Evidence for the effect of homes on wildfire suppression costs

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Abstract

This paper uses wildfires in the Sierra Nevada area of California as a case study to estimate the relationship between housing and fire suppression costs. 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. Importantly, this paper investigates wildfires in a way that other published studies have not; we analyzed costs at the daily level, retaining information that would have been lost had we aggregated the data. By using linear mixed models with serial autocorrelation and error heterogeneity covariance structures we were able 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 0.07 (p = 0.005). 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 0.07%. The findings of this study are in agreement with most other existing empirical studies that have investigated the relationship between fire suppression costs and housing using cumulative fire costs and more generalized data on home locations. The study adds to mounting evidence that increases in housing lead to increases in fire suppression costs.

1. Introduction

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), is experiencing rising population growth and new housing (Radeloff et al. 2005; Theobald and Romme 2007). The development of fire prone areas 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 motivation for residential development (Rudzitis 1999, 1996; Rasker 2006; Gude et al. 2006). This phenomenon 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, 2008).

The conversion of land to residential development in the WUI has also been driven by the increasing popularity of large residential lots (Theobald et al. 1997; Hammer et al. 2004). 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).

The cost of fighting wildfires has become a major budgetary concern for federal, state, and local agencies in the United States. The wildfire problems in the WUI have received national attention as more acres and homes are burned by wildfire (National Interagency Fire Center [NIFC] 2011). A recent government audit identified the WUI as the primary source of escalating federal firefighting costs, which exceeded $1 billion in three of the past six years (OIG 2006). In 87 percent of large wildfires reviewed in the audit, the protection of private property was cited as a major reason for firefighting efforts (OIG 2006).

WUI homes are also often difficult to protect because of remoteness, steep slopes, narrow roads and the dispersed pattern of development. These common characteristics can create dangerous situations for firefighters. From 1999 to 2010, $16.3 billion in federal funds were spent fighting wildfires (Congressional Research Service 2010) and 230 people were killed during wildland fire operations (National Wildfire Coordinating Group Safety and Health Working Team 2010); but despite the firefighting efforts, an average of 1,179 homes were lost annually to wildfires during this period (NIFC 2011).

Recent wildfire suppression has been costly, and estimates suggest these costs may increase significantly. Currently, only 14 percent of the available wildland interface in the western United States is developed (Gude et al. 2008). More development in these sensitive areas would likely lead to greater wildfire suppression costs. 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). This means that large wildfires and longer fire seasons are more likely (Westerling et al. 2006; Running 2006), and if development trends persist, more homes will be threatened by these fires.

This paper uses wildfires in the Sierra Nevada area of California as a case study to estimate the relationship between housing and fire suppression costs. California ranks first among western states in the number of homes built in the WUI (Gude et al. 2008), and has had many historically significant fires in which hundreds of structures were destroyed per event (NIFC 2011). The state offers ample opportunity to investigate the effect of residential development 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.

2. Methods

We set out to determine the evidence for the effect of homes on wildfire suppression costs. Isolating this effect required that we control for a suite of potential confounding variables, including weather, terrain, and human factors such as road access. To decide which variables should be included we sketched a diagram of theorized causal relationships of wildfire costs (Figure 1).

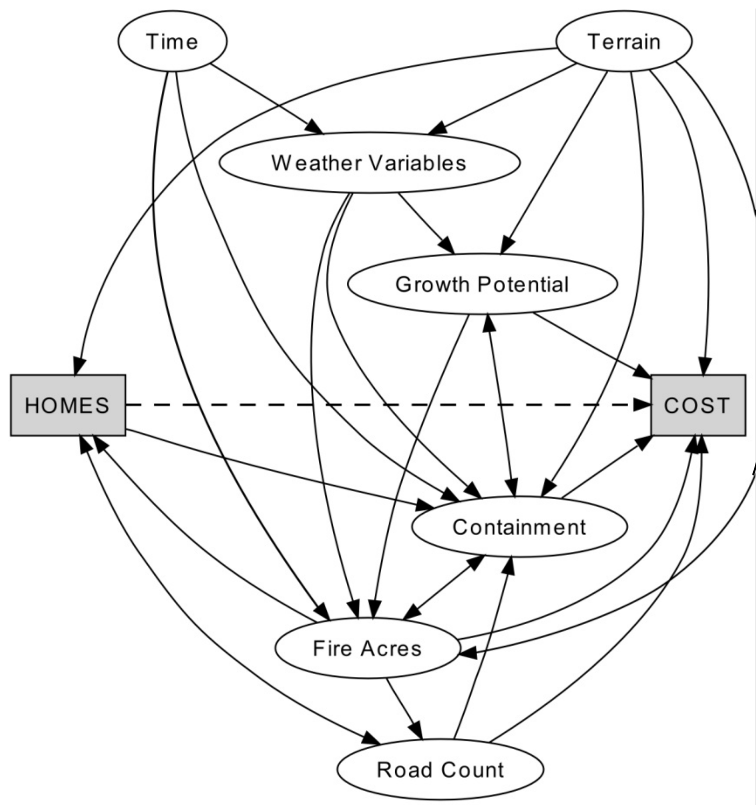

Figure 1. A diagram of potential causal relationships of wildfire costs.

2.1 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).

Table 1. Data collected for each day of firefighting for each of the 27 wildfires 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 Montana (Gude et al. 2008).

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. 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 303 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.

With the exception of grassland fires, the entire population of Sierra Nevada wildfires for which accurate data were available was included in the analyses. 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. Data explorations including histograms, boxplots, and numerical summaries revealed implausible observations and we removed 8 of the original 311 days of firefighting data.

The final dataset consisted of 303 days of information on total suppression costs and wildfire characteristics for 27 wildfires (Figure 2). The wildfires occurred in the Sierra Nevada region of California, plus portions of northwest California, from July 2006 through September 2009. Due to data availability, sample fires included only those in which the US Forest Service was the primary agency involved. The sample fires were distributed in and around 12 national forests: Eldorado, Inyo, Klamath, Lake Tahoe Basin, Lassen, Modoc, Plumas, Sequoia, Shasta-Trinity, Sierra, Stanislaus, and Tahoe. Klamath, Shasta-Trinity, and Modoc National Forests are to the north and northwest of what is typically defined as the Sierra Nevada. We included wildfires that burned around these three national forests in order to augment our sample size. 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 2. The locations of 27 California wildfires included in this study are shown.

2.3 Mixed Models

Given the longitudinal structure of the data, a logical model choice was the linear mixed model (LMM) (Littell et al. 2006; Pinheiro and Bates 2000). This model is an extension of the general linear model and can be written

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

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 within-group error vector. Because the only constraint on the **G** and **R** matrices is symmetric positive-definiteness, this model provides a great deal of flexibility in modeling residual autocorrelation and heteroscedasticty (Var[**Y**] = **ZGZ**' + **R** in contrast to OLS regression where Var[**Y**] is proportional to an identity matrix).

We built LMMs of this form with the goal of drawing valid inferences on the ß coefficient associated with the homes effect. 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.

2.3.1 Model Building

We first examined scatterplots of the response and continuous predictors with the goal of finding transformations to linearize relationships where needed. After choosing transformations we added model terms for all confounding variables, the homes variable, and the temporal structure of costs into the mean structure of the model (i.e. these variables plus a column of 1s for an intercept comprised the **X** matrix). We fit the model containing only these fixed effects and examined residual autocorrelation using an ACF plot of the empirical autocorrelations across days within fires. We judged significance of autocorrelations based on plotted Bonferroni-adjusted two-sided critical bounds for testing autocorrelations at all lags (see Pinheiro and Bates 2000 p. 241). Due to the known nested nature of the observations we then added random intercepts for each fire into the **Z** matrix, followed by random linear and quadratic slopes for the fire day, reassessing the autocorrelation diagnostics at each step. We also used *BIC* (Schwartz 1978) and examination of within-fire residual diagnostic plots to determine if structuring the **R** matrix with estimated variance heterogeneity and temporal correlation parameters improved model performance. Based on the 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 fixed effects (i.e., estimates of **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 two levels and the associated ß represented the expected change from the High level to the Extreme level. The Growth Potential variable had 4 levels and the associated coefficients represented the expected changes from the Low level to the Medium, High, and Extreme levels. We checked for quadratic fixed effects of the continuous predictors, starting with the count of homes and the terms suggested by nonlinearities in the bivariate plots. We also tested for interactions of each of the confounding variables with the homes variable.

In addition to drawing inferences based on this "full model", we created a "reduced model" which was reduced based on two criteria. First, terms that were clearly confounders or were needed due to the data structure were not considered for removal; this 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. The reason for stringency in setting the *p*-value cutoff was that 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 (Hastie et al. 2009, Harrell 2001) and an overly simplistic model structure (Schabenberger and Gotway 2005, Vittinghoff 2005, Wolfinger 1993).

3. Results

The cumulative suppression cost per sample fire ranged from $478,642 to $72,226,070, with a mean of $18,379,112 (Table 2). The number of days the sample fires were actively fought ranged from 7 to 100, with an average of 36 days. The fires ranged in size from 1 to 311 square kilometers, with an average of 57 square kilometers. The average duration and size within our sample fires are representative of US Forest Service fires in the Sierra Nevada, however wildfires in which the state is the primary responder tend to be shorter and smaller due to higher numbers of threatened structures and resources (personal communication, David Passovoy, CAL FIRE). The results presented in this paper reflect US Forest Service wildfires, not state fought wildfires, of which there were none in our sample.

Table 2. Summary data per fire for each of the 27 wildfires studied.

Fire	Cumulative Cost	Year	Firefighting Days	Days in Sample	Avg Size of Fire (sq.km.)	Percent Forest	Avg Homes within 6 mi (9.7 km)
American River Complex	$22,795,346	2008	62	15	41	95%	543
Antelope Complex	$8,433,644	2007	10	4	86	62%	229
Backbone	$16,897,750	2009	20	10	22	96%	2
Bassetts	$7,687,375	2006	12	4	7	100%	537
Big Meadow	$16,947,242	2009	25	8	22	48%	76
Canyon Complex	$45,166,766	2008	58	24	91	90%	1,808
China-Back Complex	$2,934,617	2007	12	5	9	85%	265
Clover	$8,199,100	2008	46	16	24	26%	68
CUB Complex	$21,117,153	2008	31	17	37	99%	103
Elephant	$2,094,034	2009	7	4	1	100%	12
Fletcher	$4,092,990	2007	12	3	24	34%	5
Happy Camp	$10,264,472	2006	64	9	10	100%	84
Harrington	$478,642	2009	27	3	1	100%	0
Hat Creek Complex	$7,874,824	2009	9	5	37	91%	693
Hidden	$9,182,999	2008	26	10	9	93%	15
Iron Complex	$72,226,070	2008	79	12	89	98%	1,088
Kingsley Complex	$7,998,835	2006	18	3	4	100%	1

Knight	$12,122,449	2009	21	7	15	93%	3,689
Lime Complex	$62,050,552	2008	99	35	311	89%	2,494
Moonlight	$33,088,547	2007	31	8	208	88%	1,007
Piute	$24,229,665	2008	28	11	108	41%	1,532
Ralston	$13,849,333	2006	15	8	21	97%	938
Red Rock	$4,188,332	2009	15	9	4	86%	18
Siskiyou Complex	$44,860,758	2008	100	33	204	99%	34
Ukonom Complex	$25,623,333	2008	99	34	126	96%	121
Wallow	$4,973,823	2007	29	3	6	100%	67
Whiskey	$6,857,372	2008	29	3	29	38%	63

Bivariate scatterplots suggested taking the natural log of Cost, Homes, Fire Acres, and Road Count adequately linearized relationships. Both Homes and Road Counts contained 0 values and we added 1 to them prior to log-transforming. Checks for partial linearity throughout the multivariable modeling process also supported these transformations. The dot plot shown in Figure 3 shows the observed mean log of daily cost by quartiles of the observed predictor values. Each variable is split into quartiles (shown on the y-axis), represented by the four gray lines. The location of the dot on each line indicates the mean log daily cost (shown on the x-axis) within that quartile. This exploratory analysis indicates:

- The mean log of daily cost increased across the quartiles of the log count of homes.
- The mean log of daily cost was lower in the lowest and highest quartiles of the time variable (percent complete).
- Days in which wildfires were in the lowest quartile of log fire acres had lower mean log of daily cost.
- The mean log of daily cost increased with increases in growth potential.
- Days in which wildfires were in the lowest quartile of log road count had lower mean log of daily cost.
- The mean log of daily cost was lower in the highest quartile of percent forest.
- Temperatures above the median were associated with higher mean log of daily cost.
- Terrain difficulty, wind, and humidity appeared to have little relationship with the mean log of daily cost.

Although we focus our inferential results on the effect of homes count on costs, Figure 3 provides the reader with a summary of how observed daily costs varied across levels of each predictor within the raw data. As with inferential results presented below, this figure suggests that log count of homes and growth potential, in particular, are strongly associated with log daily costs. Figure 4 provides a more detailed view of the relationship between the log count of homes and the log daily costs is shown for each day of firefighting within each fire.

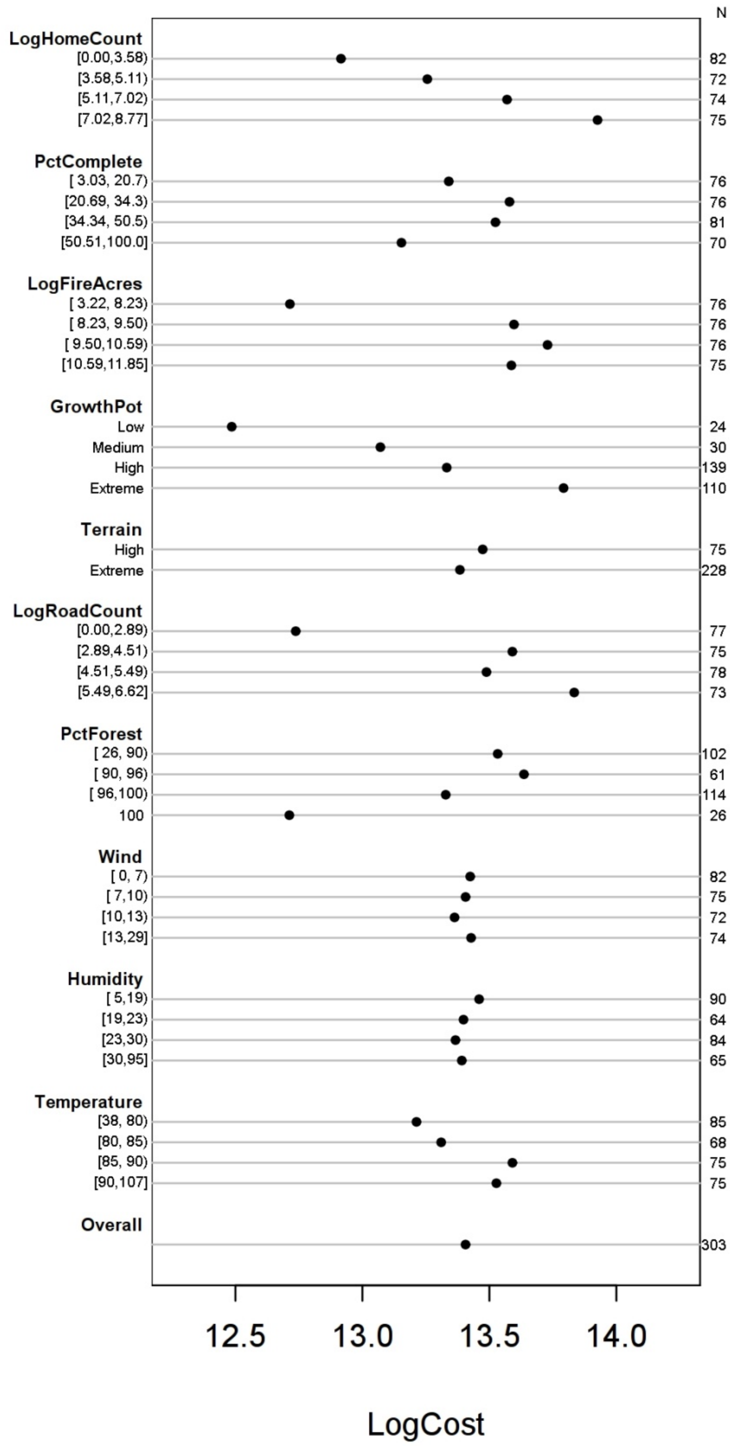

Figure 3. Observed mean log of daily cost by quartiles of the observed predictor values.

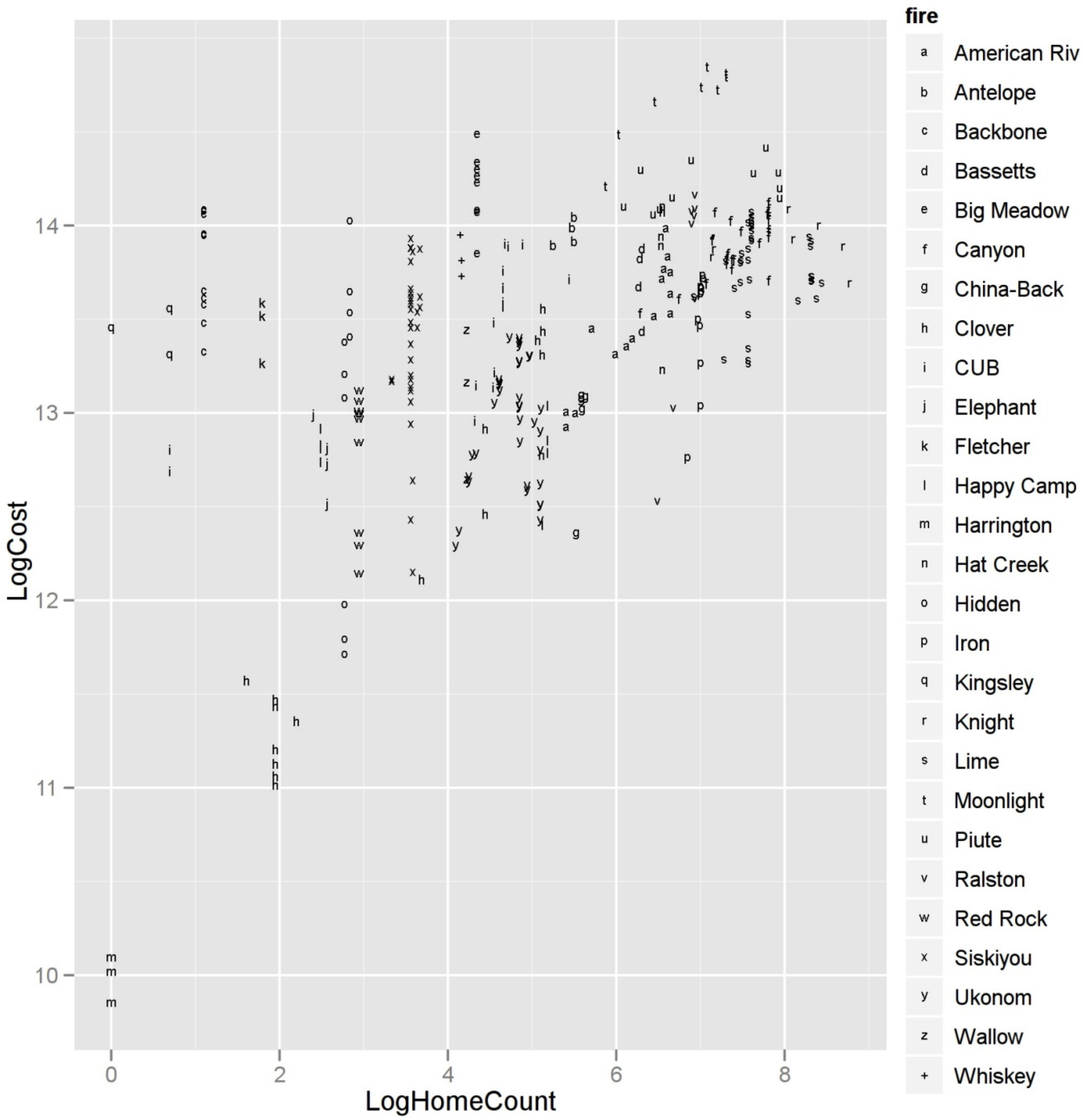

Figure 4. The log count of homes is plotted against the log daily costs in dollars for each day of firefighting within each of the 27 fires.

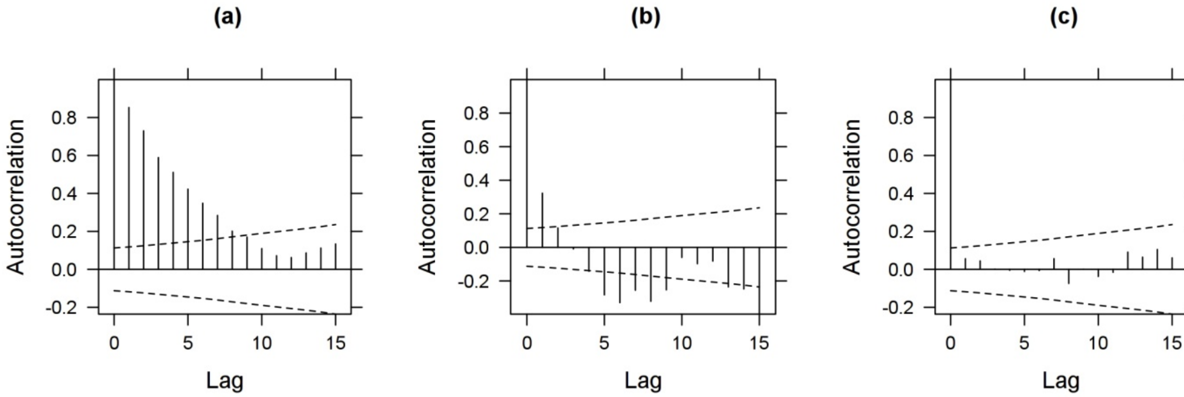

Figure 5. Plots of empirical autocorrelation functions for residuals from models with (a) fixed effects only, (b) additional random intercepts and random linear and quadratic slopes, and (c) random intercepts, linear and quadratic slopes, and within fire exponential correlation structure. The lines represent Bonferroni-adjusted two-sided critical bounds for the autocorrelations at each lag (Box et al., 1994).

3.1 Mixed Models

The ACF plot of residuals from the model containing only fixed effects indicated high levels of within-fire autocorrelation (Figure 5a). The addition of random intercepts and random slopes for the linear and quadratic temporal term (Percent Complete) decreased BIC by 412.5 points and produced visible improvements in fit (Figure 6), but significant autocorrelation remained at multiple lags (Figure 5b). Fitting an exponential correlation structure[1] to the off-diagonals of the **R** matrix accounted for the remaining autocorrelation (Figure 5c) and decreased BIC 184.5 points. However, at this point residual diagnostic plots suggested within-fire error heterogeneity, with residuals decreasing in absolute size as a function of fitted values (i.e. the models were doing better a predicting more expensive fire days). To account for this we fit a variance structure[2] to the diagonals of the **R** matrix, after which BIC decreased by 5.9 points and no apparent heteroscedasticity remained.

When we then checked the need for fixed quadratic effects we found significant convex effects of time (PctComplete), with costs tending to at first increase and then decrease during the course of each fire (Figure 6, Table 3). We found no other significant quadratic effects, nor interactions between the log homes count and other predictors.

1

This is the corExp structure from Pinheiro and Bates (2000).Letting h denote the lag distance, the correlation between two model errors h days apart within a given fire is $\exp(-h/\varphi)$, where φ is the range of the correlation function. This correlation structure is a multivariate generalization of the continuous AR1 model (Pinheiro and Bates 2000, pg 232).

2

We fit the varPower structure from Pinheiro and Bates (2000). 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. Because the error variance and fitted values are mutually dependent the variance structure is estimated through an “iteratively reweighted” optimization scheme (Pinheiro and Bates, pg 207).

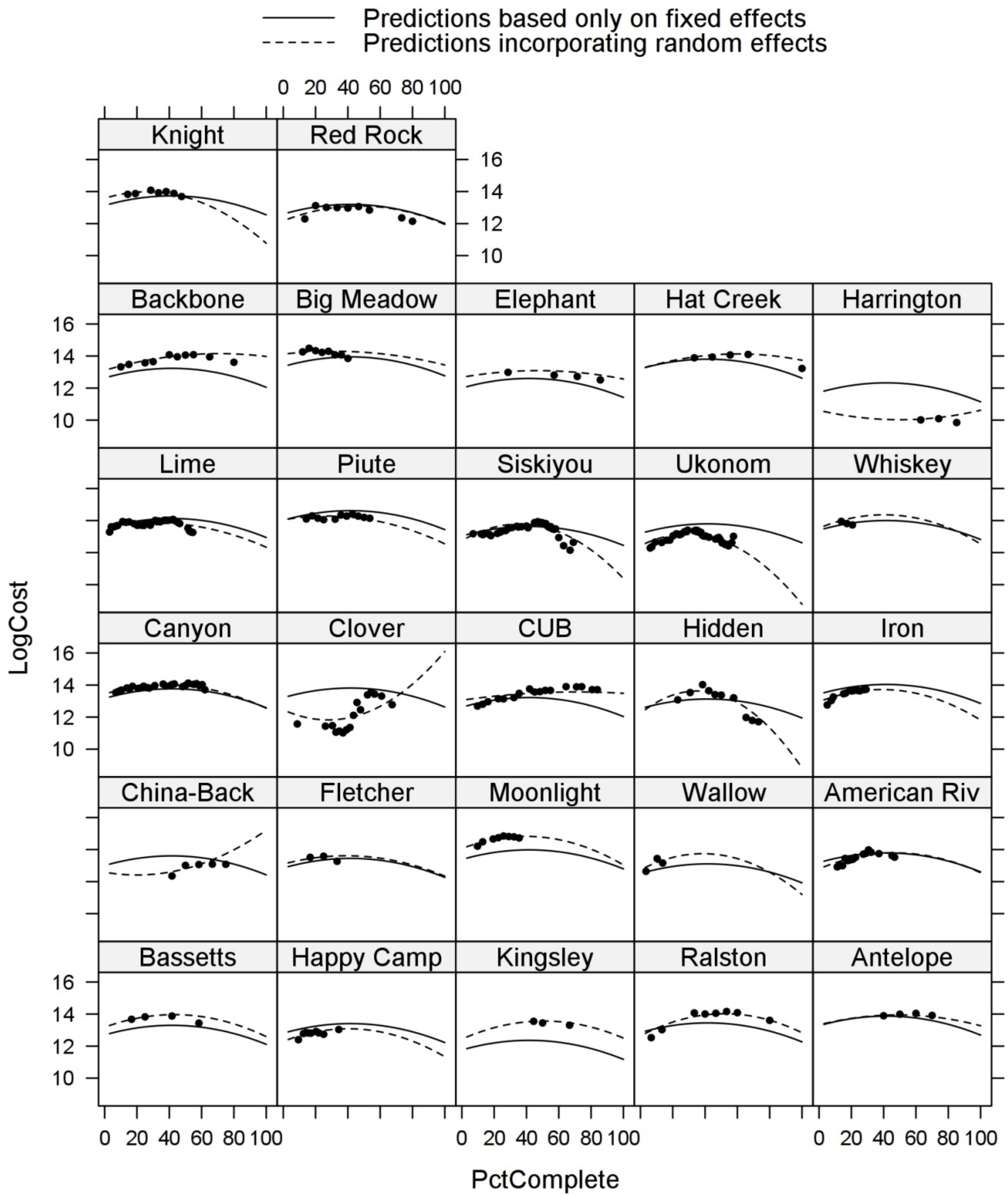

Figure 6. Values of predicted daily log cost over the life of each fire are shown with continuous predictors held at their observed mean value and categorical predictors at their most common value within fires.

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

Model	Variable	$\hat{\beta}$	95% CI	SE	df	t stat	p value
Full							
	Intercept	11.948	(10.911, 12.985)	0.540	263	22.12	0.000
	PctComplete	0.028	(0.012, 0.044)	0.008	263	3.33	0.001
	PctComplete2	-3e-04	(-5e-04, -2e-04)	1e-04	263	-3.62	$<$0.001
	logFireAcres	0.162	(0.056, 0.268)	0.055	263	2.94	0.004
	GrowPotMedium	0.020	(-0.107, 0.146)	0.066	263	0.30	0.762
	GrowPotHigh	0.258	(0.113, 0.404)	0.076	263	3.42	$<$0.001
	GrowPotExtreme	0.160	(-0.013, 0.334)	0.090	263	1.78	0.077
	ExtrTerrain	0.094	(-0.053, 0.242)	0.077	263	1.22	0.222
	PctContained	-6e-04	(-0.003, 0.002)	0.001	263	-0.42	0.678
	logRoadCount	-0.041	(-0.136, 0.0544)	0.049	263	-0.82	0.412
	PctForest	-0.010	(-0.019, -0.002)	0.004	25	-2.47	0.021
	Wind	-6e-04	(-0.004, 0.003)	0.002	263	-0.31	0.755
	Humidity	-7e-04	(-0.003, 0.002)	0.001	263	-0.50	0.621
	Temperature	-1e-04	(-0.003, 0.004)	0.002	263	0.05	0.957
	logHomeCount	**0.076**	**(0.024, 0.128)**	0.027	263	2.83	0.005
Reduced							
	Intercept	12.182	(11.324, 13.040)	0.443	269	27.52	$<$0.001
	PctComplete	0.026	(0.011, 0.041)	0.008	269	3.29	0.001
	PctComplete2	-3e-04	(-5e-04, -1e-04)	1e-04	269	-3.56	$<$0.001
	logFireAcres	0.118	(0.042, 0.195)	0.039	269	2.99	0.003
	GrowPotMedium	0.030	(-0.098, 0.157)	0.066	269	0.45	0.654
	GrowPotHigh	0.254	(0.110, 0.397)	0.074	269	3.43	$<$0.001
	GrowPotExtreme	0.206	(0.043, 0.368)	0.084	269	2.45	0.015
	PctForest	-0.009	(-0.017, -0.002)	0.004	25	-2.53	0.018
	logHomeCount	**0.075**	**(0.026, 0.126)**	0.026	269	2.87	0.004

At this point we had established the full model used to draw inferences about the effects of homes on wildfire-fighting costs. The model contained log transformations of the response (Daily Costs), the variable of interest (Homes Count within six miles), and two of the confounders (Fire Acres and Roads Count). All continuous predictors entered the mean structure of the model linearly other than the variable representing temporal progression (Percent Complete) which entered quadratically. The model also contained random intercepts and random linear and quadratic slopes for Percent Complete, as well as the error covariance parameters σ^2, δ, and φ. We viewed these covariance parameters as nuisance parameters that facilitated drawing valid inferences on the effects of interest in the face of correlated, heterogeneous errors, but were not of direct interest. Therefore we did not draw inferences on them, but for completeness report values here: the estimated range of the exponential correlation structure was $\varphi = 65.05$, the estimated error variance power parameter was $\delta = -5.75$, the estimate of σ^2 was 1.87×10^6 (note this is not the usual definition of σ^2 – see footnote 2), the estimated intercept variance was 1.69×10^{-23}, the estimated linear slope variance was 5.30×10^{-9}; and the estimated variance of the quadratic slope was 7.17×10^{-14}.

Reducing the model through backward elimination of the fixed effects resulted in the removal of the following variables (listed in the order removed): Temperature, Percent Contained, Wind Speed, Humidity, Log Road Count, and Terrain Difficulty. Removal of these variables resulted in a reduction of BIC by 15.4 points. For the reduced model the nuisance parameter estimates were: $\varphi = 54.49$, $\delta = -6.64$, $\sigma^2 = 1.75 \times 10^7$, intercept variance = 1.69×10^{-23}, linear slope variance = 5.30×10^{-9}, and quadratic slope variance = 7.17×10^{-14}.

Inference statistics for the fixed effects in the full and reduced models are shown in Table 3. Although statistics for all fixed effects estimates are shown, the focus of this paper is on the estimates describing the effects of homes on daily costs (shown in bold). Comparison of results from the full and reduced models indicates that removing the statistically insignificant predictors had little impact on the effect of interest. For each model we conclude that, given the other variables, the expected increase in daily log cost with each unit increase in log homes count within 6 miles of an active fire is 0.07 (p = 0.005 for the full model and p = 0.004 for the reduced model). Because this relationship describes log-transformed variables we can interpret it as an elasticity and conclude that the expected change in firefighting costs with each 1% change in the count of homes within 6 miles is 0.07%. Interpreting the interval estimate we conclude with 95% confidence that the true change in firefighting costs with each 1% change in the count of homes is between 0.02% and 0.12%.

4. Discussion

This research finds that wildfire suppression costs are strongly related to the number and location of homes. Interpretation of our modeling 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 0.07% increase in fire suppression costs. Similarly, after controlling for confounders, a doubling of homes (100% increase) is associated with a 7% increase in fire suppression costs.

These numbers mean that the additional fire suppression cost per home tends to be greater if development increases from 10 to 20 homes versus 1010 to 1020. In other words, the size of the effect is not as large if there are already hundreds of homes surrounding the fire, likely because at that point, fire managers are already doing all they can to stop the fire. For example, using the average daily cost within our sample ($816,439), the model predicts that daily costs would be $57,151 higher if 20 homes were within six miles of the wildfire versus 10 homes. However, the additional firefighting cost associated with 10 new homes is estimated to be only $566 per day given a scenario were 1010 homes were already present.

4.1 Comparison with other studies

Of the four existing empirical studies that investigate the relationship between fire suppression costs and housing, three studies found similar patterns and one study disagrees with our findings. Liang et al. (2008) 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) 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. 2008 found that an optimal set of explanatory variables for explaining daily fire suppression costs included the number of threatened homes, size of fire, rate of spread, and the difficulty of terrain.

Donovan et al. 2008 failed to find a relationship between housing and fire suppression cost. Donovan et al. 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). In addition, Donovan et al. acknowledge that the sample may not have contained any fires that did not threaten homes, which may have made it impossible to detect an effect of homes on fire suppression costs.

Importantly, this paper investigates wildfires in a way that the other published studies did not. Liang et al. (2008), Gebert et al. (2007), and Donovan et al. (2008) examined cumulative costs per fire, rather than daily costs. Analyzing costs at the daily level allowed us to retain information that would have been lost had we aggregated response and predictor values. 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. 2008 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.

4.3 Policy Review and Implications

Existing federal and state wildfire policies have focused more on improving fuels management rather than on patterns of home development (Stephens and Ruth 2005; Gude et al. 2007). The major wildland fire policies since 2000 have been the National Fire Policy established in 2001 and designed to be a long-term, multibillion dollar effort at hazardous fuels reduction (GAO 2003), and the Healthy Forests Initiative and Healthy Forests Restoration Act, introduced in 2002 and 2003 respectively, aimed at shortening administrative and public review by limiting appeals processes. With few exceptions, state policies addressing the wildland urban interface have not been regulatory, and 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. In some cases, these measures are prohibitively expensive. For example, markets for the products of thinning activities are limited. A comprehensive economic 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, sheltering-in-place can result in loss of life, and puts an additional burden on firefighters of having to protect not only structures, but lives.

In light of mounting evidence that increases in housing lead to increases in fire suppression costs, future policies aimed at addressing the rising costs should attempt to either reduce or cover the additional costs due to future home development. 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 aim to keep undeveloped land undeveloped and encourage new development within existing urban growth boundaries and existing subdivisions. However, 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.

For several reasons, future policies will likely need to focus on covering the additional suppression costs related to new housing. First, both federal and state agencies have had difficulty budgeting for fire suppression in the past, and these challenges will worsen when there are more homes to protect. Second, as costs rise, the public may become dissatisfied with the existing arrangement in which the general taxpayer covers the costs of protecting at-risk homes. Third, finding a more equitable means of covering fire suppression costs may change behavior and lead to lower future costs. For example, if wildfire 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, development rates in high risk areas may slow.

This study, which quantifies the recent effect of homes on firefighting costs for one part of the US West, demonstrates that policy makers can achieve future fire suppression cost savings by focusing attention on development patterns. The study demonstrates that the largest future fire suppression savings related to housing will come from keeping undeveloped lands undeveloped. Effective management of future suppression costs would likely involve a combination of policies that regulate land use, provide incentives for limiting the "footprint" of future development, and reform how suppression costs are paid.

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