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Development and application of wildfire suppression expenditure models for decision support and landscape planning

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1. Extended abstract

A major consequence of large wildfires is the budgetary impact on public agencies tasked with wildfire management and suppression efforts. In wildfire seasons with a high incidence of large and expensive fires, agency budgets for non-fire activities can be threatened when the immediate needs of wildfire management are prioritized. In the United States, wildfire management already accounts for a large and increasing share of the U.S. Forest Service's (USFS) budget, which strains other land management needs. Between 1992 and 2011, the annual budget dedicated to fire management grew from 13 to over 40 percent of total agency appropriations.

This extended abstract describes the development of expenditure models that are capable of providing spatially and temporally explicit information about costs, and provides examples of how such models can complement sophisticated fire simulation models used to support incident management decisions and landscape-scale fire planning. To date, expenditure modelling efforts have yielded insights into the geographic, landscape, socio-political, and management characteristics associated with wildfire suppression expenditures. These insights are based on models that relate characteristics associated with the location and date of ignition of wildfires to expenditure records (e.g., Gebert *et al*. 2007; Gude *et al*. 2013; Donovan *et al*. 2011; Yoder and Gebert 2012). However, decision support tools and wildfire modelling efforts increasingly use detailed spatial and temporal descriptions of geographic, landscape, and weather conditions. Accounting for heterogeneity of such conditions in management expenditure models may improve link between fire modelling outputs and expenditure models for fire management planning and decision support.

Incorporating spatial characteristics in expenditure models has limited precedent in the literature. Priesler *et al*. (2011) create spatially explicit forecasts of expenditures, but the underlying expenditure model is based on ignition-point data. Liang *et al*. (2008) incorporated spatial characteristics of the area within fire perimeters to account for observed spatial autocorrelation of expenditures for limited set of fires in the Northern Rockies region of the United States. Hand *et al*. (2014, ch.4) extend the approach in Liang *et al*. (2008) to include fires in the entire Western United States, but did not evaluate the role of heterogeneity or assess model performance relative to ignition-point models. The data and methods in Hand *et al*. (2014) form the basis of the empirical models in this paper.

To develop spatially and temporally descriptive expenditure models, final fire perimeters were gathered for a sample of large fires (greater than 121 hectares) from the western United States. In total, 406 fires from fiscal years 2006 to 2011 are used in the final estimation sample. The fire perimeters were used in conjunction with several geo-spatial data layers to describe the extent and variation of geographic and landscape characteristics that are thought to be associated with expenditures. The time period between the discovery date of the fire and the date of control or containment was used to examine landscape and geographic characteristics within the fire perimeter that may vary over time.

The spatially and temporally descriptive characteristics are used as independent variables in a regression model to predict total incident expenditures by Federal management agencies.[1] Table 1 describes the variables used in the regression model and the corresponding variables in ignition-point expenditure models that the spatially and temporally descriptive variables replace.

Table 1. Variables used in spatially descriptive regression with corresponding ignition-point variables; obs. = 406

Variable	Description	Source (see table footnote)	Corresponding ignition-point variables
lnexp	Natural log of total federal suppression expenditures in constant 2012 $ (Dep. Var.)	FFIS	--
lnacres	Natural log of area within final fire perimeter	NIFC FTP	--
erc_max	Maximum relative ERC percentile observed during the fire within the final perimeter	GIS calculation of data from Abatzoglou (2011)	ERC at ignition point and time
erc_std	Standard deviation of relative ERC observed during the fire within the final perimeter	GIS calculation of data from Abatzoglou (2011)	ERC at ignition point and time
lnavelev	Natural log of the average elevation within the final perimeter	LANDFIRE	Elevation at ignition point
wild_burn	Burned within Wilderness area (binary)	WFDSS	Ignition within Wilderness area (binary)
wild_sh	Share of final burned area within a Wilderness area	WFDSS	Distance of ignition point from Wilderness boundary
ira_burn	Burned within an Inventoried Roadless Area (binary)	WFDSS	Ignition within Inventoried Roadless Area (binary)
ira_sh	Share of final burned area within an IRA	WFDSS	Distance of ignition point from IRA boundary
other_burn	Burned within other specially designated area (binary)	WFDSS	Ignition within other specially designated area (binary)
other_sh	Share of final burned area within a SDA	WFDSS	Distance of ignition point from SDA boundary
slope1	Share of final burned area with slope less than 20% (omitted reference category)	LANDFIRE	Percent slope at ignition point
slope2	Share of final burned area with slope between 20% and 40%	LANDFIRE	
slope3	Share of final burned area with slope between 40% and 60%	LANDFIRE	
slope4	Share of final burned area with slope between 60% and 80%	LANDFIRE	
slope5	Share of final burned area with slope greater than 80%	LANDFIRE	
usfs_sh	Share of final burned area in USFS ownership	WFDSS	USFS ownership at ignition point (binary)
doi_sh	Share of final burned area in Dept. of Interior ownership	WFDSS	DOI ownership at ignition point (binary)
grass_sh	Share of final burned area with grass fuels	LANDFIRE	Grass fuels at ignition point (binary)
brush_sh	Share of final burned area with brush fuels	LANDFIRE	Brush fuels at ignition point (binary)

[1] The sample of fires includes only fires managed primarily by the U.S. Forest Service. However, other Federal agencies may incur a minority of expenses for the management of these fires. The dependent variable represents total Federal expenditures.

timber_sh	Share of final burned area with timber fuels	LANDFIRE	Timber fuels at ignition point (binary)
slash_sh	Share of final burned area with slash fuels	LANDFIRE	Slash fuels at ignition point (binary)
lnhousein	Natural log of housing value within the final perimeter in constant 2012 $	U.S. Census	n/a
lnhouse5_perim	Natural log of housing value within 5 miles of final perimeter in constant 2012 $	U.S. Census	Housing value within 5 mi. of ignition point
lnhouse10_perim	Natural log of housing value between 5 and 10 miles from perimeter in constant 2012 $	U.S. Census	Housing value within 10 mi. of ignition point
lnhouse20_perim	Natural log of housing value between 10 and 20 miles from perimeter in constant 2012 $	U.S. Census	Housing value within 20 mi. of ignition point
asp_123	Share of final burned area with North, Northeast, or East aspect	LANDFIRE	Sine and cosine of aspect (in radians) at ignition point
asp_456	Share of final burned area with Southeast, South, or Southwest aspect	LANDFIRE	
asp_78	Share of final burned area in West or Northwest aspect (omitted reference category)	LANDFIRE	
duration	Fire duration in days, top-coded at 90 days	NIFMID	--
dur2	Square of *duration*	NIFMID	--
dur3	Cubic of	NIFMID	--
reg_1	Northern region identifier (binary, omitted reference category)	NIFMID	--
reg_2	Rocky Mountain region indicator (binary)	NIFMID	--
reg_3	Southwest region indicator (binary)	NIFMID	--
reg_4	Great Basin region indicator (binary)	NIFMID	--
reg_5	California region indicator (binary)	NIFMID	--
reg_6	Northwest region indicator (binary)	NIFMID	--
fy06	Fiscal year 2006 indicator (binary, omitted reference category)	NIFMID	--
fy07	Fiscal year 2007 indicator (binary)	NIFMID	--
fy08	Fiscal year 2008 indicator (binary)	NIFMID	--
fy09	Fisal year 2009 indicator (binary)	NIFMID	--
fy10	Fiscal year 2010 indicator (binary)	NIFMID	--
fy11	Fiscal year 2011 indicator (binary)	NIFMID	--

-- indicates no change in the variable between ignition point and spatially descriptive model.
n/a indicates that the variable was not used in the ignition point model.
Data sources: FFIS – Foundation Financial Information System, which is being replaced by the Financial Management Modernization Initiative (FMMI), available at http://info.fmmi.usda.gov/, accessed 9/3/2013. NIFMID – National Interagency Fire Management Integrated Database, maintained at the USDA National Information Technology Center in Kansas City, MO; NIFMID variables are self-reported by managers for each wildfire. NIFC FTP – available at ftp://ftp.nifc.gov/Incident_Specific_Data/, accessed 7/24/2013; WFDSS – Wildland Fire Decision Support System databases available at http://wfdss.usgs.gov/wfdss/WFDSS_Data_Downloads.shtml, accessed 7/24/2013; LANDFIRE – version 1.2.0 available at http://www.landfire.gov/lf_120.php, accessed 7/24/2013.

Preliminary results suggest that spatial heterogeneity of geographic and landscape characteristics affect suppression expenditures. In particular, the spatial pattern of surface fuels, protection designation (e.g., Wilderness Areas), land ownership, and housing values are significant predictors of expenditures. Further, the temporal pattern of fire weather and fuel moisture conditions is an important predictor of expenditures. The spatially descriptive model also improves prediction accuracy and model fit as compared with analogous models based on ignition-point characteristics. Table 2 compares the size of the standardized residuals (in standard deviation, or s.d., units) in the spatial/temporal model to those in the comparable ignition-point model.

Table 2. Comparison of standardized prediction errors between spatial/temporal model and ignition-point model

Size of standardized residual	Spatial model frequency	Ignition-point model frequency
<= 1 s.d.	104	94
1 - 2 s.d.	101	77
2 - 3 s.d.	87	69
>4 s.d	114	166
All obs.	406	406

An immediate use of the spatially and temporally descriptive expenditure model is to improve the accuracy of expenditure predictions when the final burned area is known. For example, after-season reviews of fire-specific expenditures can be compared to predicted expenditures using the final fire perimeter and the spatial/temporal expenditure model. The results indicate that the modest improvements in prediction accuracy can lead to more reliable comparisons in the future.

The model can also be used to improve the functionality of decision support tools that include predictions of total incident expenditures. In the Wildland Fire Decision Support System (WFDSS), the ignition-point expenditure model is currently used to provide information about expected expenditures for an incident under given conditions (Noonan-Wright *et al*. 2011). The spatially and temporally explicit model may yield more nuanced information about expenditures because it can, in theory, be paired with fire models in WFDSS that result in predicted fire perimeters. For example, the expenditure model can be paired with fire spread models to generate spatially explicit expected expenditure maps. Such an application would leverage variations in fire behaviour generated by the fire spread model (which determines the size and areal extent of the fire), as well as spatial and temporal variations in characteristics that are related to expenditures. As risk management becomes a greater focus of wildfire management, risk-based expenditure information may assist managers in making strategic decisions during a fire incident.

Incorporating spatially descriptive data can provide richer information about how expenditures are affected by alternative land management scenarios. Planning and prioritizing the treatment of hazardous fuels to affect future fire behaviour may incorporate impacts on expected suppression expenditures (Fitch *et al*. 2013; Thompson *et al*. 2013). The spatial/temporal expenditure model could provide greater detail about how changes in fire behaviour relate to expenditures. For example, hazardous fuel treatments may not necessarily affect the expected number of ignitions or number of large fires in a given season, but could affect the spatial pattern of where fires are likely to burn. Ignition-point models of expenditures currently in use (e.g., in Thompson *et al*. 2013) only account for changes in fire size. But fuel treatments are an inherently spatial endeavour, and the location and pattern of treatments may have impacts on wildfire management that extend beyond changes in final fire size. Understanding the magnitude of any potential suppression cost trade-offs can assist managers in determining whether such investments are worth the cost.

In summary, spatially and temporally descriptive models of wildfire management expenditures show promise for improving predictions of expenditures and providing nuanced information for decision support and land management planning. Accounting for heterogeneity of characteristics in space and over time improves the fit and predictive power of wildfire expenditure models, and are readily adaptable to spatially explicit fire modelling tools. The models investigated in this paper are limited by the fact that they use relatively coarse geospatial data, and do not explicitly model how the progression of fire relates to expenditures. Future research using time-series panel data and finer scale geographic data may help alleviate these limitations.

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