*Peer reviewed and in preparation for journal submission.*

HEADWATERS
ECONOMICS

---

# Homes in Wildfire-Prone Areas:
## An Empirical Analysis of Wildfire Suppression Costs and Climate Change

Patricia H. Gude[*,A], J. Anthony Cookson[B], Mark C. Greenwood[C], Mark Haggerty[A]

[*] Corresponding author's contact information:
Telephone: (406)599-7425; Email address: patty@headwaterseconomics.org

[A]Headwaters Economics, 810 N Wallace Avenue, Suite D, Bozeman, MT 59715
[B]Univ. of Chicago, Dept. of Economics, 1126 E. 59th St., Chicago, IL 60637
[C]Montana State Univ., Dept. of Mathematical Sciences, PO Box 172400, Bozeman, MT 59717

## Abstract

This paper empirically estimates the budgetary cost of wildfire suppression and assesses how development in wildfire-prone areas and climate change may affect future suppression costs. Given reasonable assumptions for development and warming trends, our statistical model predicts expenses devoted to protecting homes from wildfires in Montana will more than double by 2025. Our analysis uses daily data from 18 large wildfires that burned during 2006 and 2007. Using a mixed models framework, we select an optimal set of explanatory variables, including the number of threatened homes, size of fire, rate of spread, and the difficulty of terrain, from a broad initial list of potential explanations for wildfire suppression cost. We estimate that for the average duration fire, the additional suppression cost associated with 125 homes is around $1 million. We applied our model to calculate the cost of protecting homes from wildfires from 1985 to 2007. The mean predicted cost of protecting homes is $42.5 million for the five warmest years and $1.8 million for the five coolest years. We find that a one degree increase in average spring and summer temperature is associated with a 305 percent increase in area burned, and a 107 percent increase in home protection costs. These results suggest that climate change and development in wildfire-prone areas will likely lead to a dramatic increase in wildfire suppression costs in the near future.

## Summary

Already a major budgetary concern in the U.S., the cost of fighting wildfires will increase if climate change and development trends continue. Using current cost data for Montana, this study projects that the cost of protecting homes from wildfires will double to quadruple by 2025 if current trends and policies continue.

Keywords: Wildland urban interface, Mixed models, AIC, Montana

## 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). 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). Additionally, access to environmental amenities and public lands can be a primary motivation for residential development (Rudzitis 1999, 1996; Rasker 2006; Gude et al. 2006).

While fire prone lands are being developed, the climate is warming, leading to more large fires (Westerling et al. 2006). Recent work has concluded that weather conditions associated with warmer climates, such as the droughts, high winds, and increased lightning, (Price and Rind 1994; Pollet and Omi 2002; Fried et al. 2004; Pierce et al. 2004; Westerling et al. 2006) will likely increase wildfire damage and costs. These researchers have pointed out that with more extreme weather, we may experience a decrease in the ability of fuels management to lower fire suppression costs and economic losses. Some regions are already experiencing fires, driven by drought and strong winds, that burn open forests, conventionally viewed as relatively fire resistant, and closed forests alike (Whitlock 2004).

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] 2007) In fact, 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 (Office of Inspector General [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, and narrow roads. These common characteristics of WUI homes can create dangerous situations for firefighters. In the five-year period from 2002 to 2006, $6.3 billion in federal funds were spent fighting wildfires (NIFC 2007) and 92 people were killed during wildland fire operations (National Wildfire Coordinating Group Safety and Health Working Team 2007); but despite the firefighting efforts, 10,159 homes were lost to wildfires during this period (NIFC 2007).

Recent wildfire suppression has been costly, but our estimates suggest that the magnitude of these costs may increase significantly. Currently, only 14 percent of the available wildland interface in the western United States is currently developed (Gude et al. 2008). More development in these sensitive areas would lead to more wildfire suppression costs, even in the absence of climate change. Climate change will only exacerbate this effect. Nearly all climate models project warmer springs and summers 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, we can expect more homes to be threatened by these fires.

This paper uses wildfire suppression costs in Montana as a case study to estimate the relationships among housing, climate, and fire costs. Montana serves as an ideal study area because wildfire suppression issues in Montana are similar to those in other parts of the world. One of those similarities is the presence of natural amenities that attract residential development in fire prone areas. Also, decision makers in Montana have become increasingly aware of the looming budgetary concerns related to wildfires. In 2008, the cost of suppressing wildfires left the state with a $40 million budget shortfall, requiring a special legislative session to determine how to cover these costs. Montana's legislature subsequently called for a special interim committee to discuss how to avoid or cover these costs in the future. At the time, a thorough quantitative assessment of the wildfire suppression costs in the WUI was unavailable.

This research was conducted, in part, to provide policy makers with information about the extent to which housing, climate, and other factors, are related to fire suppression costs. This paper addresses three specific questions:

1. What factors have been associated with variability in fire suppression costs?
2. To what extent has housing contributed to fire suppression costs?
3. How might future suppression costs change with increased housing and warmer temperatures?

## METHODS

We conducted statistical analyses to identify the fire characteristics, including the extent of surrounding development, that were most strongly related to daily firefighting costs in 18 large fires that occurred in Montana during 2006 and 2007. We used a regression model to generate cost estimates of home protection for fire seasons dating back to 1985. We also used our best fitting model to project the cost of wildfire suppression due to new development expected in Montana by 2025 based on the state's recent rate of growth and pattern of development. We then generated alternative cost scenarios, based on the intersection of the future housing projections and past fire seasons that occurred in warm versus cool years.

### Response and Explanatory Data

The sample of 18 large fires in Montana included some that burned in remote 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, and those that did not. We investigated the importance of housing relative to the other factors that may affect suppression costs, including weather, vegetation, terrain, and other human factors including road access and threatened infrastructure.

The data consisted of 294 days of information on total suppression costs and wildfire characteristics for 18 wildfires in western Montana (Figure 1). We collected the data on wildfire costs and some of the data describing fire characteristics from national databases maintained by federal and state firefighting agencies, including I-Suite Cost Reports and ICS-209 Forms. The 18 fires were selected because they met three criteria:

(1) The fire burned in either 2006 or 2007, which guaranteed the availability of daily cost data.
(2) The fire was large enough to guarantee the availability of daily Geographic Information System (GIS) data describing the fire (location, area, perimeter, etc.). These data are not consistently available for wildfires smaller than 320 acres (129.5 ha).
(3) The state of Montana contributed firefighting resources for the fire, which increased the relevance for the state of Montana legislative subcommittee that provided funding for the research.

The resulting sample did not include fires that burned exclusively in grassland or fires smaller than 320 acres (129.5 ha). The 18 fires studied were located in central and western Montana, and included: Ahorn, Black Cat, Brush Creek, Chippy Creek, Jocko Lakes, Meriwether, Novak, Pattengail, Rat Creek, Rombo Mountain, Sawmill Complex, Skyland, and W H Complex from 2007, and Derby, Gash Creek, Sand Basin, Sun Dog, and Woodchuck from 2006.

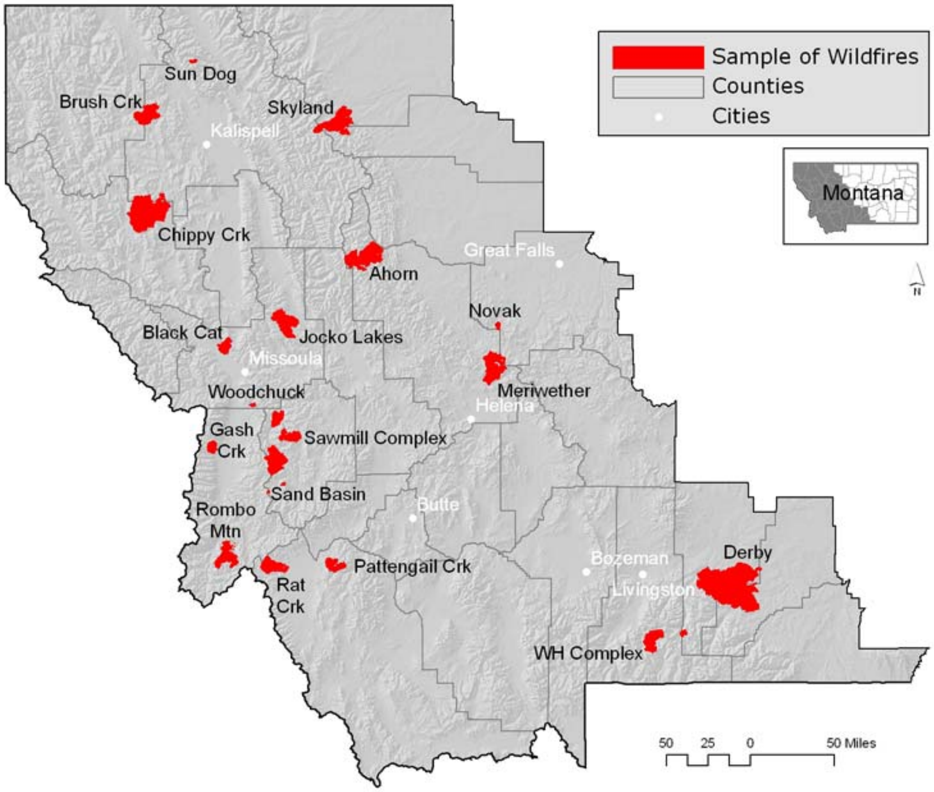

Figure 1. The locations of 18 western Montana wildfires included in this study are shown

The variables we employed in the analysis are listed in Table 1, alongside their data sources. In addition to the variables collected from fire incident reports, we compiled information from weather stations, vegetation models, and property tax databases. There were 17 housing variables, 16 of which were derived from GIS, using county tax assessor records available from the Montana Department of Revenue. For each home, the Montana Department of Revenue’s computer assisted mass appraisal database contains information about the location of the home, described in terms of the public land survey system, which delineates an approximate grid with 160 acre (64.7 ha) cells. Eight of the housing variables represented the total numbers of homes within 1 mi (1.6 km), 2 mi (3.2 km), 3 mi (4.8 km), …, 8 mi (12.9 km) of each fire perimeter, on each day that the fire burned. The next eight housing variables represented the total area of developed land within those same distances, per fire day. The last housing variable was an estimate of the number of homes at risk as reported by fire crews in the daily paperwork for each fire.

Table 1. Data collected for each day of firefighting for each of the 18 wildfires studied.

| Data | Source |
|---|---|
| Total Daily Cost | ISUITE Forms |
| Size of Fire | GIS Perimeter Files |
| Rate of Spread | GIS Perimeter Files |
| Percent Contained | 209 Forms |
| Wind Speed | 209 Forms |
| Temp. taken by Fire Crews | 209 Forms |
| Temp. Weather Station at 5 pm | Nearest Weather Station |
| Temp. Weather Station 24hr Low | Nearest Weather Station |
| Temp. Weather Station 24hr High | Nearest Weather Station |
| Relative Humidity | 209 Forms |
| Fire Growth Potential | 209 Forms |
| Terrain Difficulty | 209 Forms |
| Mean Vegetation Height | LANDFIRE |
| Mean Fire Severity Rating | LANDFIRE |
| Points of Road Access | MT Dept. of Admin. |
| Length of Intersecting Roads | MT Dept. of Admin. |
| Major Infrastructure Threatened | MT Dept. of Admin. |
| Homes within 1 mi. (1.6 km) of wildfire | Tax Assessor Records |
| Homes within 2 mi. (3.2 km) of wildfire | Tax Assessor Records |
| Homes within 3 mi. (4.8 km) of wildfire | Tax Assessor Records |
| Homes within 4 mi. (6.4 km) of wildfire | Tax Assessor Records |
| Homes within 5 mi. (8.0 km) of wildfire | Tax Assessor Records |
| Homes within 6 mi. (9.7 km) of wildfire | Tax Assessor Records |
| Homes within 7 mi. (11.3 km) of wildfire | Tax Assessor Records |
| Homes within 8 mi. (12.6 km) of wildfire | Tax Assessor Records |
| Developed area within 1 mi. (1.6 km) | Tax Assessor Records |
| Developed area within 2 mi. (3.2 km) | Tax Assessor Records |
| Developed area within 3 mi. (4.8 km) | Tax Assessor Records |
| Developed area within 4 mi. (6.4 km) | Tax Assessor Records |
| Developed area within 5 mi. (8.0 km) | Tax Assessor Records |
| Developed area within 6 mi. (9.7 km) | Tax Assessor Records |
| Developed area within 7 mi. (11.3 km) | Tax Assessor Records |
| Developed area within 8 mi. (12.9 km) | Tax Assessor Records |
| Homes at Risk | 209 Forms |
| Evacutation in Progress (Y/N) | 209 Forms |

## Candidate Models

Within each wildfire, there were cases when data were missing for particular dates. Usually this was due to a lack of GIS perimeter data on individual dates when weather did not permit flying or the capture of satellite imagery for digitizing fire perimeters. This type of data is known as repeated measures or longitudinal, with the time series within each fire containing missing or unequally spaced observations, which was important in choosing the correct statistical method of analyzing the data. In order to focus the analysis on explaining the daily variation in costs within the timeline of each individual fire, the response variable for the statistical analysis was the average daily wildfire cost since the last date with available data.

We considered four models to address the non-independence in the daily observations within each fire:

(1) A linear model that does not attempt to model correlation, and therefore does not attempt to address non-independence.
(2) A mixed model with random intercepts to account for the possibility that observations within each fire have a common mean that is not explained by the explanatory variables.
(3) A linear model that fits the residual autocorrelation with a continuous autoregressive (CAR) model, thereby accounting for the possibility that observations close in time within each fire share information not explained by the explanatory variables.[1]
(4) A linear mixed model that allows for random intercepts and fits the residual autocorrelation with a CAR model.

We fit each model with the entire set of explanatory variables in R Version 2.8.1, using the gls and lme functions in R's nlme package (Pinheiro et al. 2008). Akaike's Information Criterion (AIC, Akaike 1973) provides a framework for selecting among different candidate models as suggested above, with smaller values suggesting models that are closer to the unknown, true model. Burnham and Anderson (2004) suggest a scale for comparison of AIC values with models within 2 AIC units being essentially equally supported and larger differences suggesting more clear evidence for the model with the smaller AIC. We found that the model that assumed independence performed poorly in comparison to the other models considered. The model that accounted for a CAR process in the residuals within each fire outperformed a pure random intercepts mixed model by nearly 200 AIC units. Because random intercepts did not improve on this model further based on AIC values, we selected the CAR model but did not also incorporate random intercepts. The autocorrelation function (ACF) for the CAR model showed no apparent pattern in the residuals once we incorporated the CAR structure, indicating that the CAR model adequately accounted for the correlation structure in the daily observations.

## Selection of a Model with the Best Set of Explanatory Variables

Due to the large number of combinations of the explanatory variables that could be considered, we used a stepwise procedure, stepAIC in R's MASS package (Venables and Ripley 2002), for selecting the "best" set of explanatory variables. At each step in the model selection

---

[1] Continuous Autoregressive (CAR) models are an extension of autoregressive (AR) models for residual autocorrelation. CAR models are valid for unequally spaced time series, which is the type of data we have within each fire. Pinheiro and Bates's *Mixed-effects Models in S* (2000) describes the use of CAR models in the mixed model framework. Another good discussion of AR (and the more general ARMA) models is presented in Chapter 3 of Shumway and Stoffer's *Time Series Analysis and Its Applications with R Examples* (2006).

process, the computer fit all models with one fewer predictor than the current model and all models with one additional predictor than the current model (within the set of variables considered). The model with lowest AIC was selected, and then the process was repeated. The model selection terminated when the lowest AIC model was the current model. Due to collinearity between the housing variables and to allow for ease of interpretation, we only allowed one housing variable to enter the model for any given stepwise selection. There were 17 housing variables. Therefore, we ran the stepwise process 17 separate times, selecting the top model across the different versions of the housing variables.

## Cross Validation and Weighting of Residuals

We used cross-validation (Stone 1974) to assess the predictive accuracy of the best model. Ordinarily, researchers cross validate by dropping one observation from a dataset at a time, fitting the model using the remaining observations, and using the new fitted model to predict the deleted observations. In our case, where we were modeling the dependence of observations as a time series within each fire, dropping one observation at a time would be problematic in that it would not preserve the same basic model structure. We therefore dropped all observations from a fire at the same time, fitting the model on the other 17 fires, and then computing the predicted values and prediction errors for the deleted observations in the fire that was dropped.

After computing the predicted values and prediction errors for each observation in this manner, we computed the mean squared error in these predictions (called the mean squared error of prediction, MSEP) to obtain an estimate of the prediction error. We took the square root of MSEP to generate an estimate of the standard deviation of the predictions from the model. We also computed the square root of the MSEP divided by the average daily cost for each individual fire. The square root of the MSEP divided by the average daily cost yielded a measure similar to the coefficient of variation. Calculating these metrics for each fire allowed us to assess how the model performed on different fires and learn more about the performance of our model.

The cross validation indicated that bigger fires had bigger prediction variability, suggesting that weighting the residuals as a function of the mean cost may improve the model. We therefore repeated the stepwise model selection procedure, weighting the residuals of each model, and compared AIC values of models under the weighted and unweighted regression schemes.

## Estimated Costs associated with Home Construction and Temperature

Based on the coefficient estimates from the weighted CAR model with the lowest AIC value, we extrapolated beyond our sample of 18 fires to estimate the costs associated with homes for each year from 1985 to 2007. To generate these estimates we used spatial databases of historic fire seasons available from the U.S. Forest Service and the Montana Department of Natural Resources, and GIS estimates of the extent of housing that was threatened by the wildfires each year, derived from Montana tax assessor records. For example, to generate the home protection cost estimate for 2007, we summed the acres of residential lots within one mile of large forest fires that occurred that year. We used the acreage of residential lots within one mile of fires because this was the explanatory variable identified in the weighted CAR model with the lowest AIC value. We obtained an estimate of daily cost associated with home protection, holding other explanatory variables constant, by multiplying the acreage of development by its coefficient estimate in the best model. We multiplied this estimated daily cost by 23, which was the average number of days that homes were within one mile of a fire perimeter in our sample. This use of the model coefficients amounts to a linear transformation of the area of residential development, which affects only the units on the coefficients and allows an economic interpretation. Because our sample of 18 fires did not include grassland fires or fires smaller than 320 acres (129.5 ha), we estimated costs only for large fires that burned predominantly in forest and shrubland. As a result, our estimates of annual home protection costs are conservative.

Next, we asked "What if similar fire seasons to those we have seen in recent years occurred in the future when more homes are present?" To answer this question, we used GIS to overlay maps of all the large (greater than 129.5 ha) forest fires that occurred in each year, from 1985 to 2007, over the 2025 development projection. This method followed the same steps as those used to calculate the historic cost estimates, except that the estimates were based on the extent of threatened development in 2025 rather than the extent of threatened development that was actually present during each of the past fire seasons. The housing forecast methodology is based on a continuation of recent growth rates and trends observed in Montana. It is described in detail in Gude et al. 2007.

Finally, we compared the mean estimated cost of home protection to annual fluctuations in temperature data available from the National Climatic Data Center (NCDC). For each year between 1985 and 2007 we calculated the mean monthly temperatures for April through August (NCDC 2009), averaged across the four U.S. Climate Divisions that make up western and central Montana. We used this method, adapted from Westerling et al. (2006), to characterize annual variability in spring and summer temperatures. Whereas Westerling et al. used the mean March through August temperatures to develop an index for the entire western United States, we averaged April through August temperatures because snow continues to accumulate in March throughout most of Montana (NRCS 2009).

We ranked the home protection cost estimates for each year from 1985 through 2007 by each year's average spring/summer temperature, and compared the cost estimates from: (1) the five coolest years, (2) the five warmest years, and (3) the five most recent years. We then assessed the relationship between the annual averaged April through August temperatures and wildfire variables, including the total area of large (greater than 129.5 ha) forest fires and the estimated cost of home protection per year using similar modeling techniques as those considered above. As we did for modeling the individual wildfire data, we accounted for the correlation structure in the observations, with correlation between the two responses within each year and also between years (described in detail in the supplementary materials). Both response variables, total area burned and cost of home protection, had to be log transformed in order for the relationships to be linear and the residuals to be approximately normal. Improvements based on allowing non-constant variance models also were discovered in these models. Lastly, based on the results of this model and the intersection of the 2025 housing projections with past fire seasons, we estimate how the cost of protecting homes from wildfires may respond to temperature changes in the future.

## RESULTS

### Stepwise Model Selection and Cross Validation

Eleven of the 17 stepwise model selection processes, each run with only one of the 17 possible housing variables, yielded a top model that included among the explanatory variables a housing variable. Nearly all of the selected models also had as explanatory variables: the total area of the fire, the daily rate of spread, the number of points at which roads intersected the fire perimeter, and the terrain difficulty as reported by fire crews. The frequency in which these variables were included in the selected models suggests that they are important in their association with daily fire suppression costs.

All eight models that included counts of threatened homes within varying distance of fire perimeters performed comparably (within 2 AIC units) (Table 2). These models will be referred to as Count1, Count2, Count3, ..., Count 8. With one exception, the models with housing variables representing the area of threatened residential property did not perform as well as the models with housing variables representing the counts of threatened homes (Table 2). These models will be referred to as Area1, Area2, Area3, …, Area 8. The exception was the Area1 model, which performed similarly (within 2 AIC units) to those models including counts of homes. The other model that performed comparably well included the estimate of the number of homes at risk as reported by fire crews in the daily paperwork for each fire. This variable is interesting in that it may incorporate conditions that could not be accounted for in GIS derived housing variables. It is also interesting in that the number of threatened homes as reported by fire crews likely influences the level of resources committed to suppressing the fire.

Of the 17 models resulting from the stepwise process, the Count6 model was the top ranked model. Through the cross validation process, we found that the estimated standard deviation of predictions from the model was $205,107, or just over half of the average daily cost ($394,425). After weighting the residuals, we found that the estimated standard deviation of predictions from the weighted Count6 model was $202,879, which represents a small improvement over the unweighted model.

Table 2. AIC values for the selected models when only one development variable was allowed.

| Development Variable | AIC | AIC (weighted residuals) |
|---|---|---|
| Count6 | 7520.34 | 7513.87 |
| Count8 | 7520.70 | 7514.67 |
| Count7 | 7520.84 | 7514.51 |
| Count2 | 7521.05 | 7511.36 |
| HomesAtRisk | 7521.14 | 7510.09 |
| Count4 | 7521.38 | 7514.05 |
| Area1 | 7521.38 | 7490.09 |
| Count5 | 7521.54 | 7514.36 |
| Count1 | 7521.55 | 7510.43 |
| Count3 | 7522.31 | 7513.33 |
| Area8 | 7524.71 | 7514.75 |

Using the unweighted Count6 model, each fire, with the exception of the Pattengail fire, had a smaller standard deviation of prediction estimate than its average daily cost (Table 3). Using the weighted model, the standard deviation estimate for the Pattengail fire was 2.72 times the average daily cost. The Pattengail fire was anomalous in several ways that may have contributed to the model's overestimation of daily suppression costs for that particular fire. It was the only fire over 1000 acres (404.7 ha) in our sample with no homes within 2 miles (3.2 km) of the perimeter. It was also the longest-burning fire within our sample (burning a total of 83 days, well into October) with the fewest personnel assigned to the fire (on average 50 persons per day). It is possible that this fire was a low priority given the high level of fire activity that was occurring simultaneously throughout Montana and the rest of the western U.S. during late summer in 2007.

Table 3. Estimates of the standard deviation of prediction per fire were generated by dividing the square root of the mean squared error of prediction by the average daily cost for each individual fire.

| Fire | Sqrt(MSEP)/Mean(Cost) |
|---|---|
| Sand Basin | 0.11 |
| Black Cat | 0.19 |
| Chippy Creek | 0.23 |
| Brush Creek | 0.28 |
| Meriwether | 0.28 |
| Woodchuck | 0.39 |
| Derby Fire | 0.42 |
| Jocko Lakes | 0.44 |
| Gash Creek | 0.45 |
| WH Complex | 0.51 |
| Sun Dog | 0.52 |
| Sawmill Complex | 0.54 |
| Rombo Mountain | 0.54 |
| Ahorn | 0.55 |
| Skyland | 0.71 |
| Rat Creek | 0.75 |
| Novak | 0.95 |
| Pattengail | 2.68 |

The improvement in accuracy gained by weighting the residuals suggests that the unweighted fits may have been affected by some extreme observations. Therefore, we repeated the stepwise model selection procedure, weighting the residuals of each model. For every model, weighting improved the fit (Table 2). The Area1 model had the lowest AIC after weighting. Among the count variables, the Count1 model had the lowest AIC after weighting. Both of these models resulted in slightly higher estimated standard deviation of predictions ($212,104.90 and $209,021.50 respectively) than the weighted Count6 model. This is possible since the AIC and the cross-validated MSEP estimate predictive accuracy in different ways, with cross-validation using withheld observations to measure predictive accuracy and AIC estimating prediction error using a function of the likelihood and the complexity of the model. In this paper, we provide interpretation of the explanatory variables and coefficient estimates from each of these three models to give a more complete picture of the underlying process. In the following interpretations of the model coefficients, it is important to remember that the effect of each variable is interpreted conditionally on the other variables that are included in that model.

## Interpretation of Top AIC Models for 2006-2007 Cost Data

In the Count1 and Count6 models, the response variable, daily fire suppression cost, was positively correlated with the area of the wildfire (Table 4). This explanatory variable was not included in the Area1 model, possibly due to redundancy between the area of the wildfire and the area of development within 1 mi. (1.6 km) of wildfires.

Table 4. Coefficient estimates and significance levels for models predicting the average daily wildfire suppression cost. The entries in the table are coefficient estimates from a weighted gls fit accounting for CAR(1) errors. P-values in parentheses.

| Explanatory Variable | Count1 Model | Count6 Model | Area1 Model |
|---|---|---|---|
| Homes within 1 mi. (1.6 km) of wildfire | 344.90 (0.0223) | - | - |
| Homes within 6 mi. (9.7 km) of wildfire | - | 53.92 (0.0150) | - |
| Developed area within 1 mi. (1.6 km) | - | - | 28.88 (0.0000) |
| Size of Fire | 2.24 (0.0012) | 2.65 (0.0006) | - |
| Rate of Spread | -2.40 (0.0312) | -2.65 (0.0183) | -1.02 (0.2696) |
| High Terrain Difficulty | 636.91 (0.9764) | 2744.57 (0.9011) | -13527.90 (0.4702) |
| Med. Terrain Difficulty | 125567.49 (0.0225) | 138867.36 (0.0095) | 100232.98 (0.0910) |
| Points of Road Access | 3375.97 (0.0001) | 3114.71 (0.0003) | 3827.26 (0.0000) |

In all three models, the cost was negatively related to the rate at which wildfires spread (Table 4). In other words, days in which more costs were incurred tended to be days in which fires decreased in size. In all three models, daily suppression costs were positively associated with the number of points in which roads intersected a fire perimeter. Fewer access points to the fire suggest that the fire is more remote. In general, higher densities of roads exist on private lands where development or resource extraction has taken place. The positive relationship between road access and cost may reflect that more resources are used to battle fires on land utilized for development or resource extraction than on remote public lands.

The nature of the relationship with terrain difficulty also appears to incorporate remoteness, with the higher levels of cost incurred on days when fire crews reported the terrain difficulty as medium and high, when compared to days when the fire crews reported the terrain difficulty as extreme. In all models, the cost differences between medium and extreme were much larger (at least $100,000) than the differences between high and extreme (no evidence of a difference between high and extreme costs except in the Area1 model where high difficulty was found to cost less than extreme). Across the fires in our sample, those that spread into valley bottoms and intersected with greater levels of human development were consistently reported to have medium to high terrain difficulty, and those that burned on remote or rugged mountainous landscapes were reported to have extreme terrain difficulty. Low terrain difficulty was never reported within our sample of fires.

Any measure of development pressure in the Count6, Count1, or Area1 models had a positive relationship with daily firefighting costs. For example, an additional home within one mile of a fire's perimeter is associated with a $344.90 (95% CI: 50.77 to 639.03) increase in average daily wildfire fighting cost. To put this in perspective, if one house is within one mile (1.6 km) of a fire perimeter for the entire duration of the firefighting effort (on average, approximately 38 days), this would be associated with an additional $13,106 (95% CI: $1,929 to $24,283) in wildfire firefighting cost. However, more commonly homes are only within one mile of the fire for a portion of the time the fire is burning. On average, when fires burn near homes, homes are within a mile of the fire perimeter for 23 days. Therefore, after accounting for differences in fire size, terrain, and road access, each additional home within one mile of a wildfire is associated with a $7,933 (95% CI: $1,167 to $14,697) increase in suppression costs and each additional home within six miles of a wildfire is associated with a $1,240 (95% CI: $247 to $2,233) increase in suppression costs (Figure 2). Put differently, 125 homes within one mile of a wildfire are associated with a $1 million (95% CI: $145,963 to $1,837,211) increase in fire suppression costs.

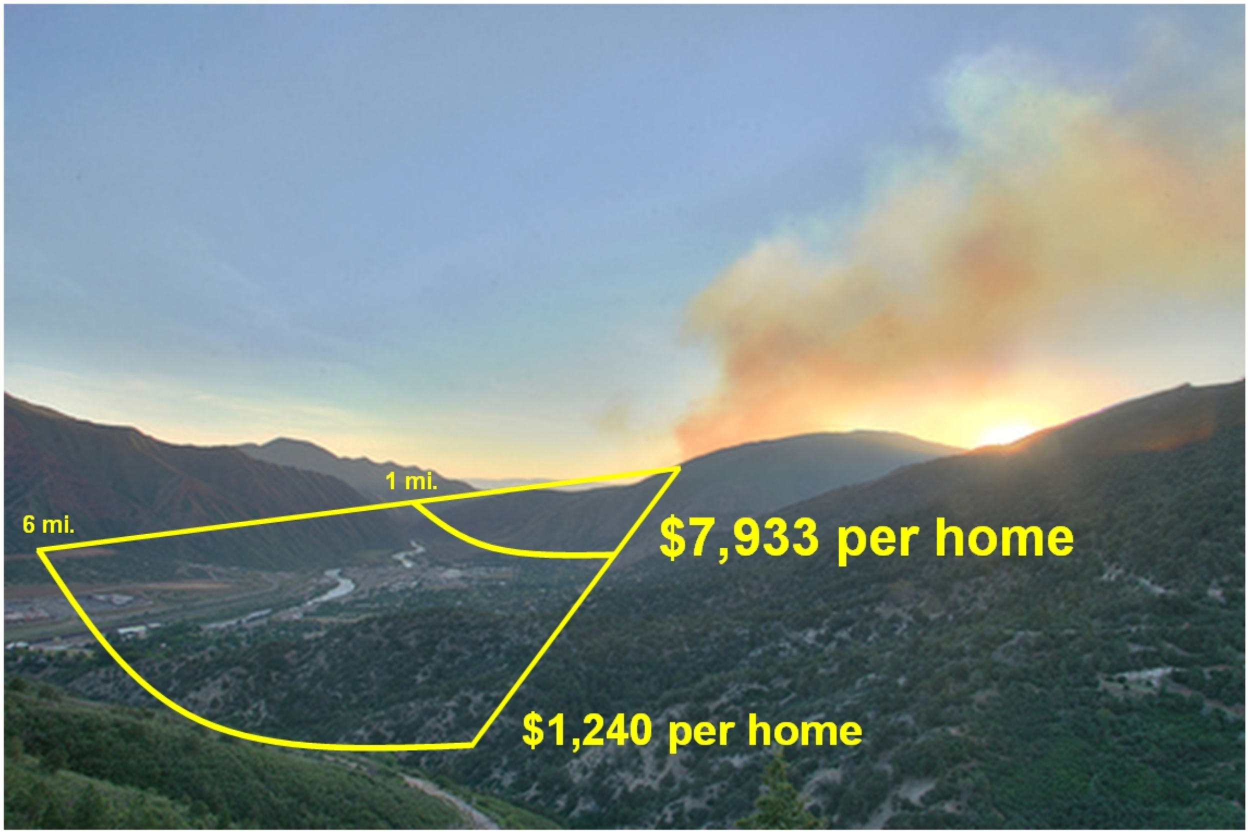

Figure 2. After accounting for differences in fire size, terrain, and road access, each additional home within one mile of a wildfire is associated with a $7,933 increase in suppression costs and each additional home within six miles is associated with a $1,240 increase.

Interestingly, the highest ranked model according to AIC values incorporated information about the area of residential lots rather than the counts of homes within one mile (1.6 km) of wildfires. We found that after accounting for differences in terrain difficulty, fire size, and road access, each additional acre of residential property within one mile of a wildfire is associated with a $664 increase (95% CI: $369 to $959) in wildfire costs (over the average duration of 23 days). The average lot size of homes that were threatened by the 18 fires in our sample was 12 acres, and if you multiply the cost per acre ($664) by 12 acres, you get $7968 (roughly the cost per home as estimated in the Count1 model, 95% CI: $4,430 to $11,512). One possible reason that the Area1 model outperformed the Count1 model is that the Count1 model is missing information about the spatial distribution of those homes. In other words, the pattern of development (dense vs. spread out) appears to be related to fire suppression costs.

We used the most parsimonious of the top ranked models (Area1) to estimate the portion of each fire's suppression costs that were related to housing. Within our sample of 18 fires, the resulting estimate of the portion of the fire suppression costs related to housing varied from 0 to 56% depending on how much development surrounded each fire (Figure 3). Estimated home protection costs made up more than 25 percent of total costs in seven of the 18 fires.

We also estimated from the Area1 model that costs related to housing exceeded $1 million for the ten fires in our sample that were greater than 2000 ac. (809 ha.) and that occurred in more densely developed areas. For these fires, which were neither remote nor small, estimated suppression costs related to housing totaled $35 million (30% of the total firefighting costs). For the 18 fires in our sample, the estimated suppression costs related to housing ranged from $0 for the Sun Dog fire to $8.4 million for the Derby fire (Figure 3).

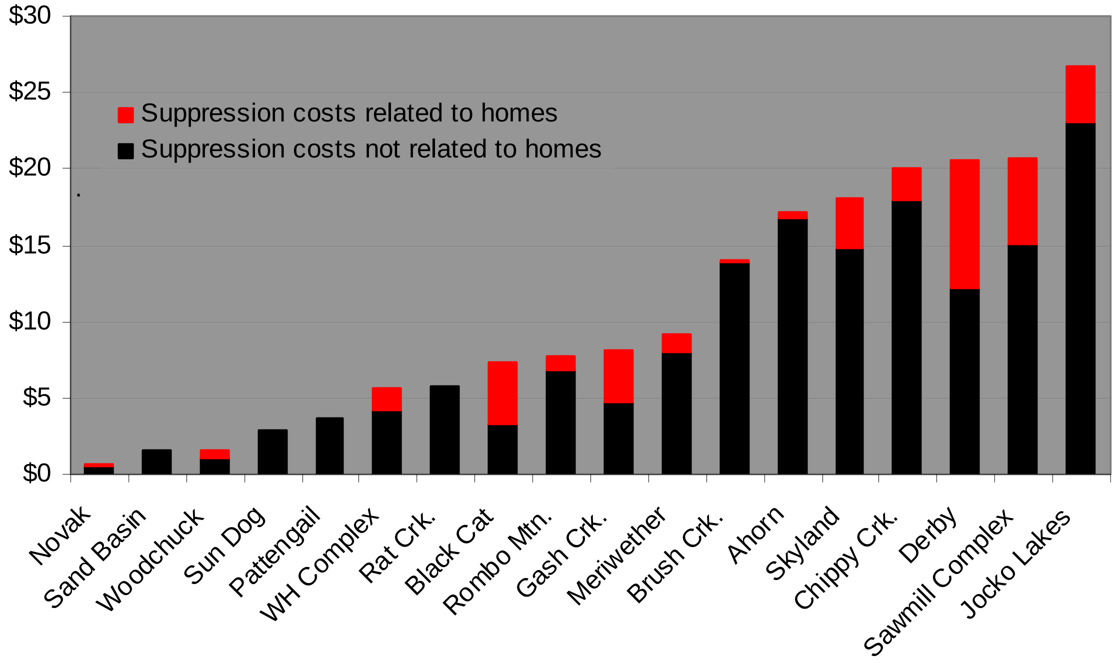

Figure 3. The estimated suppression costs related to homes ranged from 0 to 56 percent of the total suppression costs for this sample of fires.

## Implications of the Model beyond Our Sample

We used the coefficient estimates from the Area1 model to predict beyond our sample the component of firefighting costs associated with housing for each year from 1985 to 2007 (Figure 4). To stay within the range of conditions present in our sample, we estimated costs only for fires greater than 320 acres (130 ha) that burned predominantly in forest and shrubland. The estimated costs of home protection ranged from $106,000 in 1997, a year in which only 661 acres (261 ha) burned, to $71 million in 2000, a year in which 723,092 ac (292,625 ha) burned. Five of the past 23 years (1988, 2000, 2003, 2006 and 2007) stand out as having exceptionally high costs related to home protection.

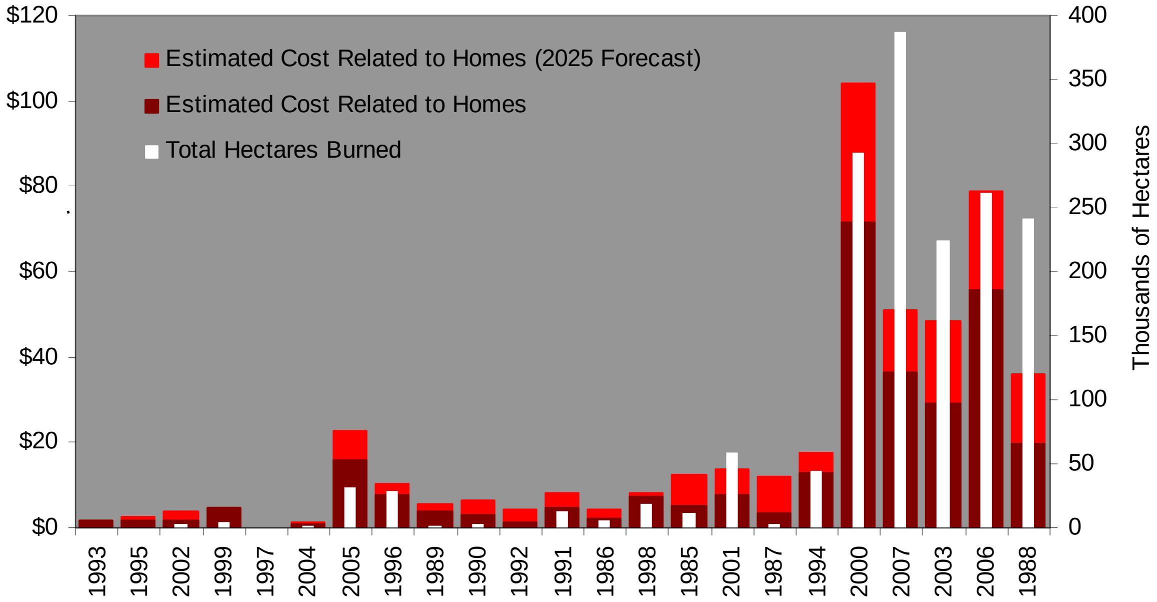

Figure 4. Since 1985, five years (1988, 2000, 2003, 2006 and 2007) stand out as having exceptionally high estimated costs related to home protection.

The locations of wildfires relative to housing vary from year to year, and, consequently, so do the suppression costs associated with home protection. Although years with many large fires tend to result in high costs related to home protection, the highest estimated expenditure on home protection in the past decade occurred in 2000. This was the year in which the most residential land was threatened, but not the biggest fire year in terms of total area burned. The years 2006 and 2007 are also interesting to compare since, in total, more acres burned in Montana in 2007, yet the estimated cost related to protecting homes near the 2007 fires was less (Figure 4). One explanation for this is related to the development pattern in the areas surrounding the fires. In 2006, forest fires burned in areas with more housing. In 2007, there were more forest fires, but many of those fires burned in remote areas.

We estimate the total suppression cost related housing to be $92.2 million for large fires in Montana during the 2006 and 2007 fire seasons. Although we do not have sufficient data to estimate the portion paid by the state of Montana, we do know that in our sample of 18 fires, the state of Montana paid approximately 25 percent of the total fire suppression costs in those fires where more than 1,000 acres (404.6 ha) of residential land were within one mile of the fire (personal communication, Matt Hedrick, MT DNRC, July 31, 2008). Based on this figure, we estimate that Montana paid \$13.9 million in 2006 and \$9.1 million in 2007 on home protection. Most of the remainder was paid by federal agencies, including the Federal Emergency Management Agency (FEMA). These estimates of Montana's share of home protection costs are likely conservative because most homes in the interface occur where the state and local governments are responsible for providing wildfire protection. Montana may pay 25 percent of the total firefighting costs, but a larger share of the cost related to home protection. What's more, as the development in fire prone areas continues, it is likely that state and local government will pay an increasing share of the costs related to home protection (personal communication, Bob Harrington, MT DNRC, August 6, 2008).

## The Relationship between Suppression Costs, Future Housing, and Temperature

When we overlapped past fire seasons with the 2025 housing forecast (Gude et al. 2007), we found that average home protection costs from 1985 to 2007 would have been 72 percent higher had the additional homes from the 2025 forecast been present (Figure 4). For example, we found that the 2025 development forecast resulted in an additional 35 thousand acres of residential land occurring within one mile of the 2006 fires. Had these additional homes been present in 2006, firefighting costs related to home protection would have been roughly \$23 million higher, totaling \$78.9 million[2] (a 41 percent increase).

When we ranked years by their average spring/summer temperature, the five coolest years (1993, 1995, 1997, 1999, and 2002) had a mean average April-August temperature of 54.8˚F (12.6˚C) (Table 5). The average estimated cost of protecting homes from wildfires that occurred during these years was \$1.9 million (\$1.6 million median). By comparison, the average estimated cost of protecting homes from the wildfires that occurred during the five warmest years (1988, 2000, 2003, 2006, and 2007) was \$42.5 million (\$36.2 million median). During these five years, the mean average spring/summer temperature was 58.7˚F (14.8˚C). During the five most recent years in our sample (2003 through 2007), the mean average April-August temperature was 57.5˚F (14.2˚C), and the average estimated cost of protecting homes from the wildfires was \$27.6 million (\$29.1 million median).

Table 5. Each year from 1985 through 2007 was ranked by its average spring/summer temperature. Estimates are given for the cost of home protection during the five coolest, warmest, and most recent years. Estimates of how home protection costs may change if similar fire seasons occur in 2025 are also presented.

| | Average April-Aug. Temp. | Average Estimated Cost of Protecting Homes from Wildfires |
|---|---|---|
| Five Coolest Years | 54.8 | \$1.8 Million |
| Five Warmest Years | 58.7 | \$42.5 Million |
| Five Most Recent Years | 57.5 | \$27.6 Million |
| Five Most Recent Years + 2025 Housing | 57.5 | \$40.4 Million |
| Five Most Recent Years + 2025 Housing + 1°F | 58.5 | \$83.6 Million |

---

[2] In 2025 dollars, this figure adjusted for inflation using the Congressional Budget Office's inflation projections is \$124.0 million. This figure is a rough estimate since future inflation rates are unknown.

In the model relating the bivariate fire times series to average spring/summer temperatures, we found evidence (using a similar approach to the previous model building) to support a model that includes a relationship between the log-area and log-dollars responses and temperature after accounting for the bivariate-AR(1) correlation structure and non-constant variance. Diagnostics showed no apparent violations of model assumptions  We found that a one degree increase in average spring/summer temperature is associated with a 305 percent increase in hectares burned (95% CI: 164 percent to 523 percent), and a 107 percent increase in home protection costs (95% CI: 52 percent to 180 percent). These results are interpreted as percentage increases since the models were fit using a log-transformation, making the results on the original scale nonlinear as can be seen in Figure 5.

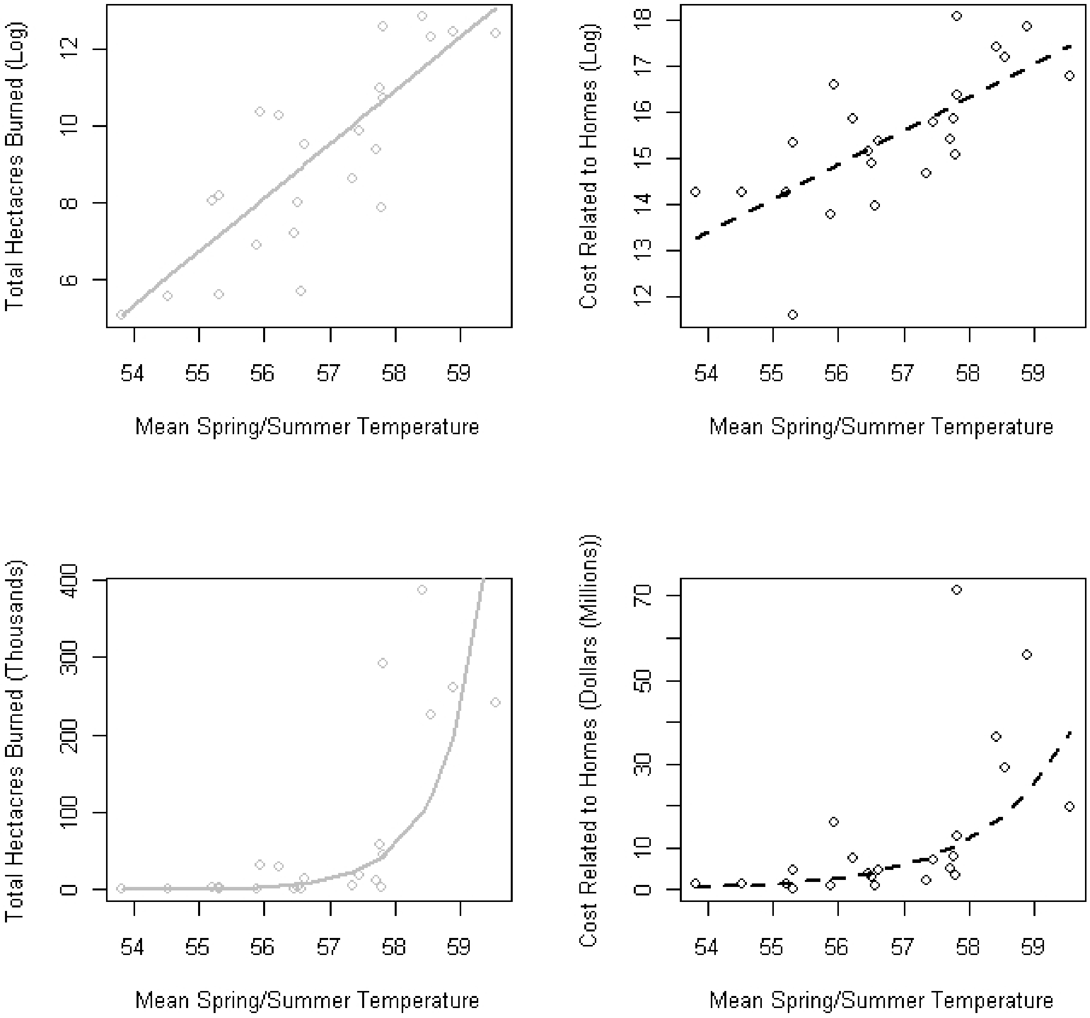

Figure 5.  The natural logs and raw data of total area burned and estimated home protection costs are plotted against mean March through August temperatures for each year from 1985 to 2007.

Based on the intersection of the 2025 housing projections with past fire seasons, we estimated that, had the projected homes been present during the fire seasons that occurred during the past five years, the cost of home protection would have been 46 percent higher ($40.4 million) (Table 5). According to the Intergovernmental Panel on Climate Change's more conservative scenarios (SRES A1B and B1), Montana may experience an approximate one degree Fahrenheit (0.55 degree Celsius) increase in temperature by 2025 (Intergovernmental Panel on Climate Change 2001). If, in addition to the projected homes, the average spring and summer temperature increased by one degree, our regression model suggests that home protection costs could grow by another 52 to 180 percent ($61.4 million to $113.2 million).

## DISCUSSION

Through quantifying the additional wildfire suppression cost associated with housing, our research informs policymakers on the consequences of residential development in wildfire prone areas. The local determinants of wildfire suppression cost, such as terrain difficulty, cannot be managed once a wildfire has begun to burn. Nevertheless, our analysis suggests that long-term policies restricting development in the wildland-urban interface and addressing climate change can significantly reduce the budgetary cost of wildfire suppression.

We find that when large forest fires burn near homes, costs related to housing exceed $1 million per fire, on average. Importantly, we find that, in addition to the number of homes that firefighters have to protect, the pattern of development (dense versus spread out) is strongly associated with suppression costs. For example, one dense subdivision is less costly to protect than the same number of homes spread across a large area of land. In fact, we found that as few as 100 threatened homes, if distributed on 160 acre (64.7 ha) lots, could result in a $10 million increase in suppression costs in a single year. In the Western United States, the wildland interface is less densely developed than other private lands (Gude et al. 2007). We find that dispersed housing spread across large areas of fire-prone forest costs more to protect than similar numbers of homes in a more concentrated development pattern.

We also found that for all agencies involved in fire suppression in Montana, the estimated average annual costs related to home protection during 2003 through 2007 was approximately $28 million. If current development trends continue, similar fires seasons could cost $13 million more by 2025, bringing total fire suppression costs associated with homes to $40 million dollars. If, in addition to increased housing in fire prone areas, average spring and summer temperatures increased by one degree, home protection costs in Montana would likely grow to between $61 million and $113 million annually, a two to four fold increase in costs.

Although federal agencies, such as the Forest Service, Bureau of Land Management, and Federal Emergency Management Agency, cover the bulk of wildfire suppression costs, the state of Montana covers a meaningful portion of the costs, conservatively, one quarter of the total cost of protecting homes from wildfires. Using this figure, we estimate Montana's annual share of home protection costs to be between $15 million and $28 million by 2025. This range of home protection costs exceeds the state of Montana's total fire suppression costs in the majority of recent years.

Montana does not budget for wildfire suppression costs on an annual basis (Montana Legislative Fiscal Division 2008). As a result, the Department of Natural Resources and Conservation is forced to pay suppression costs by spending funds appropriated for other purposes, seeking disaster funds from the Governor, or taking a loan from the state's general fund. Fire suppression costs are typically reimbursed from the General Fund at the end of the fiscal year, but this requires that the General Fund have a positive ending balance. In case of a shortfall, a special session of the legislature must be convened (as in September 2008) to make appropriations to cover costs. As costs increase in the future, and state budgets are stressed during recessions, Montana's current budgeting system will become more untenable. If the state is forced to make annual appropriations for tens of millions of dollars, funding will be cut from other programs unless new revenue is generated to cover fire suppression costs.

For context, it is instructive to point out that the projected fire suppression cost associated with housing development and climate change, even at the lower end of the range ($15 million), is greater than the Montana Department of Agriculture's entire budget, and exceeds the state's annual contributions to such programs as child support enforcement, the department of military affairs, the library commission, and the department of environmental quality.

## Policy Review and Implications

Existing federal and state wildfire policies have focused on improving fuels management (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, particularly in the wildland urban interface, is unknown. In many cases, these measures are prohibitively expensive. For example, markets for the products of thinning activities are limited. A comprehensive economic analysis is needed that evaluates whether investments in fuels treatments reduce firefighting costs.

It is possible that fuels management in the WUI has little impact on firefighting costs, or even increases costs by sending the message that homes can be built safely in fire prone areas. 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, as was recently seen in Australia's Victorian bushfires in which more than 200 people lost their lives. This also puts an additional burden on firefighters of having to protect not only structures, but lives.

In the United States, state policy makers have responded to growing WUI concerns by encouraging local government to act. For example, the majority of western states have enacted legislation that either encourages counties to prepare plans that would reduce wildfire problems or clarifies that counties can legally deny subdivisions that do not mitigate or avoid threats to public health and safety from wildland fire. However, there is little incentive for local governments to act. Although local governments may approve new subdivisions in high wildfire risk areas, they pay little of the cost of protecting those homes from forest fires. And, most county commissions ultimately control whether or not local ordinances pass. Even in cases where state laws allow for citizen initiated zoning, the county commissions vote whether or not to pass each resolution.

Policymakers have not enacted laws that would ensure land use patterns that are more efficient to defend when fires inevitably burn. No federal or state laws require that counties regulate housing densities in high wildfire risk areas. This is not surprising since, in much of the rural United States, zoning is controversial due to its perception as a regulatory taking, where the government effectively takes private property when zoning laws limit how it can be used. Despite this general opposition to zoning on a state level, state-wide "zoning" already exists in many forms, including statewide building codes and subdivisions regulations.

An alternative policy would be to reform who pays the costs of protecting homes from wildfires. Currently the costs of the firefighting efforts are not borne by those who build at-risk homes, or by local governments who permit them. One solution that would dramatically change land development patterns in fire prone landscapes is to shift the cost burden, or at least a substantial portion of it, from the taxpayers and federal land managers to states, counties, and/or home owners.

In any scenario, wildland fire policies across all levels of government will need to be reformed and coupled with strong national and international climate policies to effectively address the growing cost of protecting homes. With this study, we hope to refocus the attention of policy makers and communities on the ramifications of current growth trends, and set the stage for discussion about the need for a course correction to keep homes and firefighters safe and firefighting costs in check.

## Acknowledgements

Funding for this research was made possible by the Montana Legislative Fire Suppression Interim Committee, LaSalle Adams Fund, and the Wilburforce Foundation. We are also indebted to staff at the Montana Department of Natural Resources, including Lowell Whitney, Matt Hedrick, Ted Mead, and Bob Harrington. The authors would also like to thank Dr. Steve Running, who reviewed the paper and provided valuable comments. We express gratitude to wildland firefighters. We owe them a debt far beyond the cost in dollars.

## References

Akaike, H. 1973. Maximum likelihood identification of Gaussian autoregressive moving average models. *Biometrika* **60**:255-265.

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.

Burnham, K. P., and D. R. Anderson. 2004. Multimodel Inference: Understanding AIC and BIC in Model Selection. *Sociological Methods and Research* **33**(2): 261-304.

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.

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.

Fried, J.S., M.S. Torn, and E. Mills. 2004. The impact of climate change on wildfire severity: a regional forecast for northern California. *Climate Change* **64**(1-2):169-191.

GAO (U.S. General Accounting Office). 2003. *Forest service fuels reduction*. Rep. GAO-03-689R.

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., 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.

Hammer, R.B., S.I. Stewart, R.L. Winkler, V.C. Radeloff, AND P.R. Voss. 2004. Characterizing dynamic spatial and temporal residential density patterns from 1940–1990 across the north central United States. *Landscape and Urban Planning* **69**(2–3):183–199.

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.

Montana Legislative Fiscal Division. 2008. *Focus on Wildfire Suppression Funding*. Fiscal Pocket Guide.

Moss A.G. L. 2006. The amenity migrants: ecological challenge to contemporary Shangri-La. The Amenity Migrants: Seeking and Sustaining Mountains and Their Cultures. Cromwell Press, Trowbridge. 1-25

NCDC (US Department of Commerce, National Climatic Data Center). 2009. Time Biased Corrected state climatic division monthly average temperatures. Available online at http://www1.ncdc.noaa.gov/pub/data/cirs/drd964x.tmp.txt; last accessed Mar. 2, 2009.

NIFC (National Interagency Fire Center). 2007. *Wildland fire statistics*. Available online at http://www.nifc.gov/fire_info/fire_stats.htm; last accessed Mar. 2, 2009.

NRCS (US Department of Agriculture, Natural Resources Conservation Service). 2009. *Montana SNOTEL Snow Water Equivalent Averages: 1971-2002*. Available online at http://www3.wcc.nrcs.usda.gov/nwcc/sweavg.jsp?state=MT; last accessed Mar. 2, 2009.

NWCG (National Wildfire Coordinating Group Safety & Health Working Team). 2007. *Safety Gram: Fatalities, Entrapments and Serious Accident Summaries for 2002-2006.* Available online at http://www.wildfirelessons.net; last accessed Mar. 2, 2009.

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

Otera, A., Gallego, E. amd Lonac A. 2008. Amenity migration: a challenge for better understanding of gateway communities and national parks to conserve common pool resources: a case study of San Martin de los andes and Lanin National Park, Argentina. Proceedings of Understanding and Managing Amenity-led Migration in Mountain Regions. May 15-19. The Banff Centre. Banff, Alberta, Canada.

Otera, A., Kakayama L, Marioni S., Gallego E., Lonac A., Dimitiu A., Gonzalez R., and Hosid C. 2006. Amenity Migration in the Patagonia Mountain community of San Martin de los Andes, Neuguen, Argentina.

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 Alps. The Amenity Migrants:

Pierce, J.L., G.A. Meyer, A.J. Jull. 2004. Fire-induced erosion and millennial-scale climate change in northern ponderosa pine forests. *Nature* **432**(7013):87-90.

Pinheiro, J.C., D.M. Bates, S. DebRoy, D. Sarkar, and the R Core Team. 2008. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-89.

Pinheiro, J.C. and D.M. Bates. 2000. "Mixed-effects Models in S and S-PLUS." New York: Springer.

Pollet, J., and P.N. Omi. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire* **11**(1):1–10.

Price, C., and D. Rind. 1994. The impact of a 2 × CO2 climate on lightning-caused fires. *Climate* **7**(10):1484–1494.

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.

Ramsey, F.L. and D.W. Schafer. 2002. "The Statistical Sleuth: A Course in Methods of Data Analysis". Second Edition. Belmont, CA: Duxbury Press.

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

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

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

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.

Shumway, R.H. and D.S. Stoffer. 2006. "Time Series Analysis and Its Applications: with R Examples". Second Edition. New York: Springer.

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

Stone, M. 1974. Cross-Validatory Choice and Assessment of Statistical Predictions. *Journal of the Royal Statistical Society* **B36**(2):111-147.

Theobald, D.M., J.M. Miller and N.T. Hobbs. 1997. Estimating the cumulative effects of development on wildlife habitat. *Landscape and Urban Planning* **39**(1):25–36.

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

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.

Whitlock, C. 2004. Forest, fires, and climate. *Nature* **432**:28-29.

Venables, W.N. and B.D. Ripley. 2002. Modern Applied Statistics with S. Fourth Edition. New York: Springer.