Risk Externalities, Wildfire Hazard, and Private Investment to Mitigate Wildfire Risk in the Wildland-Urban Interface

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Abstract: Homeowners in areas adjacent to wildlands – in the Wildland-Urban Interface (WUI) – can mitigate the risk that their home will be damaged in a wildfire by creating “defensible space” on their property. This article explores homeowners’ incentives to invest in defensible space using a unique data set on 35 WUI communities in Nevada. This is the first study to analyze homeowners’ incentives to invest in defensible space, comparing across both forested (alpine forest) and non-forested (sagebrush rangeland, pinyon pine and juniper woodland, grassland) communities. This article explores two explanations for perceived homeowner underinvestment in defensible space: (i) homeowners’ misjudging their wildfire risk and (ii) spatial interdependencies between neighbor’s defensible space investments due to risk externalities. We find no evidence to suggest that homeowners’ systematically misjudge their wildfire risk, though we do find evidence of strategic complementarities in defensible space investments due to risk externalities in certain communities, depending on predominant vegetation. Our results suggest that wildland fire policy to promote defensible space should focus on financial and regulatory barriers to investment in defensible space, rather than on educational programs, and that “tipping policies” to encourage early adopters to invest in defensible space may be appropriate in communities where the majority of homeowners have not invested in defensible space and whose predominant vegetation suggests the presence of strategic complementarities.

Keywords: Wildland-Urban Interface, Defensible Space, Fire-Safe Investments, Interdependent Security, Strategic Complements, Strategic Substitutes, Risk Externalities, Natural Disasters, Wildfire, Spatial Economics, Spatial Econometrics, Risk-Mitigating Investments

Abbreviations: Wildland-Urban Interface (WUI), U.S. Forest Service (USFS), and Bureau of Land Management (BLM)

JEL Classifications: D8O - Information, Knowledge, and Uncertainty: General
Q54 - Environmental Economics: Climate; Natural Disasters; Global Warming
R20 - Household Analysis: General

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Introduction

Recent decades have witnessed a continued increase in wildfire activity and wildfire costs throughout the United States (Stephens and Ruth 2005; Calkin et al. 2005; Gebert, Calkin, and Yoder 2007; Westerling et al. 2006; GAO 2004; GAO 2007). An important driver of the increase in wildfire costs over this period has been the growth of housing stock in areas adjacent to wildlands in what is known as the Wildland-Urban Interface (WUI). The growth of housing stock in the WUI increases wildfire costs because residences in the WUI are at increased risk of property damage due to wildfire (NIFC 2004), wildfires in the WUI are more difficult and costly to suppress by public agencies (Cohen 2000; Winter and Fried 2001), and human caused wildfire ignitions are more common in the WUI (Cardille et al. 2001).

Homeowners in the WUI can undertake a number of investments that can mitigate the risk of their homes would be damaged in a wildfire. These risk-mitigating investments include the use of fire-resistant building material (roofing, siding, etc.) and the creation of what is known as "defensible space". Defensible space is the management of trees, bushes, and other flammable material in the area surrounding a residence in order to reduce the risk of damage to the residence by a wildfire. Numerous studies on wildfire behavior have established the efficacy of defensible space at reducing the risk that a home will be damaged by wildfire (Cohen and Saveland 1997; Cohen 2000). Furthermore, it has argued that investment in defensible space is the most promising approach to reducing wildfire damages and suppression costs in WUI communities in the United States (Brenkert-Smith, Champ, and Flores 2012). Despite the apparent benefits of investment in defensible space in terms of reduced wildfire risk, however, many homeowners in the WUI choose not to invest (Bright and Burtz 2006; Brenkert-Smith et al. 2006; Talberth et al. 2006; Parente et al. 2011).

In this article, we investigate homeowners' private incentives to invest in defensible space on their property using a unique data set on homeowners' observed investments in defensible space for 35 WUI communities in Nevada. The 35 communities were chosen so that there is variation between and within communities in the "wildfire risk" faced by homeowners, where a homeowner's wildfire risk is defined as the risk that their home will be destroyed in a wildfire in the absence of adequate defensible space.[2] There is variation in homeowner wildfire risk between communities due to differences in firefighting resources, physical infrastructure, and biophysical features that determine wildfire frequency and hazard.[3] In addition, there is variation in wildfire risk between homeowners within each community related to site characteristics, such as slope and aspect, and to property characteristics, such as lot size and a home's proximity to wildlands. Our empirical approach uses this between and within community variation in homeowner wildfire risk to explore why certain homeowners in the WUI choose to invest in defensible space while others do not.

This article makes four contributions to the literature on homeowner investment to mitigate wildfire risk. First, we analyze how a homeowner's decision to invest in defensible space is influenced by the predominant vegetation in their community. We sort the 35 communities in our data set into four groups based on predominant vegetation: grassland, sagebrush rangeland, pinyon pine and juniper woodland (henceforth pinyon-juniper woodlands), and alpine forest. Predominant vegetation determines the wildfire frequency and hazard in a community, as well as the efficacy of defensible space at reducing the risk that a home will be destroyed should wildfire reach the property. Previous studies that have analyzed homeowner incentives to invest in defensible space have focused exclusively on forested communities (Shafran, 2008; Kaval, 2009; Schulte and Miller, 2010; Brenkert-Smith, Champ, and Flores, 2012), and, as such, their conclusions concerning the appropriate wildland fire policy to promote homeowner investment in defensible space may not hold for non-forested WUI communities.

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[2] In most wildfires in the WUI, homes are either undamaged or are destroyed and require rebuilding; partial damage to homes is relatively rare (Cohen, 2000).

[3] Wildfire hazard refers to the physical situation on the landscape (fuel loads, vegetation, climate, topography, etc.) that determines the intensity that an area is likely to burn in the event of a wildfire (Scott and Reinhardt, 2001).

Second, we use the between and within community variation in homeowner wildfire risk to analyze whether homeowners' investments in defensible space reflect an understanding of how their wildfire risk is determined by factors such as community firefighting resources and the biophysical determinants of wildfire hazard in the vicinity of their property. If homeowners' defensible space investments reflect, on average, an understanding of the observable determinants of their wildfire risk, this suggests that homeowners have a relatively sophisticated understanding of wildfire, and that wildland fire policy should focus on financial and regulatory barriers to investment in defensible space.[4] On the other hand, if homeowners' defensible space investments do not appear to be influenced the observable determinants of their wildfire risk, this suggests that the appropriate wildland fire policy should instead focus on educational programs to help homeowners understand their wildfire risk. Previous studies that have analyzed homeowner investments to mitigate wildfire risk have focused on small numbers of communities, and, as a consequence, do not have sufficient variation to analyze how homeowner investment is influence by many of the determinants of homeowner wildfire risk considered in this study, including predominant vegetation (Shafran, 2008; Kaval, 2009; Schulte and Miller, 2010).

Third, we examine how the predominant vegetation in a community influences the role of "risk externalities" in homeowners' defensible space investments. Defensible space investments are subject to risk externalities in that a homeowner's investment in defensible space, through lowering fuel loads on their property, will slow the spread of a wildfire through their neighborhood and thereby reduce the wildfire risk faced by their neighbors. As homeowners do not to capture the benefit from the reduction in their neighbors' wildfire risk, they are likely to underinvest in defensible space relative to what would be socially optimal. If the importance of risk externalities depends on predominant vegetation, then wildland fire policy to encourage defensible space should focus on communities whose predominant vegetation suggests that risk externalities are likely to be important, as it is these communities where the potential for socially-inefficient underinvestment in defensible space is greatest. Following Shafran (2008), we examine the importance of risk externalities in defensible space investment by analyzing how homeowner investment in defensible space is influenced by neighbors' investments in defensible space.

Fourth, for communities where risk externalities are present, we investigate whether differences in predominant vegetation cause defensible space investments to be "strategic complements" in certain communities and "strategic substitutes" in others. Defensible space investments are strategic complements (substitutes) when the benefit of defensible space to a homeowner increases (decreases) as their neighbors increase their defensible space (Shafran, 2008). Defensible space investments will be strategic complements in communities whose predominant vegetation, and, hence, wildfire behavior, implies that defensible space will do little to reduce a homeowner's wildfire risk unless their neighbors also undertake defensible space. In these communities, "tipping" policies that provide financial incentives for early investors in defensible space in order to achieve a "critical mass" of defensible space investment may be appropriate. Conversely, defensible space investment will be strategic substitutes in communities whose characteristic vegetation implies that neighbors' investments in defensible space will act as a buffer that reduces the likelihood that a wildfire will reach a given property. In these communities, a policy that binds homeowners to a program of defensible space may be preferred in order to overcome free-riding. Previous studies have found that defensible space investments are strategic complements for homeowners in forested communities, but have not addressed the question for homeowners in non-forested communities (Shafran, 2008).

2. Methods and Materials

2.1 Empirical Approach

As we discussed in the Introduction, we posit that a household's defensible space investment decision will be influenced by the defensible space investments on neighboring properties. To capture the spatial

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[4] Note we are not able to evaluate whether homeowners are correctly evaluating their wildfire risk, only whether or not, on average, their defensible space investments reflect an understanding of the objective determinants of their wildfire risk.

interdependency in defensible space investments, we estimate a spatial autoregressive probit (SARP) model that includes a spatial-lagged dependent variable:

$$y = \rho W y + \alpha \iota_n + X\beta + \varepsilon \qquad \varepsilon \sim N(0_{nx1}, \sigma^2 I_n)$$

Where y in an $n \times 1$ vector of 0,1 binary dependent variable ($y = 1$ indicates that home i has defensible space); X is an $n \times k$ matrix of explanatory variables; W is are the $n \times n$ spatial weighting matrices (with zero diagonal elements and row-sums of unity), Wy is the $n \times 1$ spatial lag vector. In addition, ρ is the scalar spatial autoregressive parameter; β is a $k \times 1$ parameter vector; and ε is a $n \times 1$ vector of statistically independent disturbances$\left(E(\varepsilon_i \varepsilon_j) = E(\varepsilon_i)E(\varepsilon_j) = 0\right)$.[5]

The spatial autoregressive parameter, ρ, captures the effect of neighbors' defensible space investments on a homeowner's defensible space investment decision. As we discuss in the Introduction, defensible space investments are subject to "risk externalities" in that a homeowner's decision to create defensible space on their property depends on the risk of wildfire reaching their property, and the risk of wildfire reaching their property depends on their neighbors' decisions to create defensible space.[6] The spatial autoregressive parameter allows us to draw inference on role of risk externalities in homeowners' defensible space decisions. In addition, the spatial dependence between neighbors' defensible space investments creates spatial autocorrelation among observations. Given this spatial autocorrelation, estimation using an ordinary probit would not produce consistent parameter estimates. Smith and LeSage (2000) show that a spatial autoregressive process is an effective method for controlling for spatial dependencies that allows for consistent parameter estimates.

As is argued in Shafran (2008), $\rho > 0$ provides empirical support that the defensible space investments of neighbors are strategic complements in that the benefits of defensible space for a homeowner increase as their neighbors increase their defensible space. Defensible space investments will be strategic complements when the reduction in fuel loads in the neighborhood of a home makes it less likely that a wildfire that reaches the vicinity of the home will be an intense fire against which defensible space offers minimal protection, thereby increasing the effectiveness of defensible space as a protective measure. Conversely, $\rho < 0$ provides empirical support that the defensible space decisions of neighbors are strategic substitutes in that the benefits of defensible space decline as neighbors increase their defensible space. Defensible space investments are likely to be strategic substitutes is when the fuel load reductions of neighbors of a home acts as a buffer that reduces the likelihood of a wildfire reaching the property and therefore reduces the need for defensible space. Figure 1 demonstrates how a homeowner's overall wildfire risk, and the reduction in their wildfire risk they achieve through investment in defensible space, changes with their neighbors' investments in defensible space for the cases of (i) strategic complements, (ii) strategic substitutes, and (iii) no significant risk externalities.

In stating that ρ captures the effect of neighbors' defensible space decisions on a homeowner's defensible space decision, we are effectively evoking the "time-dependent" motivation for the spatial autoregressive model. According to LeSage and Pace (2009), a cross-section spatial autoregressive model, such as the model that we estimate in this article, can arise from "time-dependence of decisions by economic agents located at various points in space when the decisions depend on those of neighbors." In our application, we assume that homeowners make their defensible space investment decisions after observing the defensible space investments of their neighbors in previous time periods. Although the defensible space investments have been made over time through this dynamic process, the observed cross-sectional defensible space investments in our sample will exhibit spatial dependence. Given this

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[5] Estimation was performed in Matlab using the James P. LeSage's Spatial Econometrics Toolbox. Using the Spatial Econometrics toolbox, the spatial autoregressive probit model is estimated using a Bayesian Markov Chain Monte Carlo (MCMC) technique that samples sequentially from the conditional posterior distributions of the model parameters. For more details on the estimation procedure used in this article, please see LeSage and Pace (2009).

[6] Shafran (2008) notes that this empirical test for strategic interactions in homeowners' defensible space investments is analogous to empirical tests of other strategic interactions, tax competition, welfare competition, and public good spillovers. See Brueckner (2003) for a review of this literature.

motivation, the coefficients on the explanatory variables in our model reflect how a marginal change in one of these variables would work through the system over to time, culminating in new steady state equilibrium in the community.

We use the variation in wildfire behavior across the 35 communities in our sample to investigate whether differences in wildfire behavior between communities, as they are determined by characteristic vegetation in a community, may cause defensible space investments to be strategic complements in certain communities and strategic substitutes in others. In order to empirically identify ρ, the model assumes that the strategic interaction in defensible space decisions (i.e., whether defensible space decisions are strategic complements or substitutes) is fixed across the sample. Therefore, in order to explore how wildfire behavior in a community influences where defensible space investments are strategic complements or strategic substitutes, we divide our sample into groupings of communities with the same predominant vegetation type and analyze how ρ varies across these groupings.

Given that our results are conditional on the choice of the spatial weighting matrix, W , we explore how robust they are to several ways of weighting neighbors.[7] In particular, we present results for two definitions of W: inverse distance and inverse distance squared. Our preferred definition of W is inverse distance squared, because the effect of a homeowner's defensible space decisions on a neighbor's wildfire risk is likely to be most intense for direct neighbors and drop off rapidly with increasing distances between properties. We do not consider nearest neighbor weighting (e.g., only giving weight to the 8, 16 or some other chosen number of nearest neighbors) because this definition is not directly related to how a homeowner's wildfire risk is determined by the fuel load in the direct vicinity of their home.

2.2 Data

We estimate the empirical model developed in the previous section using data on homeowners' observed investments in defensible space from 35 WUI communities in Nevada. The 35 communities were chosen to include variation in homeowners' socio-economic status, as well as variation in physical infrastructure, firefighting resources, and biophysical determinants of wildfire hazard such characteristic vegetation, topography, and climate. Figure 2 is a map of the location of the 35 communities in Nevada. Table 1 provides summary information for each of the 35 communities, including population, predominant vegetation, and percent of homes with defensible space. Table 2 provides summary statistics for the variables included in our empirical model.

2.2.1 Property-Level Information

As part of this research, during the summer of 2011 we contracted with Resources Concepts, Inc. to use a standardized protocol to conduct hazard assessments at 8867 homes in 35 WUI communities in Nevada (the assessment protocol is described in Resources Concepts, Inc. 2005). Assessments included information on the location of the property (physical address and latitude/longitude coordinates) and property-specific observations of whether or not private residences exhibit 30 feet of defensible space around the residence [DEFSP]. Thirty feet is considered the minimum level of defensible space that will provide protection against a wildfire (Northwest Pacific Wildfire Coordinating). For more information on the hazard assessment and data used in this study see Rollins, Christman, and Will (2011). Data on assessed home value [HHVL] and the size of the lot [LOT] (in acres) were obtained from county tax assessor records.[8] [9] To control for the potential influence of homeowner's associated restrictions on

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[7] Each W used in this article has zeros on the diagonal and row sums normalized to one.

[8] Data from county tax assessor records had some missing data for the following variables: land value, home value, residential square footage, and size of the property. We used an imputation procedure in Stata 11 to generate the missing data. This process iteratively regresses the variables with missing values on all other variables in the model. Four imputed datasets were generated using this procedure. There were no statistically significant differences in summary statistics (mean and standard deviation) for the variables with imputed observations across the four data sets. In addition, a spatial autoregressive probit model estimated using each of the four imputed data sets showed no significant differences in model fit or individual coefficient estimates.

homeowners' defensible space investment decisions, we include a dummy variable [HOA] equal to 1 if the property falls within the jurisdiction of a homeowner's association. Finally, to control for the fact that properties directly adjacent to wildlands face a greater wildfire risk relative to properties in the interior of a community, because the exterior homes act as a buffer slowing wildfire spread, we include a dummy variable [PUBLIC] equal to 1 if the residence is within 30 feet of public land. This variable was created using a GIS dataset on federal lands obtained from The National Atlas of the United States (2012).

2.2.2 Biophysical Determinants of Homeowner Wildfire Risk

We include several biophysical determinant of wildfire risk in our analysis. The predominant native vegetation type in the community is indicated by three dummy variables [GRS, BRUSH, PJ], which are equal to 1 if the predominant vegetation is grassland, sagebrush rangeland, or pinyon-juniper woodland, respectively. In addition, the hazard assessments described above provide data on the average fuel loading [FUEL] (ton/acres) in each community. Daily weather observations during prior fire seasons (May 1 - September 30) were collected from the Remote Automated Weather Station (RAWS) closest to each community using data from the National Fire and Aviation Management FTP (https://fam.nwcg.gov/fam-web/). Wind speed [WIND] is measured as the average maximum wind speed (mph) recorded near each community over the previous 5 years.[10] The total number of lightning strikes that occurred within 10 miles of each residence [LGTHN] over the last six years (2005-2010) was included using data provided by the Western Great Basin Coordination Center. We included the slope of a property [SLOPE]; slope is an important determinant of both the direction of fire and rate of fire spread. Finally, we included a dummy variable equal to 1 if the residence was on a southern exposure [ASPECT]. Southern facing homes have lower vegetation moisture content and face windier conditions, on average, due to greater solar heating.

2.2.3 Firefighting Resources, Infrastructure, & Fuel Treatments

Several variables capture community firefighting resources and physical infrastructure. Data on local firefighting resources was obtained through the Nevada Wildfire Interagency Dispatch Offices. Fire department capacity is captured with two dummy variables: one dummy variable that is equal to 1 if the community does not have a fire department [FD_NONE] and another that is equal to 1 if the fire department is part time [FD_PT]. In addition, the total number of local fire protection resources within 10 miles of each residence, normalized by community population, was calculated [RES]. We normalize by community population to control for the fact larger communities are likely to have more fire protection resources, such a fire trucks, but have greater demand on these resources in the event of a wildfire. Water source availability [WATER] is a dummy variable equal to 1 if there is a water source available for fighting wildfires within a 20 minute drive of the community.

We use data from the National Fire Plan Operations & Reporting System (NFPORS) to construct a variable [RX] for the number of hazard fuel reduction treatments performed on public lands within 10 miles of each residence in the previous five years (2006-2010), normalized by community population. Fuel treatments have been shown to be effective at achieving short run reductions in wildfire hazard (Omi and Martinson 2002; Van Wagtendonk 1996). To capture community wildfire preparedness, we include a dummy variable [FSC] equal to 1 if the community had an active Nevada Fire Safe Council as of 2011. Previous research has indicated that social capital in a community, which may be reflected in the presence of organizations such as Fire Safe Councils within a community, is an important determinant in homeowners' likelihood to undertake fire-safe investments (Brenkert-Smith, Champ, and Flores, 2012).

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[9] The size of residence (in square feet) was excluded from the regressions reported in this article because it was highly correlated with assessed home value [HHVL]. In addition, we elected to use assessed home value rather than assessed land value in our analysis because, as we explain below, we believe that home value is a better proxy for homeowner wealth than land value.

[10] We chose to omit average daily temperature and average minimum relative humidity from the analysis, even though they were available in the RAWS dataset, because they were correlated with several variables, including lighting activity, predominant vegetation in a community, and previous wildfire activity, that we believe to be more important determinants of wildfire hazard in a community and/or of a homeowner's decision to invest in defensible space.

Concerning community physical infrastructure, primary road width [ROAD] is a dummy variable equal to 1if the primary roads are less than 24 feet wide. Road width aids both firefighting resources access to points within the community and increases the ease with which homeowners can evacuate a community under threat from wildfire. Architectural design of the community [NTRMX] is a dummy variable equal to 1 if native vegetation is intermixed throughout the neighborhoods and 0 if there is a clear demarcation between wildland vegetation and landscaping within the community. Population size [POP] used to calculate per capita variables (e.g., RES and RX; see above) for each community was obtained from United States Census Bureau data.

2.2.4 Previous Wildfire Activity

In addition to objective determinants of wildfire risk, previous studies have found that a homeowner's subjective perception of wildfire risk is strongly influenced by their prior experience with wildfire (Martin et al 2007; Sattler et al 1995). To test whether previous wildfire activity influences investment decisions, we use a GIS dataset on wildfire activity during 2005-2010, provided by the Western Great Basin Coordination Center, to create a variable [FIRE] that measures the distance from each residence in our sample to the nearest "large" (greater than 300 acres) wildfire in the previous 6 years.

3. Results and Discussion

Table 3 reports results for our spatial autoregressive probit model using the two spatial weighting matrices (inverse distance and inverse distance squared). As explained in the previous section, we prefer the inverse distance squared weighting matrix because it most reflects the fact that the effect of a homeowner's defensible space decisions on a neighbor's wildfire risk is likely to be most intense for closest neighbors. Comparison of log likelihood functions reported in Table 3, confirms that the inverse distance squared specification is preferred to the inverse distance specification.

Table 4 reports results with the 35 communities categorized into four predominant vegetation groups (henceforth the "vegetation sub-samples"): grassland, sagebrush rangeland, pinyon-juniper woodlands, and alpine forest. As explained above, we divided our sample into these "vegetation sub-samples" in order to identify how the predominant vegetation in a community influences the sign and magnitude of the spatial autoregressive parameter, ρ. We were forced to omit several of the explanatory variables included in the full sample model from three of the vegetation sub-sample models due to the lack of variation in the data at the sub-sample level.[11]

3.1 Property-Level Information

We begin by examining how several property-level variables influence homeowner investment in defensible space. First, assessed home value [HHVL] is positive and significant in the full sample model, as well as in each one of the vegetation sub-sample models. That homeowners in more expensive homes are more likely to invest in defensible space is not surprising. In absolute terms, these homeowners face a greater potential financial loss in the event that a wildfire destroys their homes. Furthermore, assessed

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[11] The following variables were omitted from the vegetation sub-sample models. For the grassland sub-sample, the dummy or count variables HOA, PUBLD, RX, RES, FD_NONE, FD_PT, FSC, ROAD, NTRMX, and WATER do not vary within the subsample and are omitted. The continuous variable WIND is also omitted from the grassland sub-sample because it is highly correlated within the subsample with the variable FUEL, which is included. For the pinyon-juniper sub-sample, the dummy or count variables RX, FD_NONE, FD_PT, FSC, and WATER do not vary within the subsample and are omitted. The continuous variables WIND and FIRE are omitted from the pinyon-juniper subsample because they are highly correlated within the subsample with the variable FUEL, which is included. For the alpine forest sub-sample, the dummy or count variables HOA, RX, FD_NONE, FD_PT, FSC, NTRMX, and WATER do not vary within the subsample and are omitted. The continuous variable WIND is also omitted from the alpine forest sub-sample because it is highly correlated within the subsample with the variable FUEL, which is included. In the grassland, pinyon-juniper, and forest subsample, we elected to include average fuel loading in each community [FUEL] in the sub-sample models because we believe that it is a more important determinant of wildfire hazard in a community than the correlated variables that we chose to omit (i.e., WIND and/or FIRE). There was sufficient variation to include all the independent variables from the full-sample model in the sagebrush sub-sample model.

home value is a proxy for household wealth. Previous studies have found that household wealth, and hence, ability-to-pay, is a significant determinant of mitigation behavior (Collins, 2008).

Table 3 also reports that the average direct effect of a permanent marginal change in home value on the owner's propensity to invest in defensible space (0.0207) is smaller than the average indirect effect (0.0306). The average indirect effect captures the cumulative spatial spillover impacts arising from a marginal increase the value of all homes in a community. These spatial spillovers arise because an increase in home values increases each homeowner's propensity to invest in defensible space, which increases their neighbors' propensity to invest in defensible space because of risk externalities. Indeed, the significant and positive average indirect effects for home value and other variables in the full sample model indicate that risk externalities, and, more specifically, strategic complementarities, are an important determinant of homeowner defensible space investment. Section 3.5 below confirms the importance of risk externalities and strategic complementarities for homeowner defensible space investment in our sample, with an in-depth discussion of the issues.

We find that lot size [LOT] is not a significant determinant of homeowner investment in defensible space for the sample as a whole (Table 3), but that lot size is positive and significant in pinyon-juniper communities (Table 4). Shafran (2008) finds that lot size is positive and a significant determinant of defensible space for homeowners in Boulder County, Colorado. Shafran hypothesizes that owners of larger properties are more likely to invest in defensible space because they can reduce vegetation while still maintaining privacy from neighbors. Our results support Shafran's hypothesis for pinyon-juniper communities, where the average lot size is 5.9 acres, which is similar to the average lot size in Shafran's sample of 4.9 acres. We do not find support for his hypothesis, however, in alpine forest communities where the average lot size is less than an acre (0.88 acres). It is possible that the small average lot size in alpine forest communities means that defensible space and privacy are in conflict for the majority of homeowners in these communities, so that increases in lot sizes do not have a significant impact on defensible space investment for homeowners in these communities.

We also find that membership in a homeowners association [HOA] does not significantly influence decisions to invest in defensible space. This suggests that in the 35 communities in our sample, homeowner association requirements to maintain defensible space, or, conversely, homeowner association landscaping requirements that prevent homeowners' from creating adequate defensible space (i.e., requirements to maintain trees/shrubs/etc. in the vicinity of a home), are not a significant determinant of investment in defensible space.

3.2 Biophysical Determinants of Homeowner Wildfire Risk

Table 3 indicates that the dummy variables for sagebrush rangeland [BRUSH] and pinyon-juniper woodlands [PJ] are positive and significant, but that the dummy variable for grassland [GRS] is not significant. This implies that, all else equal, homeowners in communities where the predominant vegetation is sagebrush rangeland and pinyon-juniper woodlands are more likely to invest in defensible space relative to homeowners in grassland or forested communities. This is somewhat surprising given that forested communities tend to exhibit the most intense wildfire behavior. This result may be explained by the fact that many determinants of a homeowner's wildfire risk also determine the efficacy of defensible space at reducing the risk that their home will be destroyed by wildfire should fire reach their property. For example, it may be the case that while homeowners in forested communities are at greater wildfire risk than homeowners in sagebrush and pinyon-juniper communities, they may believe that defensible space will not offer them adequate protection in the event of a severe "crown fire", which is an intense, fast-moving wildfire that spreads through tree canopies in forested communities (Scott and Reinhardt 2001).

The dummy variable for whether the property is within 30 feet of public land [PUBLD] is not significant for the full sample (Table 3), but is significant and positive for homeowners in sagebrush communities (Table 4). Homeowners adjacent to public lands are likely to face greater wildfire risk than homeowners in the interior of a community because public lands are often left untreated and have high fuel loads as a consequence. Our result that homeowners in close proximity to public land in brush communities are, on average, more likely to invest in defensible space suggests that defensible space investments are strategic substitutes, i.e., that homeowners are more likely to invest in defensible space when neighboring properties have high fuel loads. However, as we report in Section 3.5, we find that in sagebrush communities, defensible space investments are strategic complements, not substitutes. Our result that homeowners adjacent to public lands are more likely to invest in defensible space despite the evidence for strategic complementarities in defensible space investments for homeowners in sagebrush communities as a whole may be explained if either (i) being adjacent to public lands does not increase wildfire risk, on average, for homeowners in sagebrush communities, or (ii) that homeowners adjacent to public lands share other characteristics, such as a heightened awareness of their wildfire risk or fewer concerns about privacy offered by vegetation, that make them more likely to invest in defensible space. Our finding that the public land dummy is significant and positive stands in contrast to previous studies that have found that bordering public lands reduces homeowners' propensity to invest in defensible space (Shafran, 2008; Brenkert, Champ, and Flores, 2005).

The number of lightning strikes within 10 miles over the past six years [LGTHN] is positive and significant (Table 3), which is to be expected because lightning strikes are an important cause of wildfire ignitions in western states. In addition, average maximum wind speed during the wildfire season [WIND] is positive and significant for the full sample (Table 3), which is also to be expected because homeowners face greater wildfire risk in windier communities. In a counterintuitive result, we find that the slope of the property [SLOPE] is negative and significant, which indicates that homeowners on steeper slopes are less like to invest in defensible space. This result is counterintuitive because homes on steeper slopes are generally believed to have greater wildfire risk. Indeed the *Pacific Northwest Wildfire Coordination Group* (1999) recommends that homes on properties on steep slopes perform more than 30 feet of defensible space to mitigate the risk that their home will be destroyed in the event of a wildfire. This result indicates that in addition to increasing wildfire risk, steeper slopes may reduce the perceived effectiveness of defensible space by homeowners.

The fact that several of the biophysical determinants of a homeowners' wildfire hazard are not significant in our regressions (e.g., aspect [ASPECT], average fuel loading in a community [FUEL]) may be explained by the fact that biophysical determinants of a homeowners' wildfire risk influence defensible space investment both by determining wildfire behavior within a community and in influencing the extent to which a homeowner's wildfire risk is determined by the defensible space decisions of their neighbors. It is possible that variables such as aspect and fuel load influence a homeowner's defensible space investment decision by influencing the degree to which wildfire risk is determined by the defensible space investments of their neighbors. If this is the case, much of the variation associated with these variables will be absorbed the spatial autoregressive parameter, ρ, rather than in the coefficient associated with the variable in question.

Overall, these results indicate that on average, homeowners' defensible space investments reflect an understanding of the biophysical determinants of wildfire risk, particularly as wildfire risk is related to the likelihood of wildfire ignition in their community (lighting strikes), average maximum wind speed and predominant vegetation in their community, as well as the effectiveness of defensible space. This result agrees with previous studies that find that no evidence that homeowners in WUI communities are uninformed or irrational about wildfire (McCaffrey, 2008; Cohn, Williams, and Carroll, 2008). Furthermore, these results suggest that educational programs may be an overemphasized component of wildland fire policy in WUI communities, and policies focusing on financial or regulatory barriers to investment in defensible space may prove to be more effective at increasing homeowner defensible space investment.

3.3 Firefighting Resources, Infrastructure, & Fuel Treatments

For the full sample (Table 3), we find that proximity to water sources [WATER], whether or not the community has a fire department [FD_NONE], and, in communities with fire departments, whether the department is part-time or full-time [FD_PT], are not statistically significant determinants of homeowners' defensible space investments, but that the number of local firefighting resources [RES] is negative and significant. This latter result suggests that homeowners may perceive that more fire protection resources within 10 miles of their home lowers the risk that their home will be affected by wildfire. The vegetation sub-sample results (Table 4) confirm this finding for forested and pinyon-juniper communities. This result adds support to previous studies that have found homeowners report not undertaking investments to mitigate wildfire risk because they believe the fire department will protect them (Collins 2005; Vogt and Stanley 2003).

In addition, we find that fuel treatments performed on public land neighboring the community [RX] are negative and significant for the full sample (Table 3) and for the sub-sample of sagebrush communities (Table 4), which suggests that the expected benefits of public investments in fuel treatments may be undermined because the reduction in wildfire hazard makes homeowners less likely to invest in defensible space.[12] This result confirms the findings in Prante et al. (2011), who find that public investment to mitigate wildfire risk lowers private incentives to invest using data from an economic experiment. Conversely, Table 3 shows RX as positive and significant for forested communities, which suggests the opposite result, that fuel treatments on public land complement homeowner's private investment in defensible space. The conflicting results for sagebrush rangeland and alpine forest communities may be explained by homeowner perceptions that fuel treatments on sagebrush rangeland are more effective at reducing community wildfire hazard than similar treatments in forested communities where there is potential for crown fires that can jump fire breaks. More research is required to fully explore the relationship between public and private investment to mitigate wildfire risk and predominant vegetation in a community.

We also find that neither the width of primary roads in the community [ROAD] nor the architectural design of the community [NTRMX] (i.e., whether native vegetation is intermixed throughout the community) are significant for full sample (Table 3), but that road width is positive and significant in sagebrush communities. This result is unexpected given that wider roads increase the ease with which firefighting equipment and personnel can access locations within the community and, as such, should lower homeowner wildfire risk. Finally, we find that the dummy variable for being an active Nevada Fire Safe Council in a community [FSC] is negative and significant. This finding is surprising given that previous research has indicated that social capital in a community, reflected in the presence of organizations such as Fire Safe Councils, is an important determinant of homeowners' likelihood of undertaking fire-safe investments (Brenkert-Smith, Champ, and Flores, 2012). Further research beyond the scope of this paper is required to fully explore the role of community-based natural resource management groups, such as Fire Safe Councils, and social capital in homeowner defensible space investment decisions.

3.4 Previous Wildfire Activity

We find that homeowners' recent experience with wildfire – as measured by distance to the nearest "large" wildfire (greater than 300 acres) in the past six years – is not a significant determinant of their decision to invest in defensible space for the sample as a whole, but is positive and significant for homeowners in pinyon-juniper and alpine forest communities (note that as FIRE is the distance to the nearest large wildfire, a negative coefficient on FIRE indicates that homeowners that are closer to a recent large wildfire are more likely to invest in defensible space). This finding suggests that homeowners in pinyon-juniper and alpine forest communities interpret recent large wildfires in the area surrounding their community as an indication that their wildfire risk is greater than they believed and respond to this increased in perceived risk by investing in defensible space. This finding is at variance with several previous studies that have found that recent experience with wildfire leads homeowners to believe that subsequent wildfires are less likely (Cohn, Williams, and Carroll, 2008; McCaffrey, 2004).

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[12] Note that it is more likely that defensible space investments will be responsive to short-term (several years) changes in community wildfire hazard than other investment to mitigate wildfire risk because defensible space investments must be periodically renewed to maintain their effectiveness because of plant growth.

There are, of course, several ways to measure homeowners' experience with wildfire. We only report one measure of homeowners' previous experience with wildfire here and do not further explore the issue in article because of space considerations and because we do not have information on whether homeowners have personal experience preparing for or undertaking an evacuation related to wildfire, which has been shown to increase homeowner propensity to undertake risk mitigating investments (Magee et al, 2009; Brenkert-Smith, Champ, and Flores, 2012).

3.5 Risk Externalities and Strategic Interactions between Homeowners

As we explain above in the Model Development section, the spatial autoregressive parameter, ρ, captures the effect of neighbors' defensible space investment on a homeowner's defensible investment. We find that ρ is positive and significant for the full sample (Table 3), as well in the forested, sagebrush rangeland, and pinyon-juniper sub-samples (Table 4). A positive and significant ρ indicates the presence of risk externalities in neighbors' defensible space investments. In particular, neighbors' defensible space investments are strategic complements in that the benefits of defensible space for a homeowner increase as their neighbors increase their defensible space. Indeed, this result suggests that in forested, sagebrush rangeland, and pinyon-juniper communities, defensible space reduces wildfire hazard in a way that appreciably reduces the wildfire risk of neighboring homeowners (risk externalities) and that this reduction in wildfire risk increases the effectiveness of defensible space. Our finding that defensible space investments are strategic complements in forest, sagebrush, and pinyon-juniper woodland communities confirms Shafran (2008), who finds that defensible space investments are strategic complements for homeowners in six fire districts in Bolder County, Colorado.

As indicated in Table 4, we find no evidence of risk externalities in grassland communities, suggesting the important role of the predominant vegetation type in a community. Because the grasslands in our sample present a lower wildfire hazard relative to forest, sagebrush, and pinyon-juniper, grassland community homeowner's wildfire risk, and, hence, their defensible space investments, are not influenced by their neighbors' investments. This result suggests that wildland fire policy to encourage defensible space in this region should focus more intensely on forested, sagebrush rangeland, and pinyon-juniper woodland communities rather than on grassland communities, as it is in these communities where risk externalities are likely to be more important and where the potential for socially-inefficient underinvestment in defensible space is greatest.

In addition, we examine spatial dependency between households in our sample by calculating Moran's indices (Moran 1950). We find that defensible space decisions of neighbors are strategic complements for the sample as a whole. As we mention above, economic theory suggests that when defensible space decisions are strategic complements, communities can either be in equilibriums where the majority of homeowners invest in defensible space or where almost none of the homeowners invest. This is because, as is explained in Shafran (2008), when defensible space investments strategic complements, the "game" between neighboring homeowners concerning defensible space investment is a supermodular game with multiple Nash equilibria, so that communities can be in an equilibrium where homeowners invest too little in defensible space and where there exists a Pareto-dominated (preferred by all homeowners in the community) equilibrium for the community that involves more investment in defensible space.

Figure 3 reports Moran's scatterplots for two sagebrush rangeland communities in western Nevada: Spanish Springs and Topaz Estates. The scatterplots were calculated using inverse distance squared spatial weighting matrices. Both communities exhibit patterns of defensible space investment consistent with strategic complementarities, with homes with adequate defensible space clustered near other homes with adequate defensible space and homes without defensible space clustered near other homes without defensible space. The two communities differ, however, in that in Spanish Springs appears to be in a "good" equilibrium where the majority of homeowners have invested in defensible space, while Topaz Estates appears to be in a "bad" equilibrium were the majority of homeowners have not invested in defensible space.

There are important policy implications related to our findings of strategic complementarities in defensible space investment in sagebrush, pinyon-juniper, and forest communities, and that these communities can be in either "good" or "bad" equilibrium. Specifically, these circumstances suggest that "tipping" policies that provide financial incentives for early investors in defensible space in order to achieve a "critical mass" of defensible space investment may be appropriate for communities with these vegetation types and that have a low level of investment in defensible space. After a critical mass is achieved, the enhanced benefits of investment in defensible space for homeowners due to strategic complementarities may be sufficient to propel further investment, even while the initial financial incentives are phased out

4. Conclusions

This is the first study that we are aware of that analyzes how homeowner incentives to invest in defensible space – and, by extension, the appropriate policy to encourage homeowner investment in defensible space – differs between communities depending on predominant vegetation type. In contrast to other studies, we find no evidence to suggest that homeowners systematically misjudge their wildfire risk; though we do find evidence of strategic complementarities in defensible space investments due to risk externalities in alpine forest, sagebrush rangeland, and pinyon-juniper woodland communities. Risk externalities are not detected in in grassland communities. These results suggest that policies designed to increase private investment in defensible space by focusing on financial and regulatory barriers to investment in defensible space, are superior to policies and programs that focus on educational programs alone. Second, "tipping policies" that provide specialized assistance to early adopters of defensible space may be appropriate in communities whose predominant vegetation, and, hence, wildfire hazard, suggests strategic complementarities and that are in "equilibriums" where the majority of homeowners have not invested in defensible space. In addition, we find that previous experience with large wildfires increases homeowners' propensity to invest in defensible space, and public investment in firefighting capacity and hazardous fuel reduction treatments on public lands may sometimes be perceived by homeowners as a substitute for private investment in defensible space.

Analyzing homeowner incentives to invest in defensible space in the presence of wildfire risk allows us to draw conclusions that are applicable to other natural disasters, such as earthquakes, extreme temperatures, floods, landslides, and windstorms (tornados, hurricanes, etc.), where individuals can make investments to mitigate material damage from the disaster (Zeckhamer 1996). In particular, defensible space investments provide a venue where it is possible to analyze the role of observable natural disaster risk in driving risk-mitigating investment decisions.[13] The success of educational outreach programs at enhancing investment to mitigate natural disaster risk depends crucially on whether individuals can be expected to understand and respond rationally to information on their natural disaster risk. The results reported in this article suggest that homeowners' defensible space investments reflect, on average, a relatively sophisticated understanding of the determinants of their wildfire risk. These results suggest individuals can be expected to respond on their own with increased risk mitigating investments to changes in natural disaster risk due to environmental changes (such as those related to climate change) if and when information about these changes in risk is make available to them.

There are four caveats to the analysis in this article. First, we are not able to evaluate whether defensible space investments for homeowners are optimal for the homeowners themselves or for the

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[13] For other natural disasters, in contrast, it is often difficult for individuals to observe the determinant of their natural disaster risk or to appraise how their risk differs from others in their community. For example, an individual home's risk of damage from an earthquake depends on the seismic hazard in its environs, which is determined by its proximity to faults, the stress building in these faults, and other geological factors. These factors can vary across communities, as well as between homes within communities, but are difficult to observe by individual homeowners. Similarly, the risk that a home is damaged by a flood is determined by a home's elevation and location relative to volatile bodies of water such as rivers and wetlands. It is difficult to observe, however, how the risk of flood differs between differ between neighbors as flood risk is not necessarily related to property characteristics such as lot size and building square footage.

communities as a whole. Apprising optimality of defensible space investments would require weighing the benefits of community-level arrangement of defensible space investment in terms of reduced wildfire suppression cost and damages against the financial and time costs of investment for each homeowner, while taking into account each homeowner's willingness to face wildfire risk and their preferences for the esthetic beauty and privacy from the landscaping in the vicinity of their home. Several previous studies have found that homeowners choose not to invest in defensible space because they value esthetics and privacy of having trees and brushes in the immediate vicinity of their home more than the dis-amenity of increased wildfire risk (Bright and Burtz 2006; Cohn, Williams, and Carroll 2008; Collins 2005).

Second, we are only considering the risk mitigating decisions of individuals who have willingly chosen to live in fire prone WUI communities. These individuals may be more willing to bear natural disaster risk and place a higher value on wildland amenities associated with living in the WUI than members of the general population. One would expect, however, that homeowners' preferences for the esthetic beauty of these landscaping features will not be completely coincident with their preferences for wildfire risk (i.e., that homeowners with preferences for these landscaping features do not completely sort themselves into communities with higher wildfire risk), and that, on average, homeowners in greater risk of having a wildfire reach their property should be more likely to invest in defensible space provided that they understand this risk. For this reason, we believe that our finding that homeowners in WUI communities respond rationally to the observable determinants of their wildfire (i.e., natural disaster) risk has implications for the general population despite this endogenous selection issue.

Third, homeowners make two sequential decisions that together determine the risk that a wildfire will damage their home or property. First, homeowners choose where to live. A homeowner's wildfire risk is determined by their choice of which WUI community to live in and the location of their home within the community (homeowners, of course, can eliminate their wildfire risk entirely by choosing not to live in a WUI community). Second, homeowners can make risk mitigating investments to reduce the risk that their home will be destroyed by wildfire. Many of these investments, such as roofing and siding material, and, to a degree, landscaping and defensible space, can also be part of original home purchase decision. Several previous studies have found that households trade off wildfire risk against other home and neighborhood characteristics when purchasing a home (Stetlet et al., 2010; Hugget, 2003; Donovan et al., 2007). This article considers homeowner's defensible space decisions contingent on their home purchase decision. This means that our results onlyhave implications for wildland fire policy as it pertains to influencing investment decisions of current WUI homeowners through educational programs, community grants, financial incentive, etc. In general, wildfire fire policy aimed at influencing individual decision makers is directed at current WUI residents, rather than at influencing the location decisions of potential residents.

Fourth, if full insurance against wildfire risk were possible, no one would undertake defensible space because of moral hazard. Of course, full insurance is not possible because of the non-monetary value of loss (photos, keepsakes, etc.) and the psychological damage associate with wildfire, so the decision of whether to undertake defensible space is relevant for all homeowners. In addition, many insurance carriers drop policies of homeowners in WUI communities that don't comply with defensible space requirements (Shafran, 2008). We do not have information on homeowner fire insurance policies. As we explain above, we control for the possibility of unobserved variable bias that could occur if a homeowner's unobserved insurance status is correlated with observed variables, such as home values. This being said, examining how insurance policies influence homeowner investment to mitigate wildfire risk, including investment in defensible space, may be a fruitful avenue for future research.

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Figures

Figure 1 – How a homeowner's wildfire risk with and without defensible space changes with their neighbors investment in defensible space for the cases of (i) no significant risk externalities, (ii) strategic complements, and (iii) strategic substitutes.

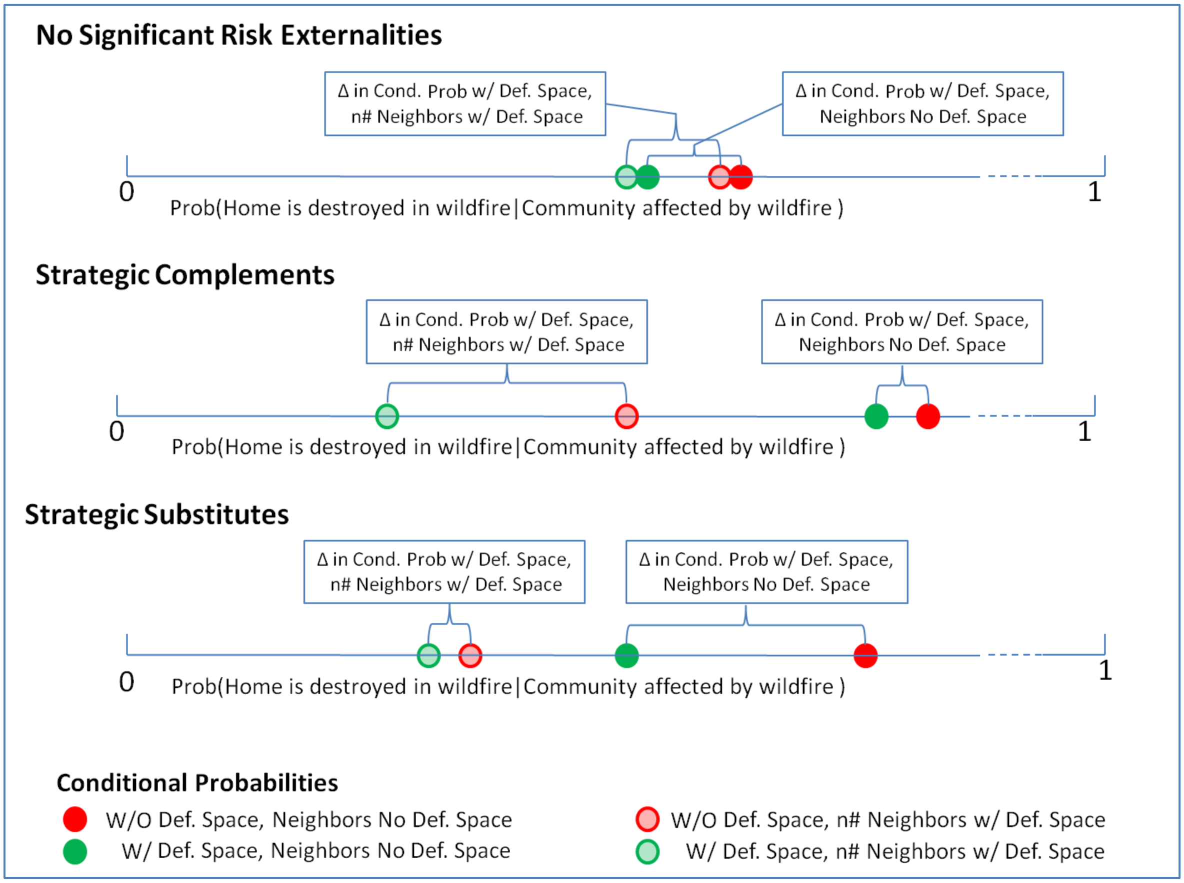


Figure 2 – Map of Nevada with 35 Wildland-Urban Interface Communities

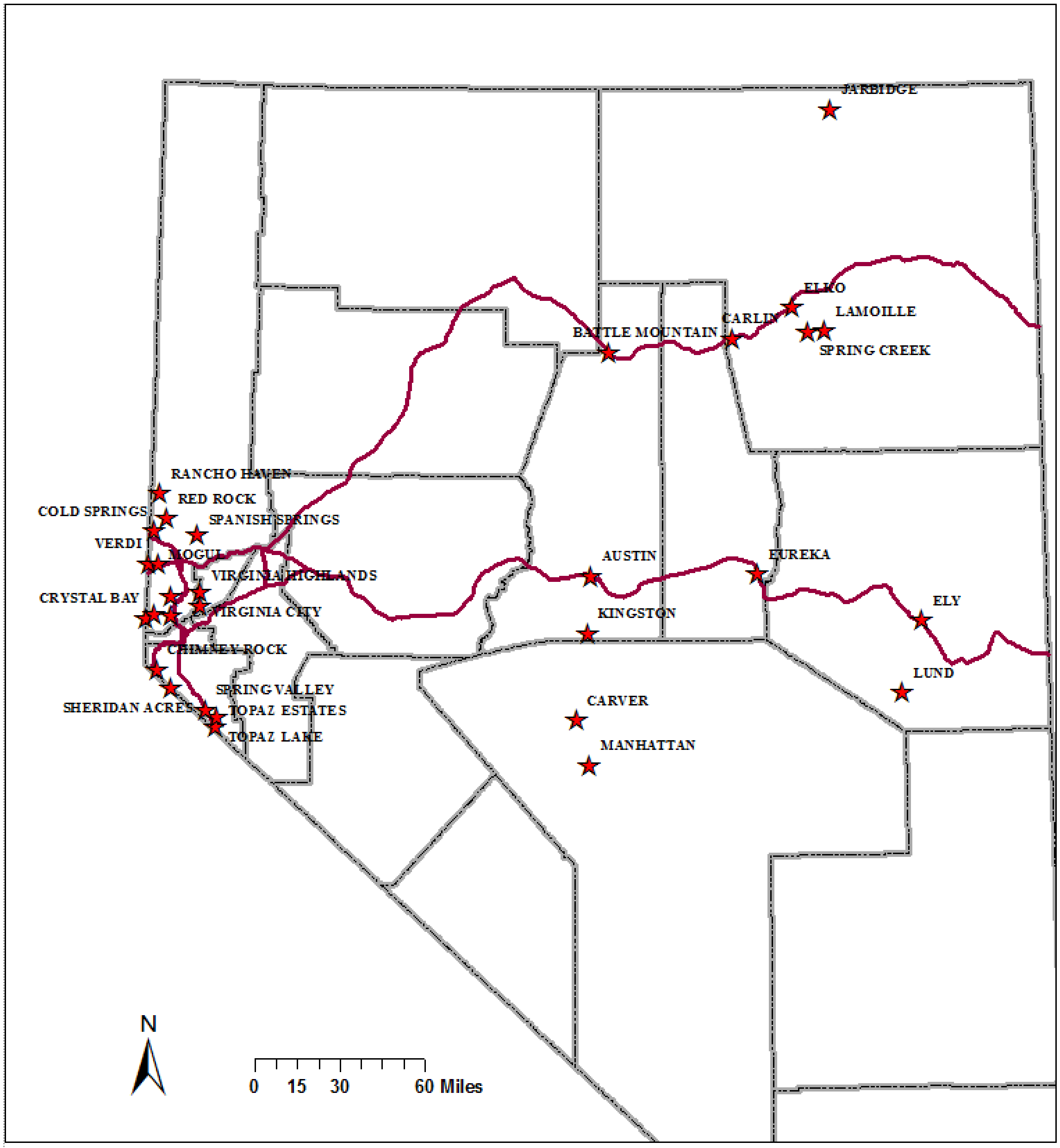


Table 1 – Community's Average Home Value and Defensible Space by Vegetation Type

Community	n	Population	Average Home Value	Defensible Space (%)
Sagebrush Communities				
Ely	247	4,255	$46,757	71%
Lund	121	282	$52,540	69%
Carvers	105	2,443	$56,772	67%
Cold Springs*	452	8,544	$139,303	60%
Virginia City*	290	855	$139,981	57%
Spanish Springs	645	15,064	$176,239	57%
Red Rock*	124	8,544	$184,511	48%
Spring Creek	786	12,361	$103,869	45%
Spring Valley*	48	157	$59,255	44%
Elko	111	18,297	$78,614	43%
Carlin	118	2,368	$47,026	41%
Topaz Lake*	123	157	$26,806	40%
Verdi	310	1,415	$218,208	39%
Sheridan Acres	44	11,312	$42,409	36%
Jarbidge	87	116	$28,048	31%
Mogul	186	1,290	$150,318	27%
Topaz Estates	717	1,501	$9,926	25%
Pinyon-Juniper Communities				
Eureka	87	610	$53,114	52%
Rancho Haven*	348	8,544	$125,560	49%
Austin	89	192	$33,664	47%
Manhattan	51	124	$25,814	39%
Kingston	119	113	$37,017	39%
Virginia Highlands*	500	855	$190,238	28%
Forested Communities				
Incline Village*	480	8,777	$319,224	32%
Galena Forest*	515	3,019	$396,711	30%
Saddlehorn Tumbleweed*	528	8,777	$329,505	21%
West Washoe Valley*	138	3,019	$419,794	19%
Tyrolian Village*	181	8,777	$143,884	18%
Champagne Burgundy*	86	8,777	$1,086,052	14%
Chimney Rock	211	2,152	$43,477	10%
Upper Tyner*	329	8,777	$310,435	9%
Allison Jennifer*	325	8,777	$232,168	5%
Crystal Bay	126	305	$360,667	1%
Grassland Communities				
Battle Mountain	145	3635	$49,118	45%
Lamoille	95	105	$152,866	32%

* The U.S. Census often aggregates small communities into larger districts, providing only a population estimate for the entire district. For those cases, the aggregated population measure is used, resulting in some communities having identical estimates.

Table 2 – Summary Statistics

Variable Name	Variable Description	Mean	Std. Dev.	Min.	Max.
	Property-Level Variables: Misc.				
DEFSP	=1 if 30ft of Defensible Space; 0 otherwise	0.36	0.48	0	1
HHVL	Log of Home Value ($)	11.37	1.39	3.69	16.12
LOT	Size of Property (Acres)	3.03	7.99	0.001	205.90
HOA	=1 if in HOA; 0 otherwise	0.26	0.44	0	1
FIRE	Distance to Nearest Large Fire (>300 Acres) in the Past 6 Years (100 ft)	207.96	159.23	3.48	763.83
	Property-Level Variables: Wildfire Hazard				
SLOPE	Slope of Property (%)	6.12	5.16	0	37.56
ASPECT	=1 if Property is South Facing; 0 Otherwise	0.14	0.35	0	1
LGHTN	Number of Lightning Strikes within 10 Miles	937.3	508.57	306	2491
PUBLD	=1 if within 30ft of Public Lands; 0 Otherwise	0.53	0.50	0	1
FUEL_PL	Interaction between PUBLD and FUEL	2.15	2.13	0	5
	Property-Level Variables: Firefighting Resources				
RES	Number of Fire Protection Resources Within 10 miles (per capita)	0.005	0.007	0	0.057
RX	Number of Fuel Treatments on Public Land within 10 Miles in Past 5 Years (per capita)	0.008	0.028	0	0.151
	Community-Level Variables: Misc.				
POP	Community Population	6086.1	4920.5	105	18287
FSC	=1 if Fire Safe Council; 0 Otherwise	0.66	0.47	0	1
ROAD	=1 if Primary Road is < 24ft wide; 0 Otherwise	0.19	0.40	0	1
NTRMX	1= if Community Architectural Design is "Intermixed"; 0 if "Classical"	0.83	0.37	0	1
	Community-Level Variables: Wildfire Hazard				
FUEL	Avg. Fuel Loading in Community (Tons/Acre)	3.68	0.92	1	5
WIND	Avg. Max. Daily Wind Speed (MPH)	30.69	9.06	14	46
BRUSH	=1 if Sagebrush Rangeland; 0 Otherwise	0.51	0.50	0	1
GRS	=1 if Grassland; 0 Otherwise	0.03	0.16	0	1
PJ	=1 if Pinyon-Juniper Woodland; 0 Otherwise	0.13	0.34	0	1
TMBR	=1 if Alpine Forest; 0 Otherwise	0.33	0.47	0	1
	Community-Level Variables: Firefighting Resources				
FD_NONE	1= if there is no fire dept; 0 otherwise	0.02	0.14	0	1
FD_PT	1= if fire dept is part-time/seasonal; 0 otherwise	0.62	0.48	0	1
WATER	=1 if water source in less than 20 mins away	0.68	0.47	0	1
WTR_PL	interaction term between water and publd	0.45	0.50	0	1

Table 3 – Spatial Autoregressive Probit: Full Sample Results (N=8867)

	Weight Matrices							
	W_1 (Inverse Distance Squared)				**W_2 (Inverse Distance)**			
Variable	**Coefficient**	**Std Err**	**Direct**	**Indirect**	**Coefficient**	**Std Err**	**Direct**	**Indirect**
constant	-0.9756***	0.2545	-	-	-0.7688***	0.2325	-	-
rho	0.6174***	0.0203	-	-	0.8089***	0.0216	-	-
HHVL	0.0602***	0.0127	0.0207	0.0306	0.0525***	0.0122	0.0175	0.0718
LOT	0.0006	0.0019	0.0002	0.0003	0.0004	0.0018	0.0001	0.0006
HOA	-0.0633	0.0396	-0.0219	-0.0324	-0.0723**	0.0394	-0.0241	-0.0995
FIRE	-0.0002	0.0002	-0.0001	-0.0001	-0.0001	0.0002	0.0000	0.0000
SLOPE	-0.0091**	0.0036	-0.0031	-0.0046	-0.0078**	0.0031	-0.0026	-0.0107
ASPECT	-0.0058	0.0381	-0.0020	-0.0029	-0.0057	0.0414	-0.0018	-0.0085
LGHTN	0.0001*	0.0001	0.0000	0.0001	0.0000	0.0001	0.0000	0.0001
PUBLD	0.0346	0.0377	0.0119	0.0177	0.0354	0.0350	0.0118	0.0481
RES	-4.5439*	2.0290	-1.5654	-2.2955	-3.0591*	1.8546	-1.0168	-4.1646
RX	-1.5706*	0.9170	-0.5410	-0.7989	-1.2051	0.8783	-0.4003	-1.6517
FSC	-0.1032*	0.0498	-0.0355	-0.0521	-0.0027	0.0515	-0.0010	-0.0016
ROAD	0.0498	0.0567	0.0171	0.0250	0.0376	0.0550	0.0124	0.0517
NTRMX	-0.0111	0.0518	-0.0038	-0.0059	-0.0238	0.0509	-0.0079	-0.0326
FUEL	-0.0554	0.0402	-0.0190	-0.0281	-0.0338	0.0393	-0.0111	-0.0472
WIND	0.0072***	0.0020	0.0025	0.0037	0.0060**	0.0020	0.0020	0.0082
BRUSH	0.1961**	0.0725	0.0675	0.0993	0.1353*	0.0704	0.0448	0.1855
GRS	-0.0034	0.1265	-0.0011	-0.0021	0.0433	0.1081	0.0143	0.0602
PJ	0.2376***	0.0804	0.0818	0.1206	0.1639*	0.0803	0.0541	0.2268
FD_NONE	-0.1964	0.1452	-0.0676	-0.1004	-0.2047	0.1404	-0.0676	-0.2832
FD_PT	-0.0149	0.0678	-0.0051	-0.0077	-0.0242	0.0637	-0.0079	-0.0347
WATER	0.0874	0.0584	0.0300	0.0440	0.0335	0.0583	0.0109	0.0466

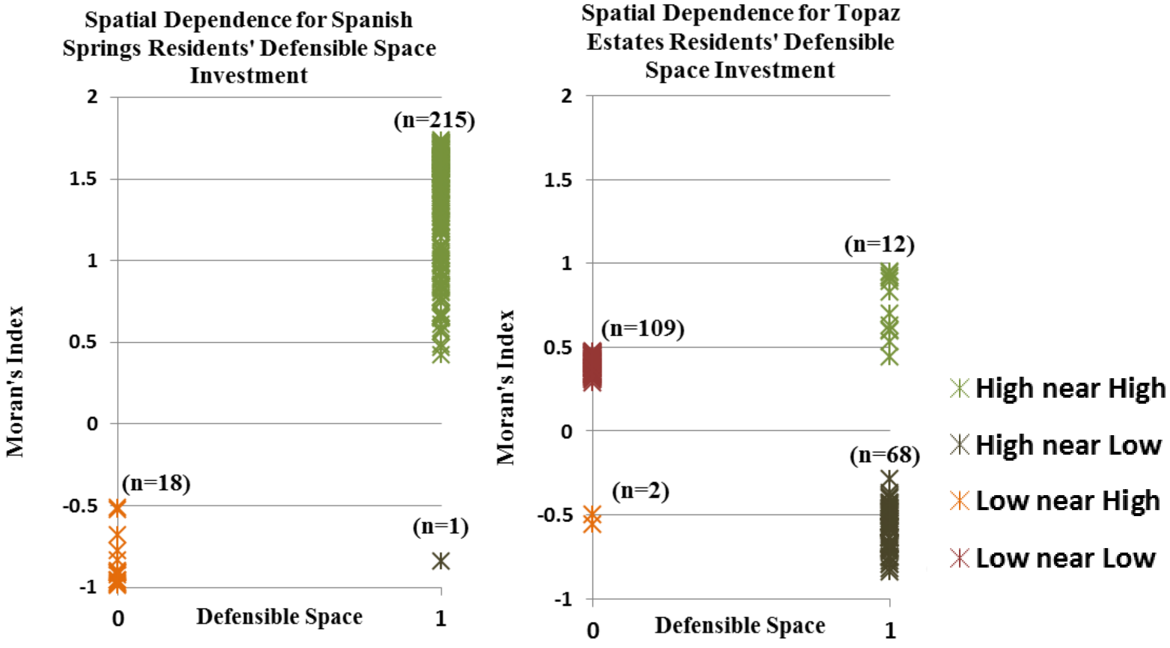
Significance level are denoted by 0.05 (*), 0.01(**), and 0.001(***)

Table 4 – Spatial Autoregressive Probit: Vegetation Sub-Sample Results

	Community Characteristic Vegetation							
	Brush (N= 4542)		**Pinyon Pine-Juniper (N= 1194)**		**Forest (N=2891)**		**Grass (N= 240)**	
Variable	**Coefficient**	**Std Err**	**Coefficient**	**Std Err**	**Coefficient**	**Std Err**	**Coefficient**	**Std Err**
constant	-0.7878***	0.3842	-2.4461	1.5735	4.2543***	1.6137	21.7142	14.791
rho	0.5941***	0.0262	0.4226***	0.0777	0.5907***	0.0794	0.1878	0.1338
HHVL	0.0454	0.0183	0.1618***	0.0524	0.1239**	0.0345	0.0853	0.0913
LOT	-0.0029	0.0027	0.0140	0.0070	-0.0062	0.0083	0.0038	0.0139
HOA	0.0512	0.0619	-0.1298	0.1413			-	-
FIRE	-0.0002	0.0002	-0.0012*	0.0006	-0.0023**	0.0010	0.0031	0.0028
SLOPE	-0.0013	0.0051	-0.0039	0.0085	-0.0161**	0.0071	0.0226	0.0448
ASPECT	0.1105**	0.0534	-0.0927	0.0843	-0.0641	0.1259	-0.2443	0.1913
LGHTN	0.0000	0.0001	0.0008	0.0009	-0.0032***	0.0011	-0.0094*	0.0053
PUBLD	0.0863*	0.0463	0.0258	0.1187	-0.1157	0.1343	-	-
RES	0.5446	4.9871	-25.4933**	10.3978	-128.9914***	30.5115	-	-
RX	-23.5064*	13.8169	-	-	6.4639*	3.0711	-	-
FSC	-0.2247*	0.0905	-	-			-	-
ROAD	0.2491*	0.1368	0.0590	0.4389	0.1104	0.0993	-	-
NTRMX	-0.1062	0.0715	-0.0695	0.2742			-	-
FUEL	0.0211	0.0866	0.0735	0.6214	-0.8376***	0.2182	-7.3306	5.1052
WIND	0.0150	0.0096	-	-	-	-	-	-
FD_NONE	-0.2959	0.2021	-	-	-	-	-	-
FD_PT	-0.1052	0.0948	-	-	-	-	-	-
WATER	-0.0834	0.1108	-	-	-	-	-	-

Significance level are denoted by 0.05 (*), 0.01(**), and 0.001(***)

Table 5 – Moran's Scatterplots for two Sagebrush Rangeland Communities in western Nevada



Appendix

Appendix A: Missing Variable Imputation Method

In this appendix we describe the multiple imputation procedure used to estimate values for variables containing missing data. Data on residential characteristics collected from multiple Nevada county tax assessors' offices and appended in a single dataset, was found to contain missing observations for the following independent variables: land value, house value, residential square footage, and size of the property. In order to keep as much information as possible and assuming the data is missing at random, missing observations were estimated using a multiple imputation procedure in Stata 11 (Stata, 2009).

This process, outlined by Rubin (1987) and others, treats the variables containing missing values as the dependent variables and iteratively regresses them, in order of most complete to least complete, on all other variables used in the full sample spatial autoregressive probit regression including the dependent variable (Schenker, 1996; van Buuren, 2007). A value for each missing observation within the dependent variable is estimated given the values of the independent variables for that observation.

Four imputed datasets are estimated and the means and standard deviations are considered reasonable compared to their former counterparts (Table A1). A spatial autoregressive probit model (SARP) for the full sample is specified using each imputed dataset. The results of each are very similar in terms of coefficient sign, magnitude and significance (Table A2). The only significant deviation is within the variable, LGHTN, which is significant at the 10% level within the fourth imputed and significant at the 5% level within the other three datasets. SARP models rely on a Markov Chain Monte Carlo (MCMC) method, known as the Gibbs sampler, to estimate the model's posterior probabilities. The Gibbs sampler routine samples for the parameter distributions over thousands of passes (Pace and Lesage, 2009). The average time to run a full sample SARP was approximately forty hours. Given the similarity in the results as well as the computational intensive nature of the SARP routine, analysis for this article uses only the first of the four imputed datasets.

Appendix A References

Pace, R. K., & LeSage, J. P. (2009). Introduction to spatial econometrics. Boca Raton, FL: Chapman & Hall/CRC.

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Schenker, N., and J. M. G. Taylor. 1996. Partially parametric techniques for multiple imputation. Computational. Statistics & Data Analysis 22: 425–446.

StataCorp. 2009. Stata: Release 11. Statistical Software. College Station, TX: StataCorp LP.

van Buuren, S. 2007. Multiple imputation of discrete and continuous data by fully conditional specification. Statistical Methods in Medical Research 16: 219–242.

Table A1- Comparison Statistics for the Missing Variables*

Variable Name	Variable Description	N	Mean	Std. Dev.	Min.	Max.
HHVL	Log of House Value - Original ($)	8161	11.41	1.38	3.69	16.15
HHVL_imp1	Log of House Value - Imputation 1 ($)	8867	11.37	1.39	3.69	16.12
HHVL_imp2	Log of House Value - Imputation 2 ($)	8867	11.36	1.39	3.69	16.12
HHVL_imp3	Log of House Value - Imputation 3 ($)	8867	11.36	1.40	3.69	16.12
HHVL_imp4	Log of House Value - Imputation 4 ($)	8867	11.36	1.40	3.69	16.27
LOT	Size of Property - Original (Acres)	8773	2.76	7.84	0.001	205.90
LOT_imp1	Size of Property –Imputation 1 (Acres)	8867	3.03	7.99	0.001	205.90
LOT_imp2	Size of Property –Imputation 2 (Acres)	8867	3.01	8.02	0.001	205.90
LOT_imp3	Size of Property –Imputation 2 (Acres)	8867	3.00	7.92	0.001	205.90
LOT_imp4	Size of Property –Imputation 2 (Acres)	8867	3.03	8.00	0.001	205.90

*Summaries of the variables used in the final spatial autoregressive probits models (SARP) are shown.

Table A2 - Spatial Autoregressive Probit: Multiple Imputation Datasets Results

	Imputed Dataset 1 (N= 8867)		Imputed Dataset 2 (N= 8867)		Imputed Dataset 3 (N= 8867)		Imputed Dataset 4 (N= 8867)	
Variable	**Coeff.**	**Std Err**	**Coeff.**	**Std Err**	**Coeff.**	**Std Err**	**Coeff.**	**Std Err**
constant	-0.9756***	0.2545	-0.8962***	0.2535	-0.9406***	0.2450	-0.9140***	0.2443
rho	0.6174***	0.0203	0.6184***	0.0206	0.6211***	0.0197	0.6177***	0.0226
HHVL_imp	0.0602***	0.0127	0.0543***	0.0125	0.0556***	0.0137	0.0550***	0.0129
LOT_imp	0.0006	0.0019	0.0007	0.0019	0.0007	0.0020	0.0008	0.0021
HOA	-0.0633	0.0396	-0.0615	0.0389	-0.0581	0.0360	-0.0582	0.0405
FIRE	-0.0002	0.0002	-0.0001	0.0002	-0.0001	0.0002	-0.0001	0.0002
SLOPE	-0.0091**	0.0036	-0.0085**	0.0032	-0.0081*	0.0036	-0.0085**	0.0034
ASPECT	-0.0058	0.0381	0.0010	0.0395	-0.0018	0.0424	-0.0027	0.0395
LGHTN	0.0001*	0.0001	0.0001*	0.0001	0.0001*	0.0001	0.0001	0.0001
PUBLD	0.0346	0.0377	0.0291	0.0357	0.0328	0.0368	0.0292	0.0383
RES	-4.5439*	2.0290	-4.3317*	2.1519	-4.7881**	2.0948	-4.7582*	2.1410
RX	-1.5706*	0.9170	-1.6325*	0.9115	-1.5884*	0.9720	-1.6795*	1.0084
FSC	-0.1032*	0.0498	-0.1008*	0.0544	-0.1098*	0.0501	-0.1066*	0.0526
ROAD	0.0498	0.0567	0.0509	0.0521	0.0521	0.0543	0.0510	0.0574
NTRMX	-0.0111	0.0518	-0.0019	0.0537	0.0022	0.0520	-0.0057	0.0560
FUEL	-0.0554	0.0402	-0.0603	0.0387	-0.0559	0.0381	-0.0566	0.0387
WIND	0.0072***	0.0020	0.0072**	0.0021	0.0073***	0.0021	0.0073***	0.0020
BRUSH	0.1961**	0.0725	0.1958**	0.0733	0.1865**	0.0715	0.1916**	0.0752
GRS	-0.0034	0.1265	-0.0216	0.1227	-0.0159	0.1193	-0.0143	0.1209
PJ	0.2376***	0.0804	0.2271***	0.0866	0.2200***	0.0797	0.2271***	0.0805
FD_NONE	-0.1964	0.1452	-0.0135	0.0675	-0.0022	0.0637	-0.1884	0.1544
FD_PT	-0.0149	0.0678	-0.1848	0.1414	-0.1626	0.1443	-0.0129	0.0647
WATER	0.0874	0.0584	0.0954*	0.0515	0.0940	0.0555	0.0948*	0.0542

Appendix B: Additional Variables not Included in the Analysis

This appendix explains why certain variables that are likely to influence private defensible space investment were removed from the final spatial autoregressive probit models (SARP). Due to the abundance of indicators for defensible space investment in dataset analyzed in this article, some variables are found to be highly correlated with others, particularly variables on weather conditions and previous wildfire activity. Within the vegetation-specific SARP models, lack of variation within and between communities limits the number of variables available for the SARPs specification.

The size of the residence (square feet) is believed to influence a defensible space decision through the amount of space that requires fire risk mitigation on a property. Residence size was included in preliminary analysis and was determined to be highly correlated with house value and subsequently omitted from the analysis. Similarly, due to collinearity with house value, land value is omitted as well.

Within the RAWS dataset, WIND is chosen as the most easily observed weather indicator that directly affects wildfire rates of spread and intensity. Variables on average daily temperature and average minimum relative humidity used in our preliminary analysis are highly correlated with variables related to biophysical determinants - lightning activity and vegetation community identifiers, as well as measures of prior wildfire activity, and were subsequently omitted.

The distance to the nearest "large" (greater the 300 acres) fire [FIRE] is chosen from a suite of GIS-generated data on wildfire activity including frequency counts for fires within 5 miles of the residence and also “large” fires within 10 miles of the residence, over the previous 6 years, as the most suitable variable to include in The empirical model. Preliminary analysis indicated the other observable indicators of wildfire activity over time, i.e., both fire count variables, are highly correlated with each other, and with distance measures to the nearest fire. Furthermore, these count variables were found to be correlated with the weather variables - average temperature and average minimum relative humidity, as well as, the several vegetation community identifiers, thus are not included in our final analysis.

Additional community level variables believed to influence a resident’s likelihood of defensible space investment were obtained from census data at the community level to include in the preliminary analysis. These included averages for the resident’s age, educational attainment, and income. Collinearity was detected between education and income and house value. Additionally, the sign for the measure of average age to be unstable under various specifications of an ordinary probit model. Due to these problems, these community demographic variables were omitted from the final analysis.