# How much do homes contribute to wildfire suppression costs?
## Evidence from Oregon and California

*Submitted to the Society and Natural Resources in January, 2012*

Patricia H. Gude[A,D], Kingsford Jones[B], Ray Rasker[A], Mark C. Greenwood[C]

Affiliation:
[A]Headwaters Economics, 270 W. Kagy, Suite G, Bozeman MT 59715
[B]ObjectiveStat Consulting, PO Box 501, Manhattan, MT 59741
[C]Montana State University, Department of Mathematical Sciences, PO Box 172400, Bozeman, MT 59717

[D]Corresponding author's contact information:
Postal address: P.O. Box 7059, Bozeman MT 59771
Phone: (406)599-7425
Email: patty@headwaterseconomics.org

**Abstract**

This paper estimates the relationship between housing and fire suppression costs using wildfires in Oregon and California. Specifically, we investigated whether the presence of homes was associated with increased costs of firefighting after controlling for the effects of potential confounding variables including fire size, weather, terrain, and human factors such as road access. Our goals were to determine the robustness and generalizability of the effect of homes on wildfire suppression costs, and calculate an improved estimate of the homes effect by replicating methods used in a previous study with a smaller sample of fires. A total of 533 days of firefighting that occurred in 60 wildfires were analyzed. Linear mixed models with serial autocorrelation and error heterogeneity covariance structures were used to estimate the effects of homes on daily costs while incorporating within-fire variation in the response and predictor variables. Our models were based on data from I-Suite Cost Reports, Geographic Information System fire perimeters, and ICS-209 forms. We conclude that the expected increase in daily log cost with each unit increase in log homes count within 6 miles of an active fire is 0.05 ($p = 0.02$). Because this relationship describes log-transformed variables we state that the expected change in firefighting costs with each 1% change in the count of homes within 6 miles is 0.05%. The study adds to mounting evidence that increases in housing lead to increases in fire suppression costs, and demonstrates that policy makers can achieve future fire suppression cost savings by focusing attention on development patterns.

## Introduction

The cost of fighting wildfires has become a major issue in the United States. Federal appropriations for all wildfire management activities have more than doubled in recent years, from an average of $1.2 billion annually during fiscal years 1996 through 2000 to more than $2.9 billion annually during fiscal years 2001 through 2007 (General Accounting Office [GAO] 2009). Spending related specifically to wildfire suppression has similarly doubled. The average annual USDA Forest Service emergency suppression spending was $1.1 billion in the 2000s, compared with $0.5 billion during the 1990s (Prestemon et al. 2010). This extraordinary investment of funds during the past decade was accompanied by more than 200 wildfire caused fatalities and the destruction of more than 10,000 structures (National Wildfire Coordinating Group Safety and Health Working Team 2011, National Interagency Fire Center [NIFC] 2011). Why have wildfires become so expensive and dangerous? Commonly suggested reasons include:

1. A build-up of fuels resulting in part from past fire suppression policies (Covington and Moore 1994, Caprio and Swetnam 1995, Moore et al. 1999),
2. Warming temperatures and drought conditions (Calkin et al. 2005, Westerling et al. 2006, Collins et al. 2006), and
3. The expansion of home development into fire prone landscapes (Snyder 1999, Canton-Thompson et al. 2006, GAO 2006).

However few quantitative studies have investigated the degree to which these factors affect wildfire suppression costs (Donovan et al. 2011). Without this information, existing policy remedies to address wildfire suppression costs are focused almost entirely on fuels treatments, ignoring the human dimension of wildfire costs (Stephens and Ruth 2005, Gude et al. 2008, Donovan et al. 2011). Although fuels management can reduce wildfire damages (Mercer et al. 2007), its effectiveness for reducing suppression costs has been questioned (Donovan and Brown 2007, Gude et al. in review). Better information on the factors affecting suppression costs is needed to guide future policies because the three major factors listed above as contributing to more expensive and dangerous wildfire seasons are unlikely to stop.

Gude et al. (2008) point out that, home construction in the western U.S. may increase future fire suppression costs dramatically since only 14 percent of the available wildland interface is currently developed. Climate change will likely exacerbate this effect. Nearly all climate models project warmer spring and summer temperatures across the West (Intergovernmental Panel on Climate Change 2001), leading to larger wildfires and longer fire seasons (Westerling et al. 2006; Running 2006). The combination of continued fuel build up, longer fire seasons, and increased development in fire prone areas may lead to future fire suppression costs substantially higher than what we have experienced in the past decade.

The escalating cost of wildfire management is germane not only because of taxpayer's pocketbooks, but also because a wide array of natural resource issues are affected as wildfires consume the majority of the managing agencies' budgets. In a 2008 memo, the Chief of the Forest Service stated that because the agency must fund the cost of wildfire suppression out of its total available funds, all other Forest Service activities have experienced a steady decline in funding (GAO 2009). In addition, the Forest Service and Interior agencies responsible for wildfire management have borrowed billions of dollars since 2000 from other programs to help pay for fire suppression (GAO 2009). Some of the affected programs include construction and maintenance, the national forest system, state and private forestry programs, and land acquisition programs.

Wildfire problems related to homes have received national attention as more acres and homes are burned by wildfire (NIFC 2011). Homes have the potential to affect suppression costs in a variety of ways: by directly influencing the quantity of flame retardant and other resources required for home protection, and by influencing management decisions, such as whether the fire should be suppressed at all. When fire managers were asked what portion of the firefighting costs was attributable to the defense of private property, some estimated it ranged between 50 to 95 percent. However, only a handful of studies have empirically investigated the relationship between homes and suppression costs. This paper adds to the small body of literature, using wildfires in Oregon and California as case studies to estimate the relationship between housing and fire suppression costs. Oregon and California rank highest both in the area of undeveloped, forested private land bordering fire-prone public lands, and in the amount of forested land where homes have already been built next to public lands (Gude et al. 2008). These two states have experienced many historically significant fires in which hundreds of structures were destroyed per event (NIFC 2011). They offer ample opportunity to investigate the effect of homes on fire suppression costs. Specifically, this research investigates whether the presence of homes increases the cost of firefighting after controlling for the effects of potential confounding variables, such as fire size and terrain.

**Literature Review**

The wildland– urban interface (WUI), generally defined as areas where structures and other human development meet or intermingle with undeveloped wildland (Office of Inspector General [OIG] 2006), has experienced rapid growth in housing (Radeloff et al. 2005; Theobald and Romme 2007). The development of the WUI has been driven, in large part, by the phenomenon of people moving to areas of high natural amenities, sometimes called amenity migration (Moss 2006). Access to environmental amenities and public lands can be a primary determinant in choice of home location (Rudzitis 1999, 1996; Rasker 2006; Gude et al. 2006). Housing is becoming increasingly dispersed, particularly in areas rich in natural amenities, resulting in extensive land conversion adjacent to lakes, national parks, wilderness areas, seashores, and forests (Bartlett et al. 2000; Rasker and Hansen 2000; Radeloff et al. 2001; Schnaiberg et al. 2002; Radeloff et al. 2005; Gude et al. 2006; Gude et al. 2007). This trend is widespread in the United States (Johnson and Beale 1994; Johnson 1999), and is occurring in many other parts of the world as well, including the European Alps (Perlik, 2006, 2008), Norway (Flognfeldt 2006), Philippines (Glorioso 2006), Czech Republic (Bartos 2008), New Zealand (Hall 2006) and Argentina (Otero et al. 2006). WUI homes are often difficult to protect because of remoteness, steep slopes, narrow roads and the dispersed pattern of development. These characteristics can create dangerous situations for firefighters.

Five empirical studies have investigated the relationship between fire suppression costs and housing. One study failed to find an effect of housing on cost, and four studies found that housing was a significant predictor of costs. Donovan et al. (2008) studied a sample of 58 wildfires that occurred in Oregon and Washington in 2002, and failed to find a relationship between housing and fire suppression cost. The study estimated total costs from the 209 forms submitted daily by fire crews, which are known to be highly inaccurate (Gebert et al. 2007, personal communication Jaelith Hall-Rivera, Deputy Area Budget Coordinator, State and Private Forestry, U.S. Forest Service). Donovan et al. (2008) also acknowledged that the sample may not have contained fires that did not threaten homes, which may have made it difficult to detect an effect of homes on fire suppression costs.

Liang et al. (2008) studied U.S. Forest Service (USFS) wildfire suppression costs for 100 large wildfires occurring in the Northern Region (R1) of the USFS, and found that fire size, perimeter to area ratio, percentage of private land, and total structure value had substantially higher independent effects than all other measured variables. They found expenditures to be positively correlated with percentage of private land and total structure value. Gebert et al. (2007) studied a large sample of USFS wildfires in the western U.S., and found that variables having the largest influence on cost included fire intensity level, area burned, and total housing value within 20 mi of ignition. Gude et al. (in review) investigated 303 firefighting days for 27 USFS wildfires in northern California and the Sierra Nevada area and found that wildfire suppression costs were strongly related to the number and location of homes. The study concluded that, after controlling for the effects of potential confounding variables including fire size, terrain, and road access, a 0.07% change in firefighting costs is expected with each 1% change in the count of homes within 6 miles from the wildfire perimeter.

The goal of the analysis described in this paper was to:

1. Determine the robustness and generalizability of our previous estimate of the effect of homes on wildfire suppression costs by replicating the California study within Oregon, and

2. Calculate an improved estimate of the homes effect by repeating the analyses on the combined California and Oregon data.

**Methods**

Our data collection and model-building methodology followed the same protocol used in the California study (Gude et al. in review). This consisted of collecting data on daily wildfire costs, daily home counts, and a suite of potential confounding variables, and then building linear mixed models to estimate the effect of homes on costs while adjusting for the confounders and accounting for the multilevel structure of the data.

*Response and Explanatory Data*

Daily cost data were compiled from I-Suite Cost Reports. Wildfires for which the cumulative costs reported in I-Suite were ten percent less than those reported by the US Forest Service's financial system were eliminated from the sample. Data describing other daily fire characteristics were generated using Geographic Information System (GIS) perimeters available from the U.S. Geological Survey's Rocky Mountain Geographic Science Center website or were compiled from ICS-209 forms (Table 1).

All explanatory variables except "Percent Forest" were time-varying within fires. The explanatory variable used to represent the temporal progression of fires, "Percent Complete", was calculated by dividing the day of the observed data by the total number of days the fire was actively fought, and multiplying by 100. We chose to represent this variable as a percent so that it would be standardized between fires. Calculations of daily fire acres, road counts, and homes within 6 mi. (9.7 km) of wildfires involved the use of GIS daily perimeter files. The "Road Count" variable was set equal to the number of road segments that intersected each daily fire perimeter. The homes variable was calculated by summing the number of homes within a 6 mi. (9.7 km) radius around each daily fire perimeter. The locations of homes were determined from county tax assessor records joined to tax lot boundaries. Generation of the "Percent Forest" variable for each of the daily observations was too costly; therefore we used the most representative perimeter file per fire to calculate this variable. The other explanatory variables, including daily weather measurements and categorical variables representing growth potential and terrain difficulty, were used as reported in ICS-209 forms.

Table 1. Data collected for each day of firefighting for each of the 33 OR wildfires and 27 CA studied.

| Data | Source |
|---|---|
| Total Daily Cost | I-SUITE |
| Percent Complete | I-SUITE |
| Fire Acres | GIS Perimeter Files |
| Percent Contained | 209 Forms |
| Wind Speed | 209 Forms |
| Temperature | 209 Forms |
| Relative Humidity | 209 Forms |
| Fire Growth Potential | 209 Forms |
| Terrain Difficulty | 209 Forms |
| Percent Forest | NASA MODIS Land Cover |
| Road Count | ESRI |
| Homes within 6 mi. (9.7 km) of wildfire* | Tax Assessor Records |

*We originally hypothesized that homes within 1 mi. (1.6 km) of a fire would better explain firefighting costs. However, we found the zero-inflated distribution of this variable resulted in violation of distributional assumptions on model errors. Distributional assumptions were met by using the count of homes with 6 mi (9.7 km) of wildfires. This distance was also found to be influencial in a study of suppression costs in California (Gude et al. in review).

With the exception of grassland fires, the entire population of Oregon wildfires for which accurate data were available was included in the analyses. Just as in the Gude et al. (in review) California study, grassland fires were not included because we expected that firefighting strategies, and therefore the relationship between cost and homes, would differ substantially between grassland and forest fires.

The final Oregon dataset consisted of information on daily suppression costs and wildfire characteristics for 230 days of firefighting on 33 individual Oregon wildfires (Figure 1). In comparison, the final California dataset consisted of 303 days of information for 27 wildfires (Figure 2). Due to data availability, sample fires included only those in which the U.S. Forest Service was the primary agencies involved, with the exception of two Bureau of Land Management fires in Oregon. For both the Oregon and California datasets, the final sample included some wildfires that burned in areas where few or no homes were threatened, and some that burned through developed areas. This sample of fires allowed for a comparison between fires that threatened homes to varying extents.

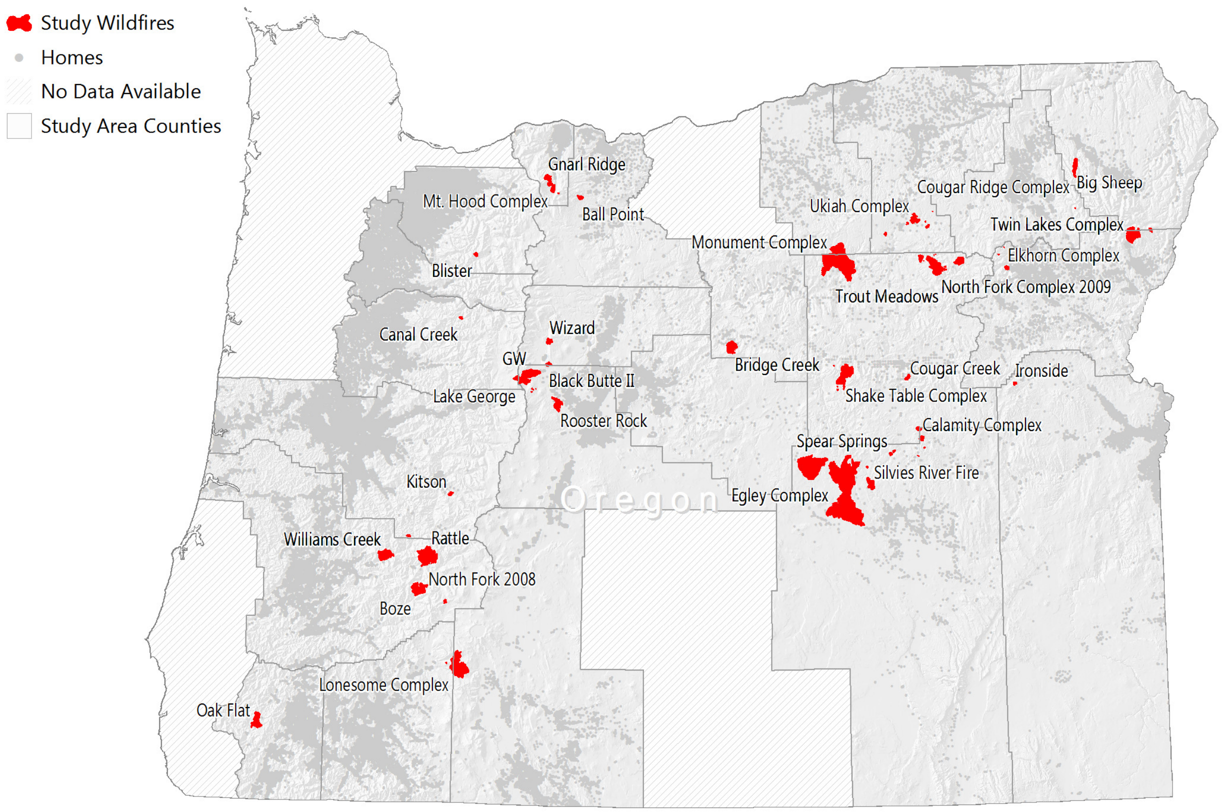


Figure 1. The locations of 33 Oregon wildfires included in this study are shown.

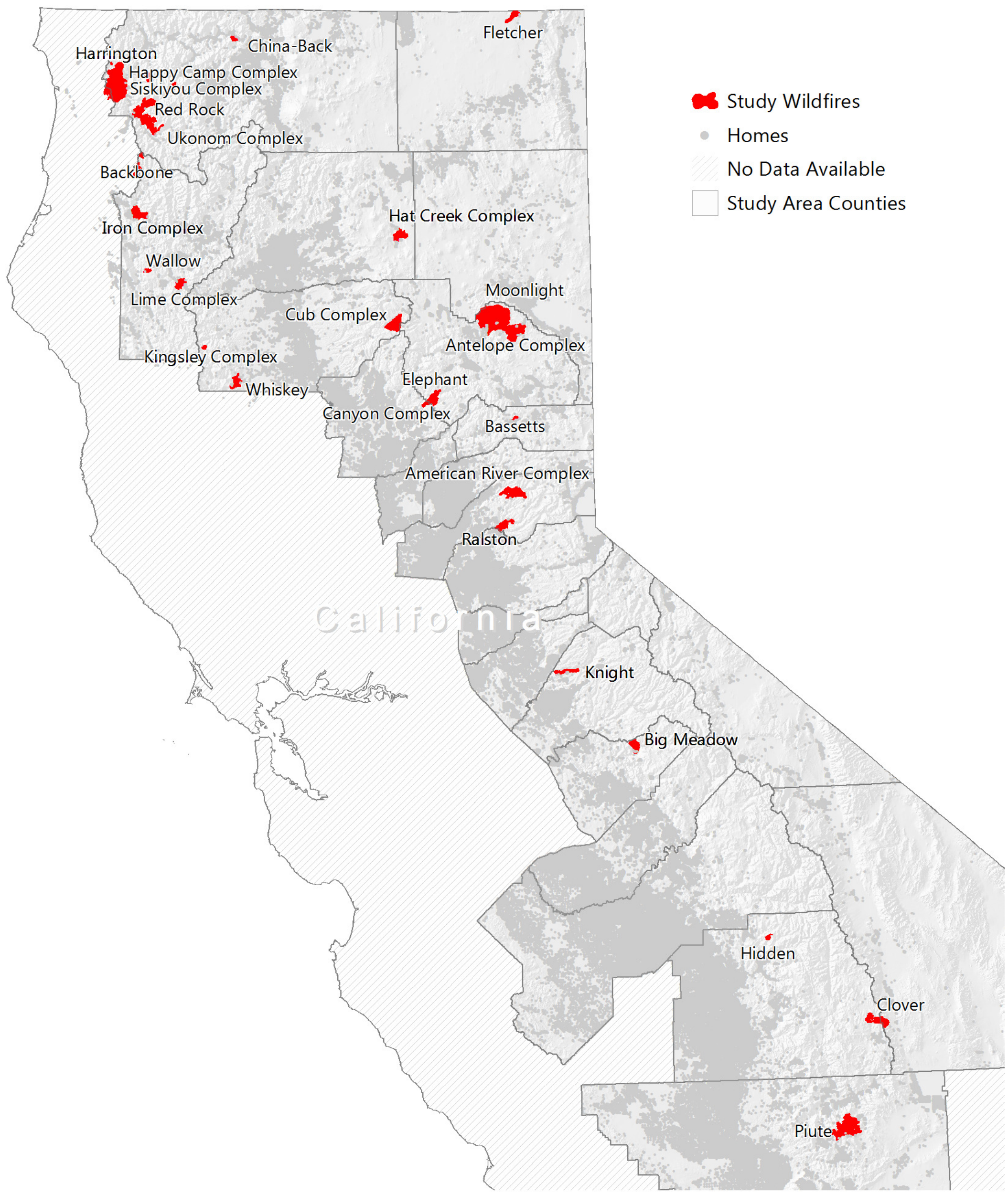


Figure 2. The locations of 27 California wildfires included in this study are shown.

*Mixed Models*

To accommodate the multilevel data structure (daily observations nested within fires) we chose linear mixed models (LMMs) to estimate paramaters of interest (Littell et al. 2006; Pinheiro and Bates 2000). Using matrix notation, LMMs are of the form

$$\begin{aligned}
&\boldsymbol{Y} = \boldsymbol{X\beta} + \boldsymbol{Zu} + \boldsymbol{e} \\
&\boldsymbol{u} \sim N(\boldsymbol{0}, \boldsymbol{G}) \\
&\boldsymbol{e} \sim N(\boldsymbol{0}, \boldsymbol{R}) \\
&Cov[\boldsymbol{u}, \boldsymbol{e}] = \boldsymbol{0}
\end{aligned}$$

where Y is a vector of response values, X is a fixed-effects design matrix, ß is a vector of fixed effects, Z is a random-effects design matrix, u is a vector of random effects, and e is the vector of within-group errors. Because the only constraint on the G and R matrices is symmetric positive-definiteness, there is a great deal of flexibility in modeling the covariance structure of the response variable (Var[Y] = ZGZ' + R in contrast to OLS regression where Var[Y] is proportional to an identity matrix).

We first constructed a set of LMMs based on the Oregon data alone, and then another set based on the combined Oregon and California data. All models were built with the goal of drawing valid inferences on the element of ß associated with the effect of homes on firefighting costs. This required controlling for confounders, fitting the grouping and temporal correlation structures, and adding other terms needed to meet model assumptions. We used the gls and lme functions within the nlme packgage in the R statistical environment for all model fitting (Pinheiro et al. 2011, R Core Team 2011). Model parameters were estimated using maximum likelihood.

*Model Building*

We built all models following the protocol developed for the California analyses. We began by examining scatterplots of the response versus continuous predictors and chose transformations and higher-order terms to linearize relationships. We proceeded by adding fixed-effects terms for the potential confounding variables, the mean temporal structure, and the homes variable; these variables and a column of 1s for an intercept comprised the X matrix described above. Because daily observations were nested within fires, we added random intercepts for each fire into the Z matrix. We also examined lattice plots (Sarkar 2008) of costs over time within each fire to assess the need for random linear and quadratic slopes in time. As we added random terms, improvements to model fit were assesed by examining residual autocorrelation using ACF plots of the empirical autocorrelations across days within fires. We judged significance of autocorrelations based on plotted two-sided critical bounds (Pinheiro and Bates 2000 p. 241). We also used BIC (Schwartz 1978) and examination of within-fire residual diagnostic plots to determine if structuring the error covariance (R) with estimated variance heterogeneity and temporal correlation parameters improved model performance. Based on residual diagnostic plots and BIC values we chose appropriate variance and correlation structures from among those listed in Pinheiro and Bates' (2000) tables 5.1 and 5.3.

To assess statistical significance of fixed effects (**ß**) we used t-tests conditioned on the estimated random effects (Pinheiro and Bates 2000, p. 90). We set contrasts such that the two categorical predictors (Terrain Difficulty and Growth Potential) were dummy-coded with coefficients representing differences from a baseline level. Terrain Difficulty had three levels and the two associated model coefficients represented the expected change from the Medium level to the High and Extreme levels. The Growth Potential variable had 4 levels and the associated coefficients represented expected changes from the Low level to the Medium, High, and Extreme levels.

In addition to drawing inferences based on the full models, we created models which were reduced based on two criteria. First, terms that were clearly confounders or were needed due to the data structure were not considered for removal -- these included variables measuring the fire size, the within-fire temporal component, and all covariance structures. The second criteria was that the p-value associated with the t-statistic for a predictor was greater than 0.2. We set the p-value cutoff at a high level because all variables were carefully chosen based on the belief that they had potential for confounding the effect of interest, and because we aimed to avoid biases induced by intensive data-driven model selection and an overly simplistic model structure (Hastie et al. 2009, Harrell 2001, Schabenberger and Gotway 2005, Vittinghoff 2005, Wolfinger 1993).

**Results**

In the Oregon sample of wildfires, the cumulative suppression cost per fire ranged from $1,073,010 to $21,057,784, with a mean of $7,580,465 (Table 2). The number of days the sample fires were actively fought ranged from 6 to 59, with an average of 20 days. The fires ranged in size from 1 to 294 square kilometers, with an average of 27 square kilometers. The average duration and size within our sample fires are representative of fires fought by federal agencies in Oregon.

The scatterplots of the response versus each of the predictors suggested natural log transformations of the Cost, Homes, Fire Acres, and Road Count variables adequately linearized relationships. The Homes and Road Count variables contained zero values and we added one to them prior to log transforming. Figures 3 and 4 provide detailed views of the marginal bivariate relationships between the log transformed costs and the log transformed homes count for the Oregon and combined datasets, respectively. The bivariate scatterplots and lattice plots of the response over time indicated a convex relationship, and we therefore added the square of Percent Complete to the fixed effects. All transformations were the same as those required in the California analyses.

Table 2. Summary data per fire for each of the 33 Oregon wildfires studied.

| Fire | Cumulative Cost | Year | Agency | Firefighting Days | Days in Sample | Avg Size of Fire (sq.km.) | Avg Num. Roads Intersecting Fire | Avg Homes within 1 mi (1.6 km) | Avg Homes within 6 mi (9.7 km) |
|---|---|---|---|---|---|---|---|---|---|
| Ball Point | $3,075,788 | 2007 | USFS | 17 | 3 | 5 | 3 | 0 | 427 |
| Big Sheep Ridge | $1,217,673 | 2009 | USFS | 10 | 3 | 13 | 17 | 1 | 141 |
| Black Butte II | $3,080,983 | 2009 | USFS | 7 | 3 | 3 | 13 | 0 | 937 |
| Blister | $5,726,503 | 2006 | USFS | 22 | 6 | 2 | 2 | 0 | 1 |
| Boze | $7,019,985 | 2009 | USFS | 22 | 9 | 23 | 45 | 0 | 0 |
| Bridge Creek | $4,410,206 | 2008 | USFS | 11 | 7 | 19 | 17 | 3 | 131 |
| Calamity Complex | $3,652,755 | 2007 | USFS | 14 | 3 | 8 | 39 | 1 | 22 |
| Canal Creek | $4,735,060 | 2009 | USFS | 11 | 7 | 1 | 2 | 0 | 0 |
| Cougar Creek | $2,544,887 | 2009 | USFS | 10 | 4 | 3 | 0 | 2 | 593 |
| Cougar Ridge | $1,657,848 | 2009 | USFS | 20 | 2 | 1 | 0 | 0 | 1 |
| Egley Complex | $16,296,760 | 2007 | USFS | 19 | 10 | 294 | 695 | 4 | 64 |
| Elkhorn Complex | $3,985,253 | 2006 | USFS | 15 | 4 | 4 | 2 | 11 | 404 |
| Gnarl Ridge | $15,047,477 | 2008 | USFS | 28 | 7 | 11 | 7 | 3 | 130 |
| GW Fire | $7,917,759 | 2007 | USFS | 23 | 4 | 26 | 45 | 0 | 700 |
| Ironside | $1,667,362 | 2007 | BLM | 9 | 2 | 1 | 0 | 0 | 25 |
| Kitson | $4,302,039 | 2008 | USFS | 13 | 4 | 3 | 7 | 0 | 44 |
| Lake George | $12,367,001 | 2006 | USFS | 34 | 3 | 13 | 0 | 0 | 16 |
| Lonesome Complex | $18,411,841 | 2008 | USFS | 55 | 26 | 41 | 15 | 0 | 3 |
| Monument Complex | $11,634,250 | 2007 | USFS | 22 | 9 | 167 | 120 | 10 | 144 |
| Mt. Hood Complex | $8,514,319 | 2006 | USFS | 25 | 9 | 5 | 3 | 0 | 14 |
| North Fork Complex 08 | $9,274,059 | 2008 | USFS | 24 | 8 | 2 | 1 | 0 | 9 |
| North Fork Complex 09 | $5,250,859 | 2009 | USFS | 59 | 5 | 14 | 3 | 0 | 8 |
| Oak Flat | $18,738,968 | 2010 | USFS | 27 | 16 | 17 | 15 | 0 | 17 |
| Rattle | $21,057,784 | 2008 | USFS | 37 | 20 | 50 | 39 | 5 | 18 |
| Rooster Rock | $5,609,299 | 2010 | USFS | 9 | 5 | 19 | 95 | 4 | 2249 |
| Shake Table Complex | $15,264,142 | 2006 | USFS | 24 | 7 | 42 | 19 | 5 | 65 |
| Silvies River | $2,531,835 | 2008 | BLM | 8 | 4 | 13 | 4 | 1 | 13 |
| Spear Spring | $1,073,010 | 2007 | USFS | 6 | 2 | 2 | 8 | 1 | 7 |
| Trout Meadows | $6,569,023 | 2007 | USFS | 23 | 6 | 14 | 4 | 0 | 1 |
| Twin Lakes Complex | $4,538,513 | 2006 | USFS | 17 | 10 | 35 | 38 | 22 | 206 |
| Ukiah Complex | $4,356,664 | 2007 | USFS | 11 | 2 | 14 | 43 | 4 | 126 |
| Williams Creek Fire | $14,630,640 | 2009 | USFS | 21 | 14 | 21 | 46 | 4 | 60 |
| Wizard | $3,994,788 | 2008 | USFS | 12 | 6 | 5 | 32 | 0 | 232 |

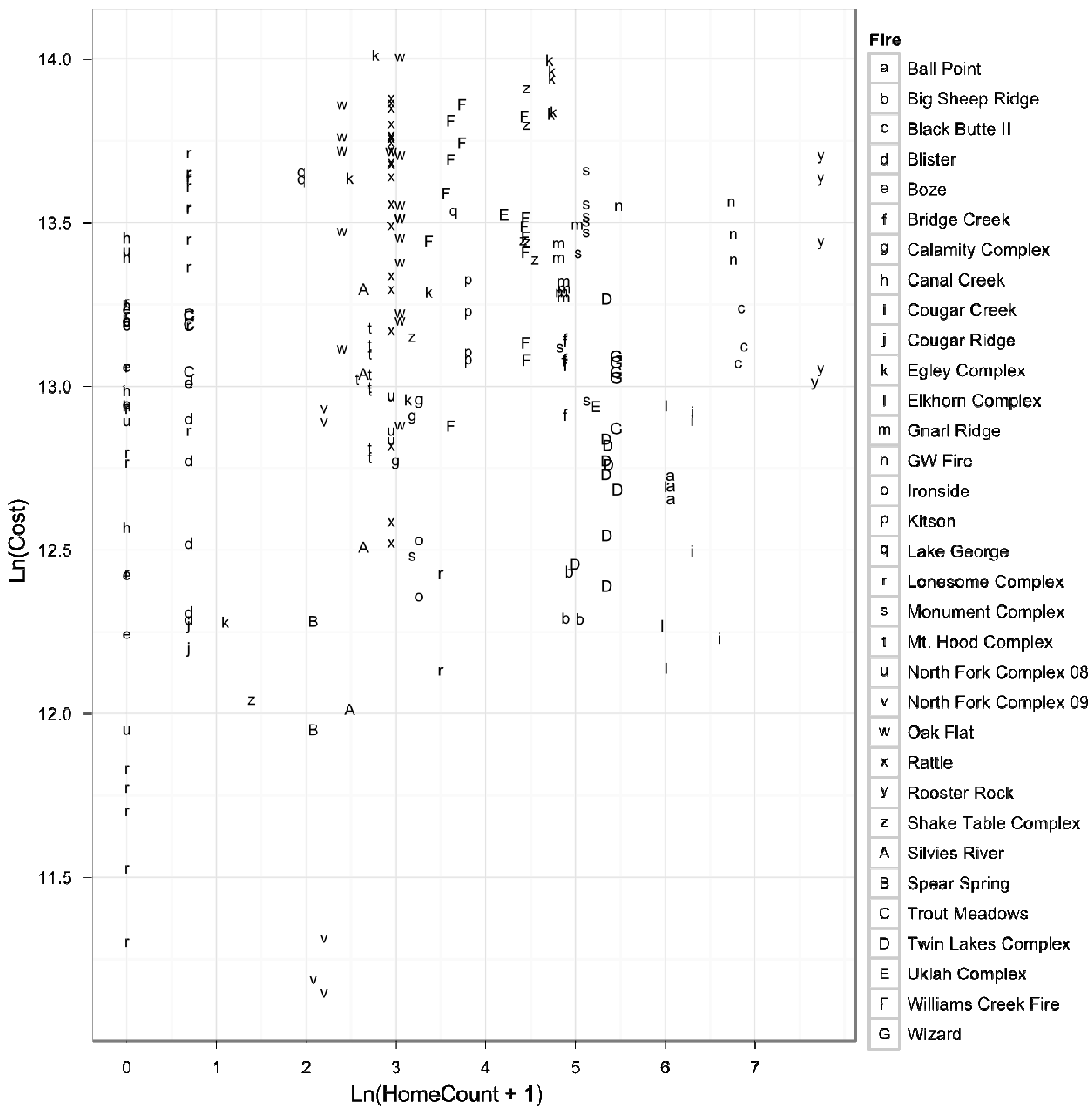


Figure 3. The log count of homes is plotted against the log daily costs in dollars for each day of firefighting within each of the 33 Oregon fires.

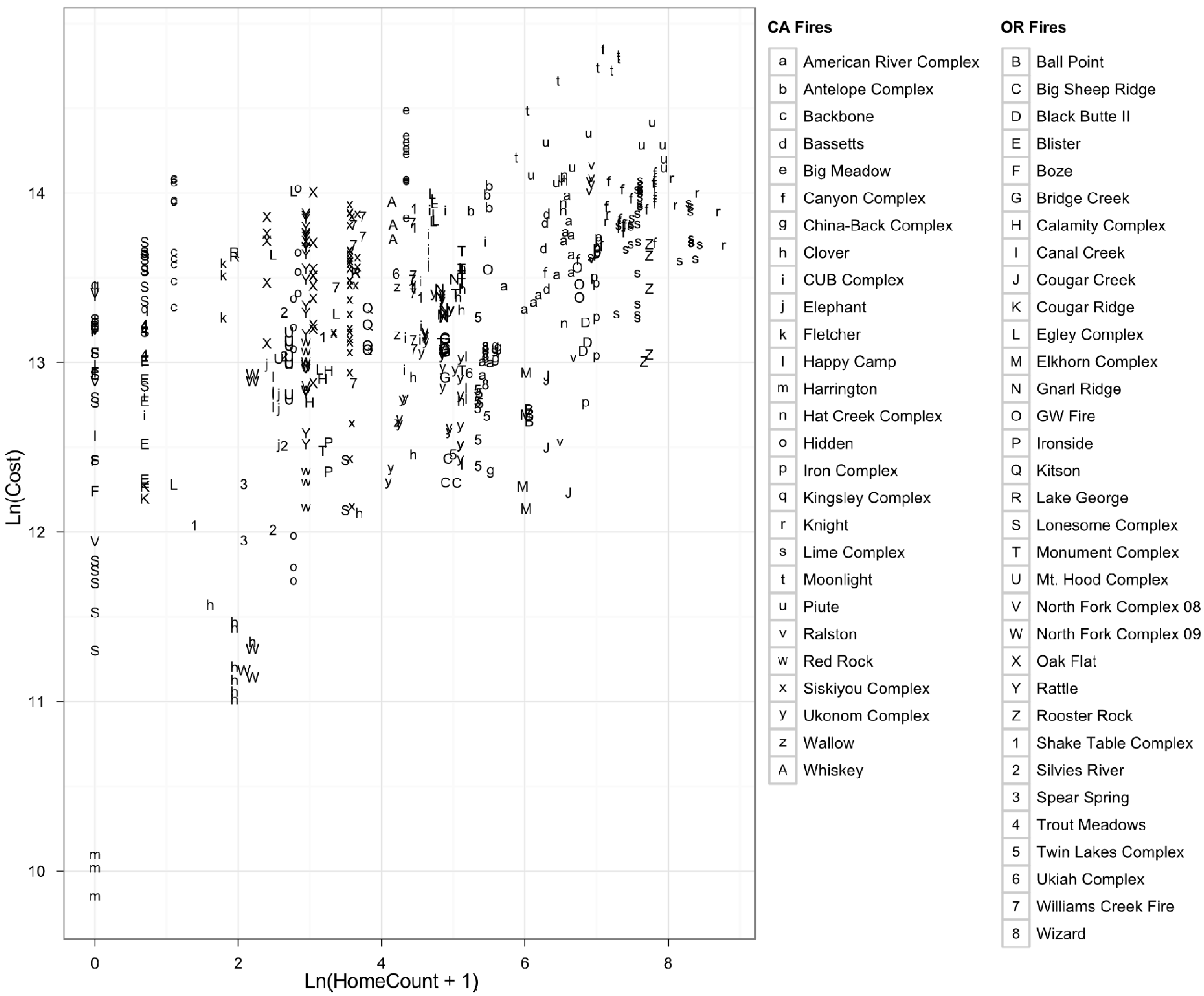


Figure 4. The log count of homes is plotted against the log daily costs in dollars for each day of firefighting within each of the 60 Oregon and California fires in the combined dataset.

*Mixed Models*

ACF plots of residuals from the models containing only fixed effects indicated high levels of within-fire autocorrelation, and we therefore structured the G and R matrices to account for the lack of independence. For the Oregon data, the BIC-selected method was to add random intercepts, random slopes for Percent Complete, and an AR1 within-fire error correlation structure[1]. For the combined Oregon and California data, the BIC-selected method was the addition of random intercepts, random slopes for Percent Complete, and an exponential within-fire error correlation structure[2]. For the Oregon data, the addition of these terms resulted in a BIC decrease of 387 points from the fixed-effects-only model, while for the combined data BIC decreased by 1076 (note that likelihoods and BIC values are not comparable between datasets).

After the addition of these terms there was no visible autocorrelation within the ACF plots for any of the models. However, for the model based on the combined data there was indication of decreasing variance with increasing fitted values, and we fit a power-of-the-mean variance structure[3] which lowered BIC another 41 points. We refer to the models completed at this stage as the "full models". The "reduced models" were created through the backward elimination process. For the Oregon data, this resulted in the elimination of the Wind Speed, Percent Forest, and Growth Potential terms. For the combined data, the Temperature, Wind Speed, and Percent Forest variables were removed.

Table 3 provides a summary of model estimates and inferences for the full and reduced models for the Oregon and combined datasets. The estimates of interest are highlighted, showing that the point estimates of the Homes effect range from 0.0454 for the reduced model on the combined data, to 0.0591 for the reduced model on the Oregon data. All estimates of the effect are statistically significant at the 0.05 level. Table 3 also indicates that within both datasets model reduction through backward elimination had little impact on the estimated effect size.

We draw concluding inferences based on the reduced model using the combined data. Because the response and predictor were each log transformed, the effect of interest is an elasticity. Therefore the expected change in firefighting costs with each 1% change in the count of homes within 6 miles is 0.045%. Using the reported standard error and a critical value from a t-distribution with 481 degrees of freedom, we conclude with 95% confidence that the true change in firefighting costs with each 1% change in the count of homes is between 0.009% and 0.081%.

---

1 Letting $h$ denote the lag distance, the correlation between two model errors $h$ days apart within a given fire is $\rho^h$, where $\rho$ is the lag-1 correlation and takes values between -1 and 1 (Pinheiro and Bates 2000).

2 Letting $h$ denote the lag distance, the correlation between two model errors $h$ PctComplete-units apart within a given fire is $\exp(-h/\varphi)$, where $\varphi$ is the range of the correlation function (Pinheiro and Bates 2000).

3 Letting $v$ denote the model-fitted values, the error variances are modeled as $\sigma^2|v|^{2\delta}$, where δ is the parameter mediating the relationship between error variance and the fitted values (Pinheiro and Bates 2000).

Table 3. Inference statistics for fixed effects in the full and reduced mixed models predicting logged daily wildfire suppression costs.

| | OR Full | OR Reduced | OR+CA Full | OR+CA Reduced |
|---|---|---|---|---|
| Intercept | 12.0753*** | 12.2392*** | 12.3268*** | 12.1362*** |
| | (0.4899) | (0.3856) | (0.3516) | (0.2603) |
| PctComplete | −0.0013 | −0.0015 | 0.0024 | 0.0023 |
| | (0.0027) | (0.0026) | (0.0021) | (0.0020) |
| PctComplete2 | −0.0003*** | −0.0003*** | −0.0003*** | −0.0003*** |
| | (0.0001) | (0.0001) | (0.0001) | (0.0001) |
| LnFireAcres | 0.0049 | 0.0034 | 0.0838* | 0.0839* |
| | (0.0510) | (0.0486) | (0.0376) | (0.0370) |
| GrowthPotMedium | −0.0604 | | 0.0319 | 0.0360 |
| | (0.0622) | | (0.0500) | (0.0497) |
| GrowthPotHigh | −0.0474 | | 0.1767** | 0.1696** |
| | (0.0709) | | (0.0542) | (0.0529) |
| GrowthPotExtreme | −0.0076 | | 0.1121 | 0.1135 |
| | (0.1126) | | (0.0656) | (0.0637) |
| TerrainMedium | | | −0.2173 | −0.1880 |
| | | | (0.1673) | (0.1655) |
| TerrainHigh | 0.1720 | 0.1690 | | |
| | (0.1430) | (0.1379) | | |
| TerrainExtreme | 0.7290*** | 0.7387*** | 0.1163* | 0.1005 |
| | (0.1665) | (0.1573) | (0.0584) | (0.0557) |
| PctContain | −0.0027 | −0.0024 | −0.0013 | −0.0013 |
| | (0.0015) | (0.0014) | (0.0009) | (0.0009) |
| LnRoadCount | 0.2567*** | 0.2563*** | 0.0943* | 0.0978** |
| | (0.0560) | (0.0546) | (0.0370) | (0.0367) |
| PctForest | 0.0024 | | −0.0024 | |
| | (0.0032) | | (0.0023) | |
| Wind | −0.0005 | | −0.0011 | |
| | (0.0033) | | (0.0015) | |
| Humidity | −0.0020 | −0.0021 | −0.0013 | −0.0012 |
| | (0.0014) | (0.0013) | (0.0010) | (0.0007) |
| Temperature | −0.0022 | −0.0024 | −0.0001 | |
| | (0.0018) | (0.0018) | (0.0012) | |
| LnHomesCount | 0.0571* | 0.0591* | 0.0492** | 0.0454* |
| | (0.0265) | (0.0262) | (0.0187) | (0.0186) |
| $\sigma_\epsilon$ | 0.4318 | 0.4258 | $2.75\times10^{8\dagger}$ | $1.92\times10^{9\dagger}$ |
| $\sigma_i$ | 0.1999 | 0.2195 | 0.2213 | 0.2538 |
| $\sigma_{s1}$ | 0.0066 | 0.0069 | | |
| $\rho$ | 0.8899 | 0.8866 | | |
| $\phi$ | | | 35.4765 | 31.6535 |
| $\delta$ | | | −7.8321 | −8.6029 |
| Log-likelihood | 7.67 | 6.78 | 72.60 | 76.48 |
| BIC | 93.43 | 68.02 | −19.63 | −46.23 |
| No. Fires | 33 | 33 | 60 | 60 |
| No. Fire-days | 230 | 230 | 533 | 533 |

Standard errors in parentheses. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. $\sigma_\epsilon$ = error StdDev; $\sigma_i$ = intercept StdDev; $\sigma_{s1}$ = PctComplete slope StdDev; $\rho$ = AR1 correlation parameter; $\phi$ = exponential correlation parameter; $\delta$ = power-of-the-mean variance parameter.

†Due to the variance structure this estimate does not represent the usual definition of $\sigma_\epsilon$ (see footnote 3).

## Discussion

This research provides further evidence that wildfire suppression costs are positively associated with the number and location of homes. Interpretation of the combined Oregon and California model suggests that after accounting for confounders, including fire size and growth potential, a 1% change in the number of homes within six miles of a wildfire is associated with a 0.05% increase in fire suppression costs. Similarly, after controlling for confounders, a doubling of homes (100% increase) is associated with a 5% increase in fire suppression costs. The similarity between the estimated effect of homes on suppression costs in Oregon (6% increase with a 100% increase in homes) and California (7% increase with a 100% increase in homes) (Gude et al, in review) indicate that these results are likely generalizable to federally fought wildfires in other western U.S. states as well.

The quantified relationship between homes and suppression costs suggests that introducing new housing units in an otherwise undeveloped area has the greatest potential to increase firefighting costs. In other words, the expansion of housing into new areas has a greater potential to increase future suppression costs than in-fill of previously developed areas. The size of the effect per home is smaller in highly developed areas threatened by wildfire. This is likely because when large numbers of homes are threatened, fire managers are already investing the maximum amount of available resources to stop the fire. For example, using the average daily cost within our sample ($700,911), the combined Oregon and California model predicts an increase in suppression costs of $31,545 if two homes instead of one were within 6 miles of the wildfire. By comparison, the model predicts an increase of only $319 if 100 homes instead of 99 were within 6 miles of the wildfire.

Our findings agree with four of the five empirical studies that investigate the relationship between fire suppression costs and housing. Importantly, this paper and the Gude et al. California study (in review) investigate wildfires in a way that the other published studies did not. Daily suppression costs were analyzed rather than cumulative costs per fire. Analyzing costs at the daily level allowed us to retain information that would have been lost had we aggregated response and predictor values across fires. Our estimates of the effects of log homes count on log daily costs, for example, incorporated associated variation in both costs and homes within fires. In addition, our study and Gude et al. (in review) used counts of threatened homes as reported by county tax assessor offices. In the other studies, housing value averaged over census tracts or blocks were used to estimate threats to development. This representation is not ideal for several reasons. Census tracts are extremely large in rural areas. Sometimes they are the same as county boundaries, sometimes there are only 2 or 3 tracts per county. Also, fire managers may or may not spend more resources protecting expensive versus moderately priced versus inexpensive housing.

### *Policy Review and Implications*

Existing federal and state wildfire policies have focused more on improving fuels management than on patterns of home development (Stephens and Ruth 2005; Gude et al. 2007). With few exceptions, state policies addressing the wildland urban interface have not been regulatory. Those states that have gone beyond incentive driven and voluntary measures, have focused almost entirely on fuels reduction projects. For example, California state law requires that homeowners in the WUI clear and maintain vegetation specific distances around structures (e.g., defensible space); Utah sets minimum standards for ordinance requirements based on the 2003 International Urban Wildland Interface Code; and, Oregon sets standards for defensible space, fuel breaks, building materials, and open burning on the property (Gude et al. 2007).

Importantly, thinning, prescribed fire, and the existing laws that address defensible space, ingress, egress, and water supply can provide a safer environment for firefighters and enable more structures to be saved. However, the extent to which these measures impact wildfire suppression costs is unknown. These measures are sometimes prohibitively expensive. For example, markets for the products of thinning activities are currently limited. An empirical analysis that evaluates whether investments in fuels treatments reduce firefighting costs would be an important contribution. In some cases, policies that address fuels may create a safe enough environment to allow some homeowners to "shelter-in-place", a strategy promoted in Australian communities in which a homeowner remains to protect his or her property (Cova 2005). However, the net effect of sheltering-in-place on suppression costs is unknown, since fire managers assume the additional burden of protecting not only structures, but lives.

In light of mounting evidence that home construction leads to higher fire suppression costs, policies meant to address rising suppression costs should attempt to:

1. Influence future home construction patterns in a way that reduces suppression costs, and
2. Generate funds to cover the additional suppression costs related to new housing.

To ignore homes in future wildfire policies is to ignore one of the few determinants of wildfire suppression cost that can be controlled. For example, governments have limited ability to control factors such as weather and the terrain in which wildfires burn.

The most obvious means of reducing additional suppression costs due to future home development would be to limit future home development in wildfire prone areas. Based on our findings, future savings may be achieved by a combination of policies that encourage open space conservation and discourage development outside existing urban growth boundaries and subdivisions. Often, regulatory approaches that would accomplish these goals are challenging for policy makers to enact. Policy tools such as zoning are highly controversial in much of the rural United States due to the perception of regulatory takings, where the government effectively takes private property when zoning laws limit how it can be used. To date, instead of attempting to regulate development in fire prone lands, the majority of western states have enacted legislation that encourages counties to prepare plans that would reduce wildfire problems and, in some cases, clarifies that counties can legally deny subdivisions that do not mitigate or avoid threats to public health and safety from wildfire. While these types of policies may be helpful, they will likely not result in significant future savings because local governments, due to a lack of resources and a lack of cost accountability, have little incentive to act.

Future policies will likely need to focus on covering the additional suppression costs related to new housing for several reasons. First, federal and state agencies are experiencing difficulty budgeting for fire suppression, and these challenges will worsen when there are more homes to protect. Second, the public may become dissatisfied with the existing arrangement in which the general taxpayer covers the costs of protecting at-risk homes. Establishing fees to encourage undeveloped parcels to remain undeveloped while aligning the cost burden with the presence of structures and expansion into new construction areas would have the most logical connection to controlling costs. Finding a more equitable means of covering fire suppression costs may also change behavior in a way that leads to lower future costs. For example, development rates in high wildfire risk areas may slow if suppression costs were borne, in part, by those who build at-risk homes, or by local governments who permit them, rather than by the federal and state taxpayer.

This study quantifies the effect of homes on firefighting costs for one part of the US West, and demonstrates that policy makers can achieve future fire suppression cost savings by focusing attention on development patterns. Since it is the initial development that has the greatest affect on firefighting costs, pursuing strategies that keep land undeveloped could lead to significant fire suppression cost savings. In the future, effective management of suppression costs will likely require a combination of policies that regulate land use, provide incentives for limiting the "footprint" of future development, and reform how suppression costs are paid.

**Acknowledgements**

We thank The Kresge Foundation for financial support of this research.

**References**

Bartlett, J.G., D.M. Mageean, AND R.J. O'Connor. 2000. Residential expansion as a continental threat to U.S. Coastal ecosystems. Popuation and Environment 21(5):429–468.

Bartos, M. 2008. Place specific character of amenity migration in the Czech Republic. Proceedings of Understanding and Managing Amenity-led Migration in Mountain Regions. May 15-19. The Banff Centre. Banff, Alberta, Canada.

Calkin, D.E., K.M. Gebert, J.G. Jones, and R.P. Neilson. 2005. Forest Service large fire area burned and suppression expenditure trends, 1970–2002. Journal of Forestry 103:179–183.

Canton-Thompson, J., B. Thompson, K.M. Gebert, D.E. Calkin, G.H. Donovan, and G.Jones. 2006. Factors affecting fire suppression costs as identified by Incident Management Teams. Res. Note RMRS-RN-30. Fort Collins, CO: US. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Caprio A.C., and T.W. Swetnam. 1995. Historic fire regimes along an elevational gradient on the west slope of the Sierra Nevada, California. Pages 173–179 in Brown JK, Mutch RW, Spoon CW, Wakimoto RH, tech. coords. Proceedings: Symposium on Fire in Wilderness and Park Management, Missoula, MT, March 30–April 1, 1993. Ogden (UT): US Department of Agriculture, Forest Service, Intermountain Research Station. General Technical Report INT-GTR-320.

Cova, T.J. 2005. Public safety in the urban–wildland interface: should fire-prone communities have a maximum occupancy? Natural Hazards Review 6(3):99-108.

Covington W.W., and M.M. Moore. 1994. Southwestern ponderosa forest structure – changes since Euro-American settlement. Journal of Forestry 92:39–47.

Donovan G. H., and T.C. Brown. 2007. Be careful what you wish for: The legacy of Smokey Bear. Frontiers in Ecology and the Environment. 5(2):77.

Donovan G.H., Noordijk, P., Radeloff, V. 2008. "Estimating the Impact of Proximity of Houses on Wildfire Suppression Costs in Oregon and Washington" IN: Proceedings of the Second International Symposium on Fire Economics, Planning, and Policy: A Global View. General Technical Report PSW-GTR-208, USDA Forest Service, Pacific Southwest Research Station, Albany, California. pp.: 697-701.

Donovan G.H., J.P. Prestemon, K. Gebert. 2011. The effect of newspaper coverage and political pressure on wildfire suppression costs. Society and Natural Resources 24(8):785-798.

Flognfeldt, T. 2006. Second homes, work commuting and amenity migrants in Norway's mountain areas. The Amenity Migrants: Seeking and Sustaining Mountains and Their Cultures. Cromwell Press, Trowbridge. 232-244.

GAO (General Accounting Office). 2009. Wildland fire management: Actions by Federal Agencies and Congress Could Mitigate Rising Fire Costs and Their Effects on Other Agency Programs.GAO-09-444T. Washington, DC: General Accounting Office.

GAO (General Accounting Office). Wildland Fire Management: Update on Federal Agency Efforts to Develop a Cohesive Strategy to Address Wildland Fire Threats. GAO-06-671R. Washington, D.C.: May 1, 2006.

Gebert, K.M., Calkin, D.E., and Yoder, J. 2007. Estimating suppression expenditures for individual large wildland fires. Western Journal of Applied Forestry 22(3), 188-196.

Glorioso, R.S. 2006. A bioregion in jeopardy: the strategic challenge of amenity migration in Baguio, The Philipinnes. The Amenity Migrants: Seeking and Sustaining Mountains and Their Cultures. Cromwell Press, Trowbridge. 261-277.

Gude P.H., K.L. Jones, R. Rasker, M.C. Greenwood. In Review. Evidence for the effect of homes on wildfire suppression costs. International Journal of Wildland Fire.

Gude, P.H., R. Rasker, J. van den Noort, Jeff. 2008. Potential for Future Development on Fire-Prone Lands. Journal of Forestry 106(4): 198-205.

Gude, P.H., A.J. Hansen, and D.A. Jones. 2007. Biodiversity Consequences of Alternative Future Land Use Scenarios in Greater Yellowstone. Ecological Applications 17(4):1004-1018.

Gude, P.H., A.J. Hansen, R. Rasker, and B. Maxwell. 2006. Rates and Drivers of Rural Residential Development in the Greater Yellowstone. Landscape and Urban Planning 77(2006):131-151.

Hall, C.M. 2006. Amenity migration in South Island of New Zealand: contestation for land and landscape in Central Otago. The Amenity Migrants: Seeking and Sustaining Mountains and Their Cultures. Cromwell Press, Trowbridge. 295-305.

Harrell, F. 2001. Regression modeling strategies. Springer Verlag.

Hastie, T., Tibshirani, R. & Friedman, J.H. 2009. The elements of statistical learning: data mining, inference, and prediction. Springer Verlag.

Intergovernmental Panel on Climate Change. 2001. Special Report on Emissions Scenarios. Available online at http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission/; last accessed Apr. 13, 2009.

Johnson, K. M. 1999. The rural rebound. Reports on Amer. 1(3):1–20. Population Reference Bureau, Washington, DC.

Johnson, K.M., and C.L. Beale. 1994. The recent revival of widespread population growth in nonmetropolitan areas of the United States. Rural Sociology 59(4):655–667.

Liang, J., Calkin, D.E., Gebert, K.M., Venn, T.J., and Silverstein, R.P. 2008. Factors influencing large wildland fire expenditures. International Journal of Wildland Fire, 17, 650-659.

Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D. and Schabenberger, O. 2006. SAS for mixed models. SAS Publishing.

Mercer, D.E., J.P. Prestemon, D.T. Butry, AND J.M. Pye. 2007. Evaluating alternative prescribed burning policies to reduce net economic damages from wildfire. American Journal of Agricultural Economics 89(1):63–77.

Moore M.M., W.W. Covington W.W., P.Z. Fule. 1999. Reference conditions and ecological restoration: A southwestern ponderosa pine perspective. Ecological Applications 9: 1266–1277.

Moss L.A.G. (Ed.). 2006. The Amenity Migration - seeking and sustaining Mountains and their culture, CABI Publishing, Oxfordshire UK, Cambridge USA.

NIFC (National Interagency Fire Center). 2011. Wildland fire statistics. Available online at http://www.nifc.gov/fireInfo/fireInfo_statistics.html; last accessed December 14, 2011.

NWCG (National Wildfire Coordinating Group Safety & Health Working Team). 2011. Safety Gram: Fatalities, Entrapments and Serious Accident Summaries for 1999-2010. Available online at http://www.wildfirelessons.net; last accessed December 14, 2011.

OIG (Office of Inspector General). 2006. Forest service large fire suppression costs. USDA Rep. 08601-44-SF.

Otero, A., L. Nakayama, S. Marioni, E. Gallego, A. Lonac, A. Dimitriu, R. Gonzalez, C. Hosid. 2006. Amenity migration in the Patagonian mountain community of San Martin del los Andes, Neuquen, Argentina. In: L. A.G. Moss (ed.) The Amenity Migrants: Seeking and Sustaining Mountains and their Cultures, Wallingford, UK and Cambridge, USA: CABI Publishing, pp 200-211.

Perlik, M. 2008. Differentiating regional development in mountain areas as a result of global change: theoretical and empirical implications for understanding amenity-seeking behavior. Proceedings of Understanding and Managing Amenity-led Migration in Mountain Regions. May 15-19. Banff, Alberta, Canada.

Perlik, M. 2006. The Specifics of Amenity Migration in the European Alps. In: MOSS, L. A. G. (ed.): The Amenity Migrants. Seeking and Sustaining Mountains and their Cultures. Wallingford (UK), Cambridge (USA): 215-231.

Pinheiro, J.C. and Bates, D.M. 2000. Mixed-effects models in S and S-PLUS. Springer Verlag.

Lanin National Park, Argentina. Proceedings of Understanding and Managing Amenity-led Migration in Mountain Regions. May 15-19. The Banff Centre. Banff, Alberta, Canada.

Pinheiro, P., D. Bates, S. DebRoy, D. Sarkar and the R Development Core Team 2011. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-98.

Prestemon, J.P., K. Gebert, and K.L. Abt. 2010. Fiscal Year 2011 September Federal Land Assistance, Management and Enhancement (FLAME) Act Forecast For the USDA Forest Service. Available online at http://www.fs.fed.us/aboutus/budget/requests/6498868_FY2011%20FLAME%20September%20Report%20-%20Report%20sent%20042711.pdf; last accessed December 9, 2011.

R Development Core Team (2011). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Radeloff, V.C., R.B. Hammer, P.R. Voss, A.E. Hagen, D.R. Field, and D.J. Mladenoff. 2001. Human demographic trends and landscape level forest management in the northwest Wisconsin Pine Barrens. Forest Science 47(2):229-241.

Radeloff, V.C., R.B. Hammer, S.I. Stewart, J.S. Fried, S.S. Holcomb, and J.F. McKeefry. 2005. The wildland-urban interface in the United States. Ecological Applications 15(3):799-805.

Rasker, R. 2006. An exploration into the economic impact of industrial development versus conservation on western public lands. Society and Natural Resources 19:191-207.

Rasker, R., and A.J. Hansen. 2000. Natural amenities and populations growth in the Greater Yellowstone region. Human Ecology Review 7(2):30-40.

Rudzitis, G. 1999. Amenities increasingly draw people to the rural west. Rural Development Perspectives 14(2):9-14.

Rudzitis, G. 1996. Wilderness and the Changing West. John Wiley & Sons. New York. 240 pp.

Running, S.W. 2006. Is Global Warming Causing More, Larger Wildfires? Science 313:927-928.

Sarkar, D. 2008. Lattice: multivariate data visualization with R. Springer Verlag, New York.

Schabenberger, O. & Gotway, C.A. 2005. Statistical methods for spatial data analysis. Vol. 64: CRC Press.

Schnaiberg J., J. Riera, M.G. Turner, P.R. Voss. 2002. Explaining human settlement patterns in a recreational lake district: Vilas County, Wisconsin, USA. Environmental Management 30:24–34.

Schwarz, G. 1978. Estimating the dimension of a model. Annals of Statistics 6: 461–464.

Snyder, G. 1999. Strategic holistic integrated planning for the future: Fire protection in the urban/rural/wildland interface (URWIN). P.159 –170 in Proc. of symp. on Fire economics, planning, and policy: Bottom lines, Gonzalez-Caban, A., and P.N. Omi (eds.). US For. Serv. Gen. Tech. Rep. PSW-173.

Stephens, S.L., and L.W. Ruth. 2005. Federal forest-fire policy in the United States. Ecological Applications 15(2):532–542.

Theobald, D.M., and W.H. Romme. 2007. Expansion of the US wildland–urban interface. Landscape and Urban Planning 83(4):340-354.

Vittinghoff, E. 2005. Regression methods in biostatistics: linear, logistic, survival, and repeated measures models. Springer Verlag.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313:940-943.

Wolfinger, R. 1993. Covariance structure selection in general mixed models. Communications in statistics-Simulation and computation 22: 1079--1106.