equilibrium curve will fall below the social marginal benefit curve because owners only consider private benefits in deciding to invest in mitigation. Hence, the Nash equilibrium level of mitigation for various levels of C will fall short of the value that is efficient for the community.

Variation in values

To generate this model and illustrate it via simulation, we must assume some distribution of house values in the community. (If houses were of identical value either all or none would mitigate.) We will assume that the location of houses of different values in the community is random. In this case, the model predicts "top down" mitigation. In equilibrium, houses above a certain value will choose to mitigate, while houses below that value will not. (This model can be modified if houses of given value tend to cluster together.)

To provide an example, we collected data on asking prices of houses offered for sale (new and old construction) in Fountain Grove CA, the site of extensive damage by the Camp Fire, to generate an example of likely mitigation behavior by individual homeowners and by a community seeking optimal mitigation.

Table 1 show the frequency distribution of house prices by percentage of houses offered for sale where varying asking prices have been collapsed into "tiers" by taking the average values in each tier:

TABLE 1

FREQUENCY DISTRIBUTION OF HOME SELLING PRICES, FOUNTATIN GROVE, 2022

| **Tier** | **Percentage of Offers** | **Value** |
|---|---|---|
| **1** | 20 | 3.75 million |
| **2** | 20 | 2.0 million |
| **3** | 40 | 1.2 million |
| **4** | 20 | 0.75 |

Now consider the example of 6 meter distance and mitigation effectiveness of 80%. Starting with zero mitigation and a probability of fire destruction of 0.97 once a fire has approached the community with annual probability P*, the marginal private benefit from mitigation as a function of percentage of houses owners expect to mitigate are as shown in Table 2

TABLE 2

EXPECTED PRIVATE MARGINAL BENEFIT FROM MITIGATION (80% EFFECTIVENESS) HOMES IN FOUNTAIN GROVE, CA

| **Tier** | **% Mitigating** | **Expected Marginal Private Benefit** |
|---|---|---|
| **1** | 0 | .97 (3.75 M) (0.8) P* |
| **2** | 20 | .55 (2M (0.8)) P* |
| **3** | 60 | .08(1.2M) (0.8) P* |
| **4** | 80 | .015 (0.75M) (0.8)P* |

Given some value of P*, if we now vary the annual price of mitigation, we can determine which value tiers of homes will choose to mitigate at a given annualized price of mitigation, given various levels of mitigation prevailing in the community.

Suppose the annualized price of mitigation was relatively high and P* were low, so that only the top tier (20%) of houses would mitigate if each of their owners assumed that no one else would mitigate. In order to induce the second tier to mitigate the price would need to fall. There are two possible scenarios here. One is that second tier owners also assume no one else would mitigate, so their private marginal benefit would be .97 (2M) P*. However, in the table we assume that the second tier owners observe the effects of mitigation by the first tier owners and s. consider the probability of damage without mitigation to each of their houses to be 0.55. If the annualized price of mitigation is higher than this amount, tier 2 owners will not mitigate whether or not they take into account the behavior of tier 1 owners.

Now, suppose the price of mitigation is just above the level needed to get tier 2 owners to mitigate given tier 1 owners had done so. Table 3 illustrates the private and social benefits if all 20 tier 2 houses mitigated and, according to the model, reduced the risk of damage to zero for the houses that mitigated but also reduced the risk from .55 to .08 (or 0.47) for the remaining houses:

TABLE 3

PRIVATE AND SOCIAL BENEFITS FROM TIER 2 MITIGATION, FOUNTAIN GROVE, CA

| Tier | Private Benefit/House | Social Benefit/House | Number of Houses |
|---|---|---|---|
| **1** | 0 | 0 | 20 |
| **2** | 0.71 (2M) (0.8) P* | 0 | 20 |
| **3** | 0 | 0.35 (1.2M) P* | 40 |
| **4** | 0 | 0.35 (.75M) P * | 20 |

However, once the second tier has mitigated the value for mitigating the remaining 60% of houses drops substantially because marginal private and social benefit both fall to very low levels. Without intervention only 20% of homes would mitigate, well below the social optimum. Increasing the percentage mitigating to 40% would provide spillover benefits to unmitigated lower value houses that would offset any shortfall between private benefits and mitigation cost for this second tier. But it would be inefficient to mitigate all houses in our model unless the cost of mitigation were minimal.

The particular configuration of marginal social benefit from mitigation that has been highlighted in this paper has implications for the practical task of using subsidies or regulations to being the level of mitigation closer to the social optimum. Given some estimate or observation on the private level of mitigation, the position of that level relative to the level at which marginal benefit is maximized can tell decisionmakers how aggressive they need to be in correcting private decisions. If it is far short of the maximum MB intervention should be strong, whereas if it is close to or even greater than that point there will be less benefit from intervention to increase private mitigation levels. This distance between private and social optimum of course depends on the cost of mitigation and the pattern of private benefits from mitigation, considerations which can be incorporated into analysis from the simulation model.

Behavioral Biases

What if homeowners are not rational and/or poorly informed about fire risk and mitigation? Then they may exhibit behavioral biases in choosing the level of mitigation without insurance. They may, for

example, show optimism bias (think the long-term probability of fire is lower than it actually is) or myopia bias (ignore the future benefits of mitigation more generally compared to worrying about the cost of mitigation). In both such cases, owners may choose even lower levels of mitigation than those described in the previous section.

The case for some collective action is even stronger when these biases are present than if owners were rational, farsighted, and informed about loss probabilities.

Adding insurance

*Insurance supply.* If homeowners are risk averse, they may gain from buying insurance that pays claims when their houses are burned if the premium charged by that insurance is actuarially fair and if the owners' subjective loss probabilities (with and without mitigation, given the level of mitigation in their community) corresponds with the objective probabilities used in the insurance premium calculation.

*Owner behavior.* Suppose that owners underestimate the benefits of mitigation on their expected losses without insurance. Myopia, inattention, or bias could cause this. Without insurance, mitigation may not be chosen. However, with insurance, the owner's decision is much clearer: the owner need only compare C to DP and mitigate if the former is less than the latter. Hence, in this case insurance may actually lead to more rational individual behavior than without insurance—as well as providing a gain in expected utility from coverage of whatever losses occur. That is, properly priced insurance may offset to some extent the behavioral biases discussed earlier. However, insurance premium reductions for mitigation which only reflect an individual decisionmaker's private benefits from mitigation and do not take into account benefits to neighbors will still fall short of an efficient outcome,

*Insurer behavior.* We have thus far assumed as have others (Baylis and Boomhower 2021) that insurance is supplied at premiums based on the loss probabilities estimated by our model, and that homeowners are risk averse. In the absence of mitigation insurance premiums would therefore equal the expected annual probability of a fire times the value of the property plus a "loading" factor to account for insurer administrative costs and competitive levels of return on equity. We assume that there is still a chance of fire from other sources so that, even with fully protective mitigation there would still be demand for insurance, offered at a discount from the no-mitigation level where the discount is the actuarial value of the reduction in probability due to mitigation times the value of the property.

*Insurance regulation.* One of the issues in regulation and marketing of wildfire insurance in California is the absence of objective historical data to determine risk and the complexity, secrecy, and imprecision of the many different models used by insurers to calculate the loss probabilities. Past data on fire losses is an unreliable guide to determining a fair premium in a world where loss probabilities are subjective, ambiguous, and changing over time. How insurance markets can or do work in such settings is not well understood, to say the least. Theory tells us that there must be some set of premiums at which profit maximizing insurance companies would be willing to sell insurance contracts if permitted to charge those premiums by regulators. Hence we assume that insurance will be supplied at premiums that reflect estimates of loss probability by suppliers of equity capital to expected profit maximizing insurance firms. There almost always are alternative sources of insurance in such situations whether from unregulated insurers specializing in high risk and ambiguous perils (unadmitted insurers) or the state established FAIR insurance plan financed by assessments on licensed insurers in California.. Both of these entities are likely to charge "high" insurance premiums which may mean that some structures of low market value are not rational to insure. And sometimes insurers themselves appear to make irrationally high if temporary short term forecasts of loss probability following recent large losses (Kunreuther, Pauly, and McMorrow 2013). It is reasonable to assume that there will be a supply curve of insurance at premiums close to the value to buyers as long as buyers and insurers have similar expectations about future loss probabilities.

*Social policy to improve efficiency.* If this latter case occurs, efficiency could be regained if the insurance premium discount for mitigation was enhanced to be larger than that which would prevail under simple insurer competition. Either a regulation or a subsidy to insurance policies sold to owners with house values near the threshold would move behavior to the optimal level. Note that if a subsidy were offered to any owner of a home who mitigates and the subsidy were set at the difference between private and social benefits of mitigation, it would not be claimed by low value owners. On the other hand, as before, there would be no need to offer subsidies to owners of high value homes.

Efficiency and market failure

The configuration of marginal social and private benefits from mitigation from the simulation model under plausible parameters implies that the socially optimal proportion mitigated is slightly higher than the proportion at which marginal benefit is maximized. Risk rated insurance discounts for mitigation can incentivize homeowners to mitigate and close this gap. Regulation or subsidization of the insurance

discount for mitigation can lead to the socially optimal level of mitigation when insurance markets are competitive.

Policy discussion.

In California some fire insurance premiums are regulated. While unlicensed insurers can sell policies with appropriate warnings to buyers, and while there is a state controlled FAIR plan that offers limited coverage for owners unable to obtain coverage in the market, the bulk of coverage is sold by licensed insurers. After recent wildfires, many insurers cancelled coverage on individual properties rather than renew coverage at state approved rates, and many insurers also increase the premiums they proposed to change. New proposed rates are often based on simulation models rather than on historical loss data, but those models are proprietary, so are difficult for the regulator to review.

Mitigation and equity.

When houses of different values and locations in a community have different expected damages from a wildfire, it is efficient to mitigate some houses and not others. Importantly, however, what is efficient will not be uniform: unmitigated houses, concentrated in the center city and lower average value, should optimally be put at risk of burning to the ground, while high value houses near the periphery should be protected. Such a pattern may be regarded as unfair.

Changes in the risk of fire (or other environmental threats) to a home will lead to changes in insurance premiums to cover the cost of damage to that home. If the structure is viewed only as an asset in a diversified portfolio of assets), the decision whether or not to buy insurance to offset possible losses can be a simple one: the owner makes a judgment about how the proposed premium compares with the current expected loss from the covered peril, and buys insurance as long as the expected benefit from coverage is equal or close to the premium. So, if recent experience caused by climate change on other factors causes the risk of wildfire to given home to increase, coverage will still be bought because the expected value of the benefit from coverage will have increased in a commensurate way.

However, private and social attitudes may change if the owner is low wealth and occupies the house—in effect, renting it from himself. In this case the owner's wealth is already reduced by the increase in loss probability, as before. The owner's primary decision then is whether to rent another house in a less risky location at a lower annual cost than the cost of living in the current house. However, the initial risk-induced reduction in house value and associated higher premium may be regarded as unfair to owners who planned to remain in their homes.

Owners of low value houses will not choose to mitigate and in an efficient outcome should not do so. This means that the pattern of risk may be one with little or no risk to high value homes (but high payments by the owners) and positive risk of harm (though lower than without mitigation of high value homes) to owners of low value homes but no cost burden for mitigation. How social policy will regard the equity of this combination of risk and cost is unclear but potentially important.

Moving closer to the optimum can either be accomplished by subsidizing insurance premium reductions associated with mitigating or regulation requiring mitigation by higher value homes, as noted above. However, these two policies would have different distributional implications in the community depending on how a subsidy would be financed. The primary external benefits from mitigating the marginal mor median value homes flow to owners of unmitigated lower value homes.

Conclusion.

When a wildfire approaches a built-up area, the configuration of homes and the extent of mitigation can help reduce the expected damage. Our simulations indicate little need for neighborhood concern about mitigation if houses are 30 meter or more apart (though private owners may still choose to mitigate because of external threat). At an average distance between homes of about 15 feet, there will be substantial gain from pushing the mitigation percentage close to 50% for the most valuable homes. Public policies to encourage mitigation where it is mort beneficial may be assisted by insurance premium incentives to offset owner misperception. Achieving efficiency will raise issues of equity toward low-income owners of unmitigated housing that will need to be resolved.

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