

## Factors influencing large wildland fire suppression expenditures

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**Abstract.** There is an urgent and immediate need to address the excessive cost of large fires. Here, we studied large wildland fire suppression expenditures by the US Department of Agriculture Forest Service. Among 16 potential non-managerial factors, which represented fire size and shape, private properties, public land attributes, forest and fuel conditions, and geographic settings, we found only fire size and private land had a strong effect on suppression expenditures. When both were accounted for, all the other variables had no significant effect. A parsimonious model to predict suppression expenditures was suggested, in which fire size and private land explained 58% of variation in expenditures. Other things being equal, suppression expenditures monotonically increased with fire size. For the average fire size, expenditures first increased with the percentage of private land within burned area, but as the percentage exceeded 20%, expenditures slowly declined until they stabilised when private land reached 50% of burned area. The results suggested that efforts to contain federal suppression expenditures need to focus on the highly complex, politically sensitive topic of wildfires on private land.

**Additional keywords:** cost containment, fire economics, geostatistics, hierarchical partitioning, hypothesis test.

### Introduction

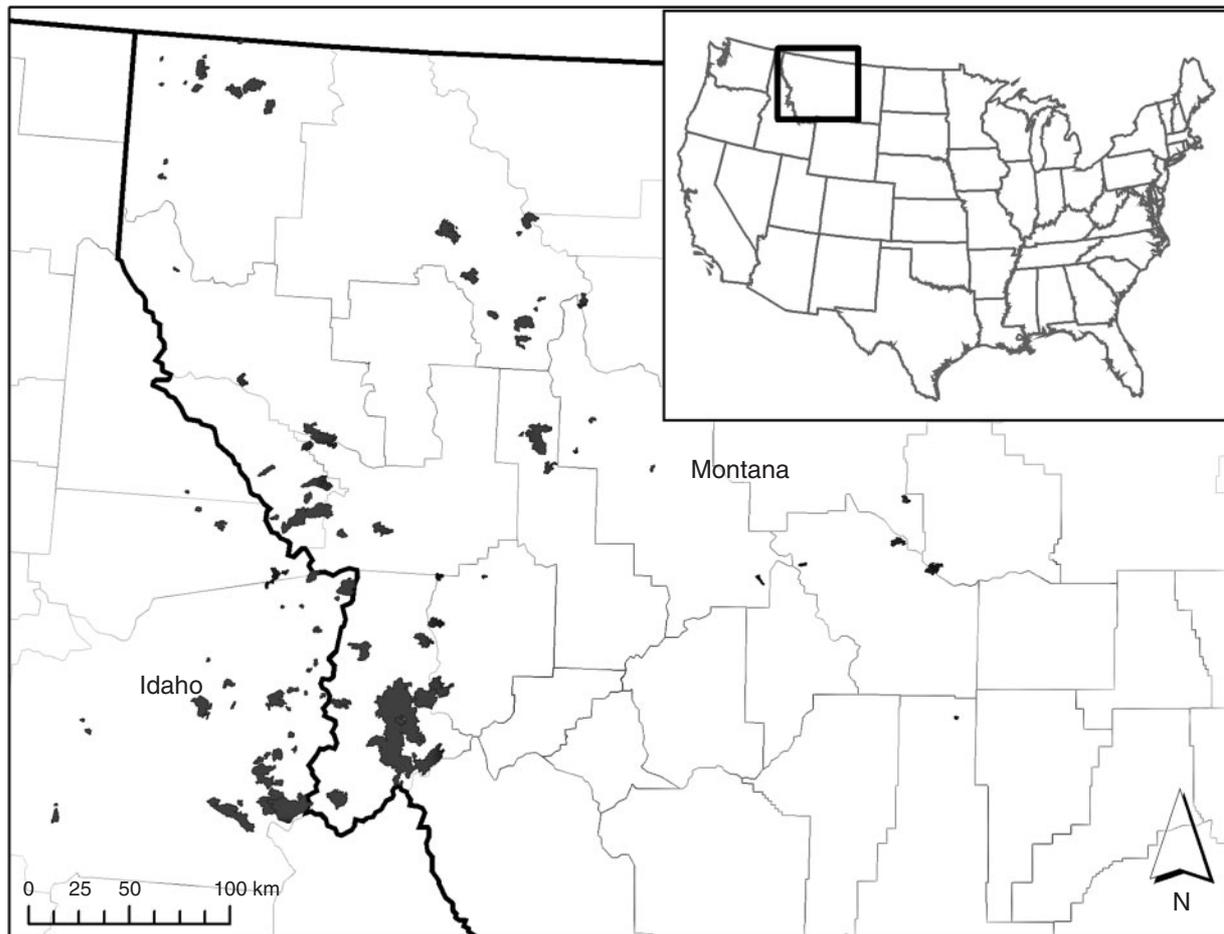
There is an urgent and immediate need to address the excessive cost of large fires. The United States' federal expenditures on wildfire suppression have dramatically increased in recent years. Since the new millennium, the federal government has spent on average over US\$1 billion per year on suppression, while its annual expenditures from 1970 to 2000 averaged below US\$400 million (all expenditures in 2005 US dollars). As suppression expenditures come to represent a higher portion of federal land management agencies' flat budgets, less money will be available for other management responsibilities. The recent extreme fire seasons and associated high costs have brought about intense public concern for reform of federal firefighting strategies and policy (Calkin *et al.* 2005).

Despite the urgent need to address the factors influencing suppression expenditures, previous studies were limited. Gonzalez-Caban (1984) pioneered fire suppression expenditures study by addressing costs of mopping up wildfires with data collected from a questionnaire. Donovan *et al.* (2004) attempted to identify factors that influenced suppression expenditures in Oregon and Washington. Their regression analysis of 58 fires from 2002 ranging in size from 10 to 20 000 ha showed that only fire size and extreme terrain conditions are significant. Gebert *et al.* (2007)

compiled a much larger dataset of US Department of Agriculture (USDA) Forest Service fires in the western United States (Forest Service Regions 1 through 6). They estimated a predictive suppression expenditures model and discovered, among other things, that higher home value within 32 km of a fire ignition increases total fire cost. However, the absence of fire perimeter records made their results susceptible to spatial errors.

It is appropriate for a study of federal fire suppression to focus on Forest Service expenditures on large fires. According to the Office of Inspector General (OIG) of USDA, the Forest Service is 'a major partner in the Federal wildland fire management community', and 'currently controls nearly two-thirds of all Federal fire management resources' (USDA OIG 2006, p. 1). Fires larger than 121 ha (300 acres), although representing only 1.4% of all wildland fires, are responsible for 93.8% of the suppression expenditures in the USA from 1980 to 2002 (USDA Forest Service *et al.* 2003).

It has been widely agreed that fire size is an obvious spatial factor in increasing suppression expenditures (Gonzalez-Caban 1984; Steele and Stier 1998; Donovan *et al.* 2004; Gebert *et al.* 2007). As fire spreads, a higher level emergency-response team is typically organised, involving more labour and resources (USDA OIG 2006), and hence increasing suppression expenditures.



**Fig. 1.** Burned areas of the 100 large wildfires shown in dark shaded units and their relative location within the United States (inset), with county and state borders. Courtesy of E. B. Butler, Forestry Sciences Lab, USDA Rocky Mountain Research Station.

Private properties might also influence suppression expenditures. The OIG report states that '50 to 95% of the cost for many large wildfire suppression operations derived directly from protecting private property' (USDA OIG 2006, p. ii), and requests congressional clarification regarding the Forest Service's role in protecting private properties. In this highly politicised environment, understanding how private properties at risk affect suppression expenditures is critical for federal agencies to address cost containment issues. Land ownership, structure value, and wildland–urban interface could all represent private properties. However, which one has the greatest influence on suppression expenditures is not yet known.

The objective of the present study was to test the effects of private properties and other non-managerial factors on suppression expenditures. Non-managerial factors were spatial explicit elements of a fire representing its size and shape, geographic settings, forest and fuel conditions, and jurisdiction of the burned area. Non-managerial factors, as opposed to managerial factors, were not subject to the attitude and experience of fire management teams. Unless otherwise stated, suppression expenditures in the current paper refer to total Forest Service suppression cost for a wildland fire.

#### Data

We investigated 100 wildfires suppressed by the Forest Service from 1996 to 2005 within the Northern Rocky Mountains. All the fires were larger than 121 ha. The high proportion of federal land and sparse population in the Northern Rockies allowed evaluation of both interface fires and more remote wilderness fires (Fig. 1). Wildland Fire Use (WFU) fires, those managed for resource benefit, were not included in this analysis.

For each of these fires, we obtained total Forest Service suppression expenditures ( $C$ ), which were costs of resources outlaid by the Forest Service in order to suppress wildland fires. The expenditures data were collected from the Forest Service accounting systems based on methods described in Gebert *et al.* (2007). The natural logarithm of suppression expenditures was studied to mitigate the influence of extremely large numbers and heteroskedasticity, as recommended by Wooldridge (2000).

We defined 17 spatially explicit variables that were most likely to influence these suppression expenditures. The variables were classified into the following groups: fire size and shape, private properties, public land attributes, forest and fuel conditions, and geographic settings (Table 1). Fire size ( $A$ ) represented

**Table 1. Definition, mean, and standard deviation (s.d.) of all variables**

Unless otherwise stated, all independent variables were obtained within the fire perimeter. UTM, Universal Transverse Mercator coordinates

Variable	Description	Unit	Mean	s.d. ( $n = 100$ )
<i>C</i>	Suppression expenditures in 2005 US dollars	ln(\$)	13.00	2.38
Fire size and shape				
<i>A</i>	Total area	ln(ha)	6.83	1.37
<i>PR</i>	Perimeter to area ratio	$10^{-3} \text{ m}^{-1}$	2.35	1.37
Private properties				
<i>P</i>	Percentage of private land	%	10.07	14.17
<i>V</i>	Total structure value (2005 US\$) within an 8-km buffer surrounding the fire perimeter	ln(\$)	11.51	6.28
<i>WUI</i>	Percentage of the wildland–urban interface area within an 8-km buffer surrounding the fire perimeter	%	5.84	8.21
Public land attributes				
<i>S</i>	Percentage of state land	%	0.94	2.11
<i>PP</i>	Percentage of public priority areas	%	0.23	0.37
Forest and fuel conditions				
<i>SA</i>	Surface-area-to-volume	$10^3 \text{ m}^{-1}$	4.84	0.37
<i>PA</i>	Packing ratio		1.53	0.40
<i>MS</i>	Moisture content	%	22.97	1.46
<i>RS</i>	Rate of spread	$\text{m h}^{-1}$	241.00	73.13
<i>FL</i>	Flame length	m	1.28	0.15
<i>FF</i>	Fine fuel load	$\text{t ha}^{-1}$	7.99	2.77
Geographic settings				
<i>SL</i>	Percentage of burned area that is less than 35% slope	%	52.43	25.29
<i>AS</i>	Percentage of burned area with a northern aspect ( $\pm 45^\circ$ from north)	%	22.75	14.64
<i>EL</i>	Average elevation of burn area	$10^3 \text{ m}$	1.69	3.39
<i>R</i>	Percentage of burned area with road access <sup>A</sup>	%	0.002	0.003
Fire central point				
<i>x</i>	Easting of UTM coordinates	$10^6 \text{ m}$	0.56	0.15
<i>y</i>	Northing of UTM coordinates	$10^6 \text{ m}$	5.19	0.11

<sup>A</sup>Any point within 12.5 m from a road was considered with road access.

the burned area within the fire perimeter. The data were obtained directly from fire history polygons in Smail (2007). For the same reason as the suppression expenditures, the natural logarithm of burned area was used. Fire shape, represented by perimeter to area ratio (*PR*), was also obtained directly from Smail (2007). In addition, we located fire central points in these polygons, and converted their graticule coordinates to Universal Transverse Mercator (UTM) coordinates (Snyder 1987), in order to detect distance-related spatial effect (Gooevaerts 1997) of suppression expenditures.

Land jurisdiction represented the percentage of land within the fire perimeter under various ownerships. Jurisdiction maps were taken from the official state websites of Montana<sup>A</sup> and Idaho<sup>B</sup>. The jurisdiction of each fire polygon was classified into three categories: private, state, and federal, all in percentage of land, and added up to 100%. Private jurisdiction (*P*) covered private, city, tribal, and non-profits land, whereas state and federal jurisdiction represented state- and federal-owned land, respectively.

Total structure value (*V*) and wildland–urban interface area (*WUI*) were measures of private development and high-valued resources. Total structure value came from the average tract-level home value multiplied by the number of structures. The average tract-level home value was taken from the official website of the US Census Bureau<sup>C</sup>, and the number of structures was obtained from cadastral data<sup>D</sup>, which represented the real property of Montana and Idaho, including the presence of residential structures. Percentage of wildland–urban interface area was obtained directly from the National wildland–urban interface (*WUI*) layers of 2000 (Radeloff *et al.* 2005). Total structure value and percentage of the wildland–urban interface area were taken within the perimeter and an 8-km buffer surrounding the final perimeter for the following reasons. First, high-valued resources threatened by a fire, but not contained within the final fire perimeter, might influence suppression effort and therefore total suppression expenditures. Second, successful fire containment lines might often be built adjacent to the location of high-valued resources.

<sup>A</sup>See <http://nris.mt.gov> (accessed 22 May 2006).<sup>B</sup>See <http://www.idwr.idaho.gov> (accessed 22 May 2006).<sup>C</sup>See <http://www.census.gov/> (accessed 29 June 2006).<sup>D</sup>Available at <http://nris.state.mt.us/nsdi/cadastral/> for Montana and <http://gis.idl.state.id.us/website/idl> for Idaho (accessed 15 August 2006).

Spatially explicit Forest Service Region One Restoration and Protection Priority Areas (*PP*; Forest Service Region One Management Team, unpubl. data), were used to identify the public resource lands of high priority including sensitive wildlife habitat, old-growth forest structure, sensitive watershed, and public land interface (Forest Service Region One Geospatial Service Group, unpubl. data).

Surface-area-to-volume (*SA*), packing ratio (*PA*), moisture content (*MS*), rate of spread (*RS*), flame length (*FL*), and fine fuel load (*FF*) represented forest and fuel conditions within fire perimeter. They were obtained from the National LAND-FIRE map (Rollins and Frame 2006), and the corresponding fire behaviour models (Scott and Burgan 2005). For simplicity, forest and fuel conditions were based on normal local weather conditions.

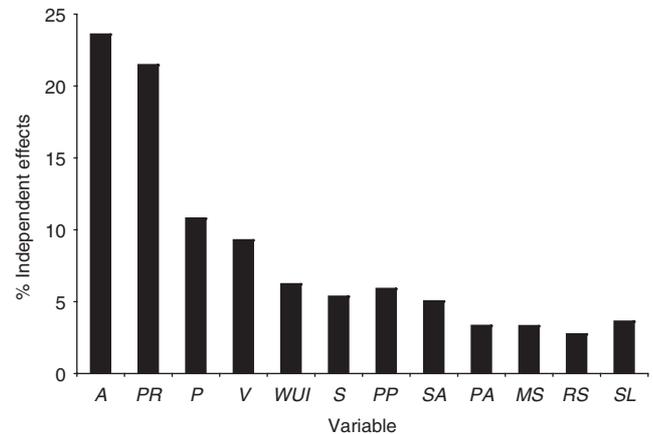
Data for slope (*SL*), aspect (*AS*), elevation (*EL*), and road access (*R*) came from the US Geological Survey (USGS) website<sup>E</sup>. *SL* represented percentage of burned area with less than 35% of slope. Most forest machines and suppression resources have difficulty operating on slopes steeper than 35%, and hence suppression may be more difficult when slope is over 35%. Extreme terrain was identified by Donovan *et al.* (2004) and Gebert *et al.* (2007) as increasing suppression cost.

## Methods

We recognised that fire size was a significant factor contributing to suppression expenditures. To identify the other important factors influencing suppression expenditures, the hierarchical partitioning (HP) method (Chevan and Sutherland 1991) was used to detect the relative importance of all the explanatory variables in terms of the contribution to the goodness-of-fit of suppression expenditures. The HP was conducted with the *hier.part* package (Mac Nally and Walsh 2004) in the R system (R Development Core Team 2006). Variables with the highest contribution were selected, and their uncontrolled effect was analysed in separate univariate regressions. Because contribution to the goodness-of-fit did not imply causality, we needed to study the effect of each factor for statistical significance and policy implications when all the other factors were controlled for.

The controlled effect of all the variables was examined with a series of tests, following three principles that assured rigour and efficiency: (1) variables selected by the HP method had testing priority, because they were most capable of explaining the variation of suppression expenditures; (2) the overall significance of a category were tested before testing the significance of single variables; and (3) if a category was not significant, all its underlying variables were discharged; otherwise, variables within a category were tested in order of increasing significance and removed one at a time, until all remaining variables were significant at the  $\alpha = 0.05$  level. A Student's *t*-test (Gosset 1908) was used to test the significance level of a single variable, and an *F*-test (Fisher 1925) was used to test the combined significance level of more than one variable.

Having identified the variables with significant controlled effect, we explored their cubic polynomials to allow for non-linearity. A parsimonious final model was obtained by removing all the insignificant terms. To check if the final model met the



**Fig. 2.** Contribution of explanatory variables to the goodness-of-fit of suppression expenditures. The goodness-of-fit was measured with the coefficient of determination,  $R^2$ . See Table 1 for definition of variables.

assumptions of Ordinary Least Squares (OLS), the normality and independence of residuals were examined.

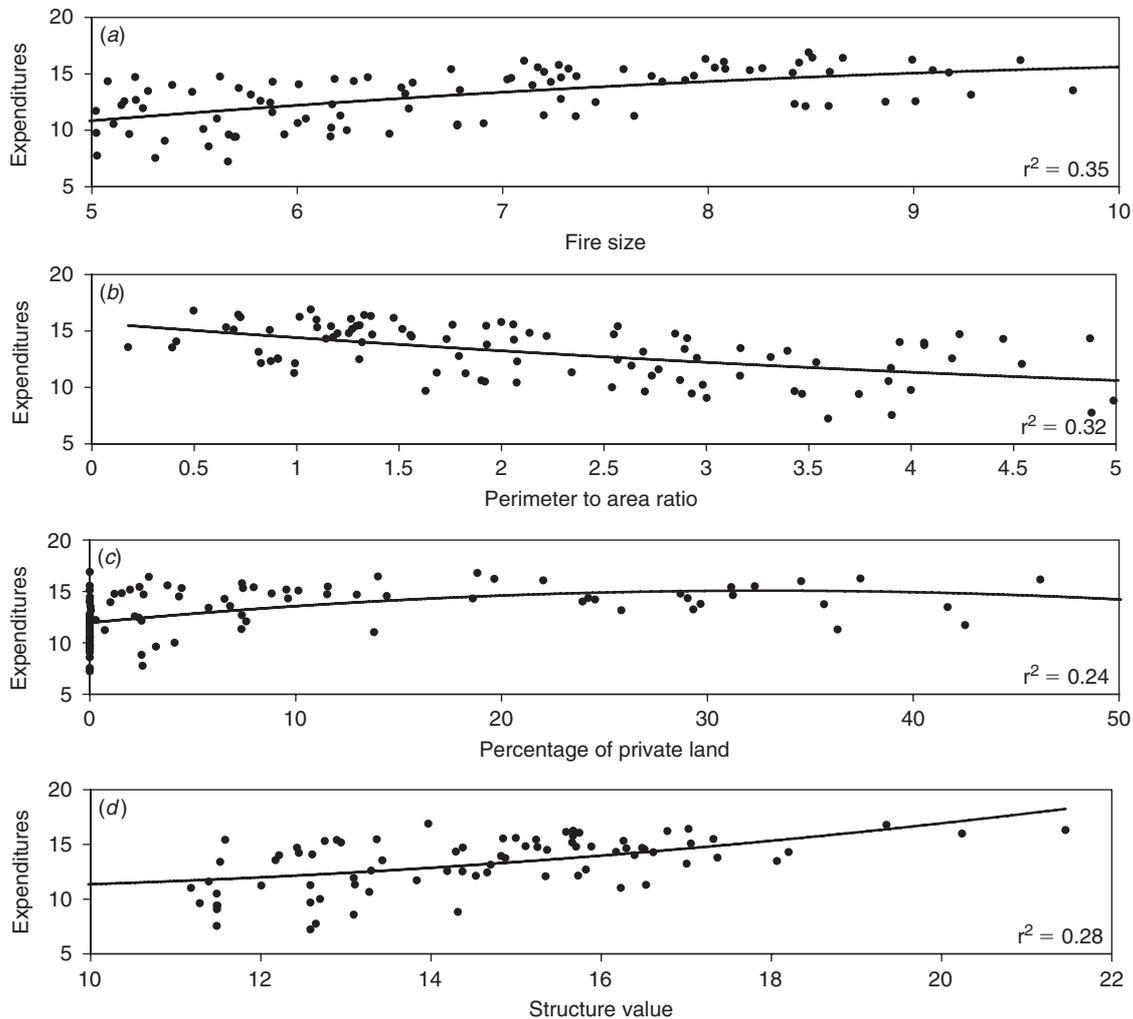
To test for spatial autocorrelation effects across fires, as well as for large-scale spatial patterns, likely caused by weather and unaccounted fuel factors, we re-estimated the final model by the Generalised Least-Squares (GLS) method with *geoR* (Ribeiro and Diggle 2004), an open-source package for geostatistical analysis to be used as an add-on to the R system. The spatial autocorrelation of residuals, if any, was assumed to be isotropic and spherical (Cressie 1993). If the semivariogram (Cressie 1993) of the residuals was not associated with distance between fires, the residuals were not spatially autocorrelated and thus our final model could be estimated by OLS. After a thorough examination of the final model, we performed a sensitivity analysis for each variable in the model to find out how suppression expenditures responded to the change in each explanatory variable, while all other variables were kept constant at their sample means.

## Results

With the HP method, we estimated fire suppression expenditures with all possible combinations of the explanatory variables, i.e. with all candidate models, and obtained the contribution of each explanatory variable to the goodness-of-fit of suppression expenditures. Compared with all the other variables, fire size (*A*), perimeter to area ratio (*PR*), percentage of private land (*P*), and total structure value (*V*) had substantially higher independent effects. These four variables contributed 65% of the goodness-of-fit, whereas the remaining 12 variables contributed only 35% in total (Fig. 2).

When analysed in separate univariate regressions, the same four variables had exclusively a strong effect on suppression expenditures ( $P < 0.01$ ). Expenditures were positively correlated with fire size (*A*) (Fig. 3a), which was consistent with previous studies. In addition, expenditures were negatively associated with perimeter to area ratio (*PR*) (Fig. 3b), and positively correlated with percentage of private land (*P*) and total structure value (*V*) (Fig. 3c, d).

<sup>E</sup>See <http://seamless.usgs.gov> (accessed 6 June 2006).



**Fig. 3.** Dependence of total fire suppression expenditures (natural logarithm in 2005 US dollars) of large fires in Forest Service Region One between years 1996 and 2005 on fire size (natural logarithm of hectares) (a); fire perimeter to area ratio ( $10^{-3} \text{ m}^{-1}$ ) (b); percentage of private land within fire perimeter (%) (c); and total structure value within 8 km of the fire perimeter (d). Curves shown were simple asymptotic functions fitted to the data (see Model 1). More complex curves did not provide significantly better fits. All curves were highly significant ( $P < 0.001$ ).

In the basic model, we recognised fire size ( $A$ ) as a significant spatial factor of suppression expenditures:

$$C = \alpha_0 + \alpha_1 A + e \tag{1}$$

where  $\alpha$  values were estimated by OLS, and  $e$  were normally distributed residuals.

The controlled effects of various spatial factors were then tested in the following hypotheses:

*Hypothesis 1*

The effect of perimeter to area ratio ( $PR$ ), given fire size ( $A$ ) was in the model, was insignificant [ $H_0^1: \beta_2 = 0 | \beta_1$ ]:

$$C = \beta_0 + \beta_1 A + \beta_2 PR + e \tag{2}$$

where  $\beta$  values were estimated by OLS, and  $e$  were normally distributed residuals.

The estimated parameters of Model 2 are summarised in Table 2. As perimeter to area ratio ( $PR$ ) was not significant at the 5% level, there was no evidence to reject  $H_0^1$ . Therefore, suppression expenditures were not decided by the fire shape, given fire size was considered.

*Hypothesis 2*

Private properties had no effect on suppression expenditures, given fire size was in the model [ $H_0^2: \gamma_2 = \gamma_3 = \gamma_4 = 0 | \gamma_1$ ]:

$$C = \gamma_0 + \gamma_1 A + \gamma_2 P + \gamma_3 V + \gamma_4 WUI + e \tag{3}$$

where  $\gamma$  values were estimated by OLS, and  $e$  were normally distributed residuals.

This hypothesis was tested with an  $F$ -test in which the residual sum of squares from Model 3 was compared with Model 1 (Table 2).  $H_0^2$  was rejected by strong evidence ( $P < 0.01$ ) from

**Table 2. Summary of regression models to predict fire suppression expenditures**

See Table 1 for definition of variables. *F*, *F*-value for statistical significance of the regression equation \*, *P* < 0.05; \*\*, *P* < 0.01, Significance level (*P*) of the overall fit; *R*<sup>2</sup>, coefficient of determination adjusted for the number of parameters

Model	Estimated right hand side of equations	<i>F</i>	<i>P</i>	<i>R</i> <sup>2</sup>
1	6.10** + 1.01** × <i>A</i>	50.03	0.00	0.33
2	9.53** + 0.66* × <i>A</i> − 0.43 × <i>PR</i>	26.88	0.00	0.34
3	5.47** + 0.94** × <i>A</i> + 0.06** × <i>P</i> + 0.04 × <i>V</i> + 0.01 <i>WUI</i>	23.86	0.00	0.48
4	5.58** + 0.99** × <i>A</i> + 0.07** × <i>P</i>	46.74	0.00	0.48
5	1.11 + 0.85** × <i>A</i> + 0.06** × <i>P</i> + 0.03 × <i>S</i> + 0.01 × <i>PP</i> + 0.42 × <i>SA</i> + 159.47 × <i>PA</i> + 0.07 × <i>MS</i> + 0.01 × <i>RS</i> − 2.21 × <i>FL</i> + 0.13 × <i>FF</i> − 1.86 × <i>SL</i> * + 0.26 × <i>AS</i> − 0.36 × <i>EL</i> + 80.90 × <i>R</i>	8.08	0.00	0.50
6	5.48** + 0.92** × <i>A</i> + 0.36** × <i>P</i> − 0.01** × <i>P</i> <sup>2</sup> + 0.001** × <i>P</i> <sup>3</sup>	34.54	0.00	0.58

the *F*-test. At least one private property variable had significant effect on suppression expenditures. As percentage of private land (*P*) was highly significant in Model 3, while total structure value (*V*) and percentage of the wildland–urban interface area (*WUI*) were not, we hypothesised that the only private properties variable that mattered was percentage of private land. The hypothesis was tested as follows.

*Hypothesis 3*

Total structure value (*V*) and percentage of the wildland–urban interface area (*WUI*) had no effect on suppression expenditures, given fire size (*A*) and percentage of private land (*P*) were in the model [*H*<sub>0</sub><sup>3</sup>:  $\gamma_3 = \gamma_4 = 0 | \gamma_1, \gamma_2$ ].

This hypothesis was tested with the *F*-test in which the residual sum of squares from Model 3 was compared with Model 4:

$$C = \zeta_0 + \zeta_1A + \zeta_2P + e \tag{4}$$

Because *H*<sub>0</sub><sup>3</sup> could not be rejected (*P* = 0.38), total structure value and percentage of the wildland-urban interface area did not matter, given fire size and percentage of private land were already in the model.

*Hypothesis 4*

Public land attributes, forest and fuel conditions, and geographic settings had no effect, given fire size (*A*) and percentage of private land (*P*) were in the model [*H*<sub>0</sub><sup>4</sup>:  $\delta_3 = \delta_4 = \dots = \delta_{14} = 0 | \delta_1, \delta_2$ ]:

$$C = \delta_0 + \delta_1A + \delta_2P + \delta_3S + \delta_4PP + \delta_5SA + \delta_6PA + \delta_7MS + \delta_8RS + \delta_9FL + \delta_{10}FF + \delta_{11}SL + \delta_{12}AS + \delta_{13}EL + \delta_{14}R + e \tag{5}$$

where the  $\delta$  values were coefficients estimated by OLS, and *e* were normally distributed residuals.

This over-sweeping hypothesis was tested with the *F*-test in which the residual sum of squares from Model 4 was compared with the one from Model 5. There was no evidence to reject *H*<sub>0</sub><sup>4</sup> (*P* = 0.29), meaning that when fire size and percentage of private land were considered, no other variables had significant effect on suppression expenditures. Slope (*SL*), although barely significant (*P* = 0.05) in Model 5, was not considered an influential factor of suppression expenditures, owing to its trivial

contribution to the overall goodness-of-fit (Fig. 2). In summary, among all the variables considered here, only fire size and percentage of private land had significant influence on suppression expenditures.

The cubic polynomials of fire size (*A*) and percentage of private land (*P*) were tested, and the final model contained the first, second, and third order of percentage of private land, and the first order of fire size. No effect of interaction terms was found in the final model:

$$C = \eta_0 + \eta_1A + \eta_2P + \eta_3P^2 + \eta_4P^3 + e \tag{6}$$

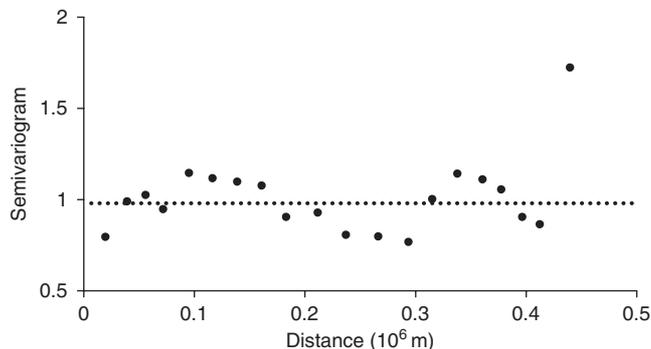
where the  $\eta$  values were coefficients estimated by OLS, and *e* were normally distributed residuals. The model was subject to little influence from multicollinearity, as fire size (*A*) and percentage of private land (*P*) were not significantly correlated (Table 3).

As the semivariogram of the final model followed a flat line (Fig. 4), the variance of the residuals was not correlated with the distance between fires. There was no evidence for the spatial autocorrelation in the residuals of the final model. The residuals had an average of 0.00 and standard deviation of 1.52 (Fig. 5a). The Anderson–Darling normality test (Stephens 1974) shows that the residuals were normally distributed (*A*<sup>2</sup> = 0.24, *P* = 0.76). The residual plot (Fig. 5b) illustrates no obvious patterns. Although we detected no effect of distance in our data, caution is advised for studies of larger scale, because the last data point in Fig. 4 shows a significant increase in semivariogram when the distance between fires approached 420 km.

From the sensitivity analysis of the final model (Fig. 6), with the average fire size (925 ha), suppression expenditures dramatically increased as the proportion of private land within the burned area increased from 0 to 20%. Suppression expenditures peaked at approximately US\$410 000 with 20% of private land. As this percentage continued to increase, suppression expenditures started to slowly decline and stabilised in the neighbourhood of US\$120 000. With the average percentage of private land within burned area (10%), suppression expenditures increased monotonically from US\$70 000 to US\$1 700 000, as fire expanded in size from 121 to 22 000 ha. The independent variables explained 58% of the variance of the dependent variable.

**Table 3. Correlation between suppression expenditures, fire size, percentage of private land, and other variables**See Table 1 for definition of variables. \*,  $P < 0.05$ ; \*\*,  $P < 0.01$  for test of significant difference of correlation from 0

	Pearson correlation and its level of significance		
	<i>C</i>	<i>A</i>	<i>P</i>
<i>A</i>	0.58**		
<i>P</i>	0.41**	0.03	
<i>PR</i>	-0.56**	-0.83**	-0.06
<i>V</i>	0.38**	0.23*	0.40**
<i>WUI</i>	0.27**	0.11	0.50**
<i>S</i>	0.24*	0.03	0.52**
<i>PP</i>	0.26*	0.10	0.16
<i>SA</i>	0.23*	0.07	0.41**
<i>PA</i>	0.11	0.14	-0.14
<i>MS</i>	0.04	0.08	-0.16
<i>RS</i>	-0.02	-0.04	0.12
<i>FL</i>	0.01	0.08	-0.23*
<i>FF</i>	-0.04	0.04	-0.31**
<i>SL</i>	-0.15	-0.02	0.08
<i>AS</i>	0.23*	0.21*	0.17
<i>EL</i>	-0.04	0.04	-0.15
<i>R</i>	0.44**	0.32**	0.24*

**Fig. 4.** Estimated semivariograms (dotted line) of the standardised residuals from the final model.

### Discussion and concluding comments

The present study represented a thorough analysis of potential factors influencing Forest Service suppression expenditures. All the data were obtained within the fire perimeter, except that structure value and percentage of the wildland–urban interface area were obtained within the fire perimeter, and within an 8-km buffer surrounding the fire perimeter, representing adjacent but unaffected resource values. A model to predict suppression expenditures was suggested. Suppression expenditures were a function of the first, second, and third order of percentage of private land, and the first order of fire size, with no interaction terms. The residuals were normally distributed, and had no spatial autocorrelation.

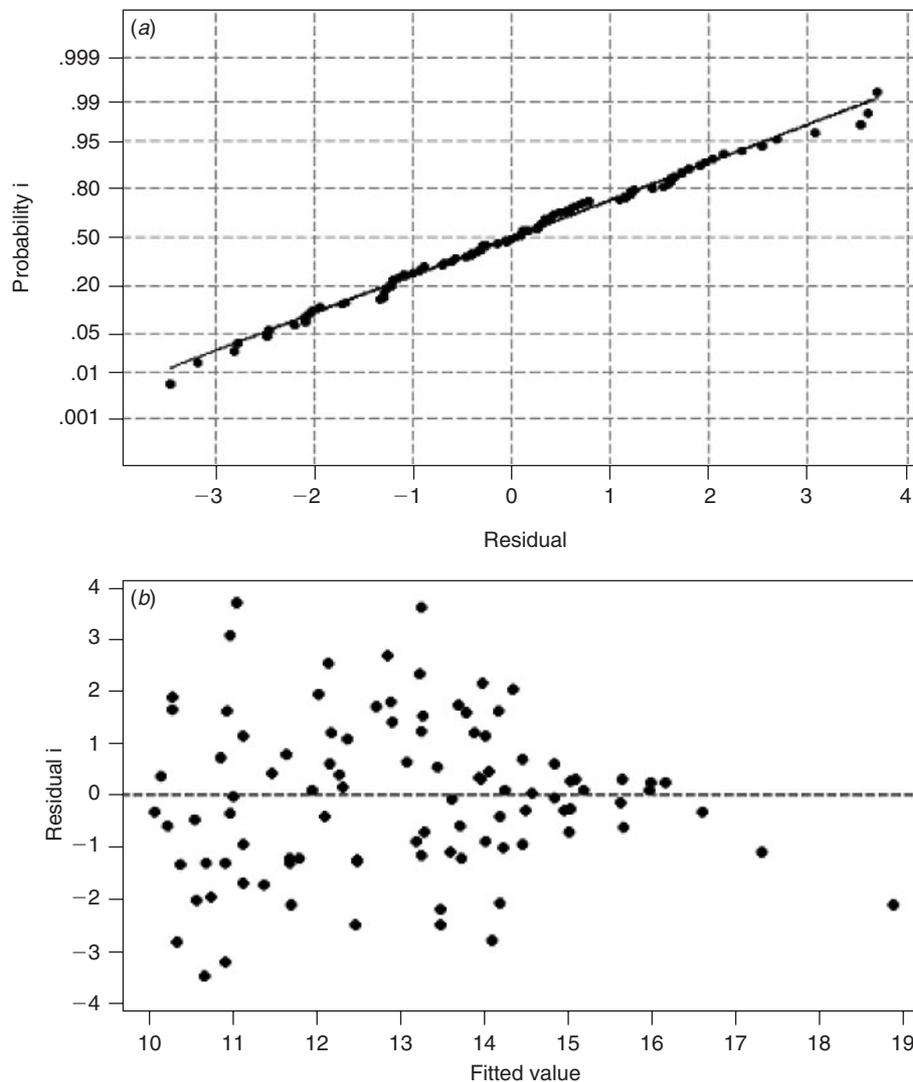
The causal effects of private land and fire size in the present study were based on the notion of *ceteris paribus*, which means ‘other factors being equal’ (Wooldridge 2000, p. 13). Evaluated factors included fire size and shape, private properties, public land attributes, forest and fuel conditions, and geographic characteristics. As our data stretched over a vast area in the states of Montana and Idaho, we also controlled for the possible large-scale spatial autocorrelation. By holding other factors fixed, the effects of private land and fire size on suppression expenditures were independent from the effects of all other factors that we studied.

The positive effect of private land on suppression expenditures, although less than 20% of burned area was private (Fig. 6), indicated that private properties adjacent to public lands greatly increased fire suppression expenditures, and ‘preserving life and property from the threat of fire’ (36 CFR 211.5, Code of Federal Regulations) is carried out by the Forest Service in fire suppression. As private land exceeded 20% of burned area, the increase of suppression expenditures slowed down to zero, slightly declined afterwards, and finally levelled off at ~50% of private land holdings. The reason for the decline was presumably the cost-share agreements between the Forest Service and the responsible state and local governments (USDA OIG 2006). As more private land was threatened by wildland fires, expenditures shared by the respective state and local governments (not considered in the model) likely represented a higher percentage of total suppression expenditures. According to our data, most fires with more than 20% of burned area as private land were close to towns. Although there was no established standard for identifying financial responsibilities through the cost-share agreements, as fires approached towns, local governments might have shouldered more responsibility in providing firefighting resources or in reimbursing the Forest Service for suppression expenditures. Unfortunately, further investigation of the cost-share agreement was very difficult. According to P. Garbutt<sup>F</sup> (pers. comm., June 2007), the cost-share agreements had been evaluated on a fire by fire basis and are linked to various predefined protection responsibilities.

How much predicative power did fire size and percentage of private land have on suppression expenditures? We measured the predicative power of one factor, when other factors were controlled, with generalised  $R^2$  (Pedhazur 1997). The generalised  $R^2$  was 0.40 for fire size, and 0.37 for percentage of private land. Both fire size and percentage of private land had similar predicative power on fire suppression expenditures. Because fire size is difficult to control after a fire has escaped initial attack, efforts to contain suppression expenditures may need to focus on the wildfires that threaten private land.

We found no evidence that the effect of fire size dominated in controlling suppression expenditures. In some previous studies (e.g. Gebert *et al.* 2007), average suppression expenditures per unit area were considered instead of total fire expenditures to avoid the overwhelming effect of fire size. Here, fire size contributed to only 25% of goodness-of-fit provided by all the explanatory variables (Fig. 2). Hence, fire size did not overwhelmingly control suppression expenditures, and there was no

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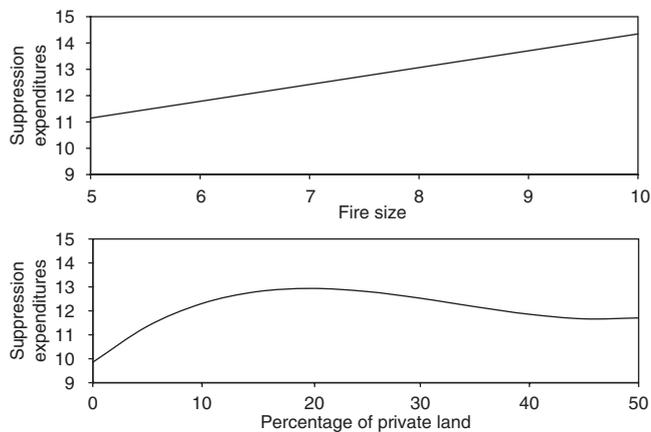
**Fig. 5.** Normal plot of residuals (a), and plot of residuals against fitted values (b) of the final model estimated from the 100 large fires in Forest Service Region One.

reason to study average expenditures per unit area instead of total expenditures. The lack of significant higher-order terms of fire size in the final model suggested that reduced average cost per unit area resulting from increasing fire size, as identified in Schuster *et al.* (1997) and Gebert *et al.* (2007), was not present in this sample.

Although the causal reasons of the effects of fire size and private land were obvious, why other explanatory variables had no effect on suppression expenditures was admittedly difficult to explain. Although we found no effect of forest and fuel conditions and geographic settings on wildland fire suppression expenditures, given that fire size and percentage of private land were accounted for, forest and fuel conditions and geographic settings could indirectly affect suppression expenditures through fire size, because fire size is determined by forest and fuel conditions and geographic settings (Finney 2004). Similarly, total structure value and percentage of the wildland–urban interface

area could be indirect factors, as they also reflected private development, and were highly correlated with percentage of private land (Table 3). As percentage of private land was much more significant than total structure value and percentage of the wildland–urban interface area, it may imply that presence of private land, rather than value of structures, was of primary concern to the Forest Service. Current national WUI layers were less effective in representing private development in wildland fire studies, presumably owing to the low-resolution of national WUI layers, especially in rural areas. There was no evidence whatsoever that public land attributes affect suppression expenditures directly or indirectly.

The year 2006 saw intensified concern about the Forest Service paying a disproportionate share of fire expenditures to protect privately owned properties (USDA OIG 2006). The OIG report recommends congressional clarification of the role of the Forest Service in protecting private properties, and suggests



**Fig. 6.** Controlled effect of fire size (natural logarithm of hectares), and percentage of private land within fire perimeter (%) on total fire suppression expenditures (natural logarithm in 2005 US dollars) of the final model (see Table 2). An explanatory variable varied between its smallest and largest observed values while the other variable was held constant at its sample mean.

renegotiation between the Forest Service and non-Federal partners to ensure the suppression expenditures in private and WUI areas are appropriately shared. These recommendations could help shift expenditures from federal to state and local entities. However, they may have no effect on reducing total suppression expenditures. To this end, county zoning and development standards prohibiting further development in areas of high fire threat<sup>G</sup> may be most effective. In addition, activities promoted within Community Wildfire Protection Plans (CWPP, see USDA Forest Service *et al.* 2004), such as fire-wise building codes and localised fuel treatments, may allow suppression resources to be more cost-effectively employed in the interface area to protect development, thus reducing total suppression expenditures.

The present study was subject to the usual caveats due to the use of non-experimental data. On the positive side, the final model satisfied the OLS assumptions, and had no spatial autocorrelation. However, selecting the right model was a pervasive problem. To avoid compromised type-I error rates and severe artefacts commonly associated with model selection procedures (Mac Nally 2000), we selected a variable by its overall explanatory power and statistical significance.

The issue of fire suppression was undoubtedly complicated. Nonetheless, we found 58% of variation in suppression expenditures could be explained by spatial factors. Management factors, such as incident team type and fire experience of the responsible land managers, were not available for the present study, but may help in understanding the unexplained variation.

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