A Risk-Based Approach to Wildland Fire Budgetary Planning

Matthew P. Thompson, David E. Calkin, Mark A. Finney, Krista M. Gebert, and Michael S. Hand

Abstract: The financial impact of wildfire management within the USDA Forest Service challenges the ability of the agency to meet societal demands and maintain forest health. The extent of this financial crisis has been attributed to historical and continuing fire management practices, changing climatic conditions, and increasing human development in fire-prone areas, as well as the lack of financial accountability of fire managers and misaligned incentive structures. In this article, we focus on incentives related to cost containment. We review the literature on the incentive structure facing wildfire managers and describe how the incentive structure does not sufficiently reward cost containment. We then cover a range of possible approaches to promote cost containment, culminating in a novel solution premised on the application of actuarial principles to wildfire budgetary planning that we believe most closely aligns with the Forest Service's transition to risk-based management paradigms and that most comprehensively incentivizes containment across the spectrum of wildfire management activities. We illustrate through a proof of concept case study how risk-based performance measures would be calculated and compare our results with historic suppression expenditures. Preliminary results suggest that our simulation model performs well in a relative sense to identify high- and low-cost forests, and we detail modeling improvements to refine estimates. We then illustrate potential extension to an actuarial system, which would further incentivize appropriate risk management and cost containment across the fire management continuum. We address the strengths and weaknesses of the proposed approaches, including potential roadblocks to implementation, and conclude by summarizing our major findings and offer recommendations for future agency direction. FOR. SCI. 59(1):63–77.

Keywords: wildfire suppression, incentives, risk assessment, wildfire economics

THE FINANCIAL IMPACT OF WILDFIRE MANAGEMENT within the USDA Forest Service challenges the ability of the agency to meet societal demands and maintain forest health. Liang et al. (2008, p. 650) cited an "urgent and immediate need to address the excessive cost of large fires." Total Forest Service emergency suppression expenditures have increased from the scale of a few hundred million dollars to more than a billion dollars since the late 1970s (Calkin et al. 2005a, Prestemon et al. 2008). Whereas before the year 2000, wildland fire management expenditures averaged less than 20% of total Forest Service discretionary funds; by 2008, expenditures had ballooned to 43% of discretionary funds, with the increasing trend projected to continue (US Department of Agriculture [USDA], 2009).

Increasing fire-related expenses can harm nonfire programs in two ways. First, when the suppression pool has been depleted in recent years, suppression expenditures have been funded by transferring money from other programs. Former Forest Service Chiefs and federal oversight agencies criticized this practice of borrowing for disrupting planning and negatively affecting accomplishments in nonfire related programs (US Government Accountability Office 2004, 2007, Peterson et al. 2008). For the fiscal years 2002–2009, the Forest Service transferred more than $2.3 billion to cover the costs of fire suppression, with only $1.85 billion being repaid in subsequent fiscal years (Wildland Fire Leadership Council 2010). Second, beyond emergency transfers and programmatic disruptions, increased suppression costs increase the subsequent year's suppression budget (updated according to a 10-year moving average), resulting in reduced future budgets for virtually every other mission of the US Forest Service. These budgetary reductions can affect complementary programs such as fuels management (Stephens and Ruth 2005) and nonfire programs such as the Forest Service's chronically undermaintained transportation network (Sample et al. 2007). Cost containment, therefore, is a prominent issue in the wildfire management arena.

The extent of this financial crisis relates to the "convergence of several decades-long trends involving historic fire management practices, climatic conditions, and land use change related to population growth" (Bruins et al. 2010, p. 471). Other posited explanatory variables and ones that we focus on here are the lack of financial accountability of fire managers and unclear agency direction on the relative importance of cost containment, which can lead to development of suppression strategies without due consideration of costs (National Academy of Public Administrators 2002,

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USDA Office of the Inspector General 2006, Canton-Thompson et al. 2008, US Government Accountability Office 2009). A review of wildfire suppression cost studies identified a common thread: physical variables alone do not explain observed variation in costs and the incentive structure facing fire managers therefore needs to be considered (Donovan and Brown 2005). Achieving cost containment objectives requires an incentive structure that clearly rewards fire managers who incorporate cost containment into decisionmaking (MacGregor and Haynes 2005).

The remainder of this article is organized as follows. First, we briefly review the Forest Service wildfire management environment and clarify our definition of a "fire manager." We then review the literature on the incentive structure facing wildfire managers and describe how it does not sufficiently reward cost containment. Next, we cover a range of possible approaches to promote cost containment, culminating in a novel solution premised on the application of actuarial principles to wildfire budgetary planning that we believe most closely aligns with the Forest Service's transition to risk-based management paradigms (Fire Executive Council 2009) and that most comprehensively incentivizes containment across the spectrum of wildfire management activities. Using existing tools and data sets, we conceptually illustrate the derivation of risk-based performance measures and explain how they can modify incentive structures. We address the strengths and weaknesses of the proposed approaches, including potential roadblocks to implementation, and conclude by summarizing our major findings and offering recommendations for future agency direction.

Wildfire Management: Context and Incentives

For the purposes of this article by "fire managers" we specifically refer to agency administrators (district rangers, forest supervisors, and others) within the Forest Service[1], who jointly manage wildfires with incident command teams. Agency administrators develop suppression strategies and objectives consistent with existing fire and land management plans and with agency policy that prioritizes human life and safety (both community and firefighter) followed by property and natural/cultural resources. Incident commanders then deploy tactical and operational decisions consistent with the overarching strategy. Incident commanders, who are not necessarily Forest Service employees, tend to have more experience managing large wildland fires than do agency administrators and in interviews have stated that local agency administrators are often an "overriding constraint" on the ability of incident command teams to curb costs (Canton-Thompson et al. 2008). There is a more direct connection between the agency administrator and cost containment than for any other position or office related to managing wildfires because the agency administrator has responsibility for selecting and approving strategies for fire incidents—the most important determinant of suppression expenditures under management control (Donovan and Noordijk 2005)—and because the agency administrator has responsibility for directing land and fuel management strategies before wildfire occurrence (which can affect incident management choices). Thus, the agency administrator has more of a long-term perspective and intimate tie to the land.

Many authors have recognized flaws with the incentive structure facing fire managers, which is thought to encourage aggressive suppression, overutilization of suppression resources, and expenditures incommensurate with values at risk (Calkin et al. 2005b, Donovan and Brown 2005, 2007, MacGregor and Haynes 2005, Canton-Thompson et al. 2008, Donovan et al. 2008, Bruins et al. 2010). The imbalanced incentive structure stems in part from asymmetrical penalties for excessive suppression costs and the consequences of damaging fires and from the fact that national rather than local accounts fund most of suppression operations. Donovan and Brown (2005) formalized this assertion within a utility maximization framework, with analytical results indicating that agency administrators would continue to invest in suppression until the increase in utility from averted fire-related damages equaled the decrease in utility associated with decreasing firefighter safety. Because the manager faces little penalty associated with additional suppression expenditures, and because the savings of not deploying suppression resources cannot be reinvested elsewhere, the opportunity cost of suppression expenditures is effectively zero (Donovan and Brown 2007). That is, "unless suppression resources are simply unavailable, fire managers may continue to spend on suppression as long as their efforts decrease damage by even a small increment" (Donovan et al. 2008, p. 331). Bruins et al. (2010, p. 474) frame the argument similarly, stating that fire managers have "little disincentive to call for increased levels of firefighting resources." An audit report by the USDA Office of the Inspector General succinctly stated that the Forest Service needs to, "Increase the financial accountability of line officers and incident commanders by incorporating into their evaluations an assessment of strategic and tactical cost effectiveness" (USDA Office of the Inspector General 2006, p. v).

Of particular concern is the prospect of sociopolitical pressures affecting the fire manager's incentive structure and possibly exerting an undue influence on suppression strategies. By sociopolitical pressures, we mean the pressures brought to bear by local residents, interest groups, the media, politicians, and other nonagency players in the fire management arena such as state foresters and local fire districts. Agency administrators are under intense pressure to spend every available resource to drive the risk of damage to private property and resources as close to zero as possible (Donovan and Brown 2005, 2007, Donovan et al. 2008). The National Wildfire Coordinating Group (2010) specifically cites sensitive media relationships and political interests as factors to consider when the type of organization necessary to manage an incident is determined. Donovan et al. (2011) presented empirical evidence from an econometric study suggesting that suppression costs increase in response to media coverage and political seniority. Canton-Thompson et al. (2008, p. 422) stated: "Agency administrators, often in response to sociopolitical pressures from their constituents, assign multiple incident management objectives that are not compatible with reducing fire suppression costs." Similarly, Stephens and Ruth (2005, p. 539) stated that making a commitment of excessive resources is not uncommon, even when success is unlikely, because "you have to at least look like you are doing something or people and politicians will protest." The prospect of civil and criminal liability for property loss, injuries, or fatalities tends to further incentivize use of additional suppression resources to avoid the possibility of catastrophic fire with legal consequences (Canton-Thompson et al. 2008).

Related to cost containment are the incentives surrounding management of risk. A recent survey of line officers found that being innovative and willing to take risks were among the least rewarded traits (Kennedy et al. 2005). A lack of positive incentives for taking risks can further induce risk-averse behavior on the part of fire managers (Maguire and Albright 2005, Wilson et al. 2011), ultimately leading to aggressive suppression and increased expenditures.

At the level of the individual fire manager, therefore, an imbalanced incentive structure does not sufficiently recognize cost containment. This fact leads to the possibility of excessive suppression expenditures at the national scale. Thus, although perhaps rational from a local perspective, decisions to request additional resources can create economic inefficiencies at larger scales and can result in fewer resources being available for other fires. Fire managers see the direct benefits of incurring additional suppression costs but share that cost broadly across the agency. In other words, the costs and benefits of fire management decisions do not reside in the same location. A policy environment that encourages overuse will lead to resource degradation and the positive feedback loop known as the "fire paradox," in which aggressive suppression today leads to accumulation of fuels and worse fires in the future (Arno and Brown 1991), in turn leading to continued excessive suppression expenditures in the absence of proactive measures to control costs.

Incentivizing Cost Containment

There are multiple lenses through which to view the issue of cost containment and the need for modifications to the incentives facing the agency administrator. The shared access of agency administrators to the national suppression funding pool engenders analogies to common pool resources, in that overuse by one individual is to the detriment of all (borrowing from nonfire programs and reduced future budgets) and controlling access to the pool is costly (suppression decisionmaking is largely decentralized and command and control is difficult in practice to implement) (Feeny et al. 1990). In theory, overutilization issues could be addressed by agency administrators directly were they to collectively identify a set of institutions and rules to govern access to the suppression funding pool, commit to adhere to the established rules, and engage in mutual monitoring of conformance to the rules (Ostrom 1990). However, it seems unlikely that the agency administrators could identify uniform rules for controlling access to suppression resources given the heterogeneous nature of fire behavior and local resources at risk across the nation or further that they would be able to in any meaningful way monitor the actions of others.

Another useful construct is to view the agency administrator as acting as an agent in a principal-agent relationship[2]. Principal-agent relationships recognize that the agent has special skills and knowledge suited to the task at hand; the challenge is to ensure that the agent is properly motivated to act exactly as the principal would if the principal had the skills/knowledge to make such decisions. As the principal, society expects the agent (agency administrator) to manage fire and fuels in such a way as to maximize social welfare, including due consideration of taxpayer expenditures on suppression (all taxpayers, not just local communities). The reality, however, is that the agent responds most directly to his or her immediate incentive structure, and it is rarely the case that the agent's immediate incentive structure is perfectly aligned to meet the principal's objectives (Sappington 1991). External costs borne solely by the agent, such as intense sociopolitical pressure to pursue aggressive suppression, can lead to a misaligned incentive structure.

Thus, improved abilities to monitor and evaluate the performance of fire managers and to modify their incentive structure are warranted. Existing tools for performance evaluation include the after action review, which may be triggered for large fires that exceed a certain cost threshold, and the Stratified Cost Index. The Stratified Cost Index relies on a regression cost model (Gebert et al. 2007) that estimates suppression expenditures as a function of variables relating to the fire size, fire environment, and values at risk. The model can be used to identify relatively high-cost fires (i.e., fires that exceed 1 or 2 SDs above the expected suppression cost), and during incident management the model can inform managers of their current cost trajectory relative to historic fires with similar characteristics (Noonan-Wright et al. 2011). Although useful for evaluating single fire incidents, these evaluation tools do not extend across fire season(s) and thus have a limited long-term perspective for evaluating agency administrator decisionmaking and fire management. Donovan and Brown (2005) proposed a system designed to address cost containment objectives across a fire season. Specifically, they proposed eliminating emergency funding and instead establishing a suppression budget for every fire manager. Establishment of a budgets changes the environment from a decision environment in which the fire manager faces diffuse costs for overutilization (shared across all forests) to an environment with concentrated costs for overutilization. To account for variability between fire seasons, the authors proposed "carryovers," which would allow fire managers to carry surpluses or deficits into future years.

Enacting a budget, however, would only address one component of fire risk management: managing active wildland fires. If isolated to this use alone, risk management is disconnected from the broader framework of wildland fire or land management. For instance, having a budget for suppression expenditures might encourage less aggressive suppression strategies, but it might not necessarily induce an agency administrator to pursue fuel treatments or other proactive measures to reduce overall fire risk. What is needed is a feedback loop that encourages proper risk management and due consideration of suppression costs.

In the next sections, we describe a possible alternative: the application of actuarial principles to wildfire budgetary planning and performance evaluation. We build on the incentive modification work of Donovan and Brown (2005), incorporating these ideas into a broader wildfire risk management framework (Bachmann and Allgower 2000, Finney 2005, Scott 2006, Ager et al. 2010, Calkin et al. 2011a, Thompson et al. 2011). We introduce the use of statistical expectations for fire season expenditures as a performance measure, provide a proof-of-concept calculation of annual suppression cost expectations, review data and modeling needs to implement such a framework, and then explore a possible extension to a more comprehensive framework that is analogous to an insurance system. Improvements associated with our proposed framework include a better representation of the stochastic nature of wildfire, increased alignment of who bears risk with who manages risk (whereas currently fire managers see little direct risk to their nonfire program budgets due to excessive spending), and extension beyond management of active incidents to connect to strategic issues of fire and fuels management. Reliance on actuarial principles provides an appropriate risk-based feedback mechanism to incentivize cost containment and appropriate risk management.

Risk-Based Performance Measurement: Explanation and Illustration

As outlined above, statistical expectations of annual suppression expenditures could augment existing performance measures by expanding the scope of analysis to the entire fire season. Further, expectations could be updated in response to fuels and fire management (which in turn affect fire risk, expected fire occurrence/behavior, and likely suppression activity) thereby providing a dynamic, responsive performance measure. The fundamental information required for this approach is a probability distribution for fire suppression costs. These distributions could be established for national forest ranger districts, forests, or even regions; here we restrict our focus to the forest level. Below, we define some important mathematical notation. Let X represent annual suppression costs ($) and $p(x)$ represent the probability distribution for suppression costs. The annual expected suppression cost is calculated as in Equation 1:

$$E(X) = \int_0^\infty xp(x)dx \qquad (1)$$

In theory, distributions could be derived via analysis of historical cost data; however, observed data are probably insufficient. This insufficiency is due in part to issues related to data collection and data quality and also to the fact that the nature of natural disturbances is such that we may not have yet observed extreme events to gauge their magnitude and frequency (e.g., a 1,000-year event). This factor is critical because the average modern burn probabilities (past 50 years) are on the order of 1/1,000, meaning most areas have not burned in the modern period. Historical data are also insufficient for estimating the magnitude of wildfire risk reduction that can be achieved through changes in fire or fuel management practices (e.g., the reduction in expected losses for a 50% increase in fuel treatment area).

Thus, modeling is required to estimate suppression cost probability distributions. Calculation of the fire cost probability distribution is based on a mapping between simulation results describing ignition location, fire intensity, and fire size (among other attributes) and a fire cost regression model. In the following, we describe in more detail our modeling approach, which for illustrative purposes is constructed using available models and tools.

Fire Simulation

To characterize fire spread and behavior, we used outputs from the large fire simulation model, FSim (Finney et al. 2011). FSim models the spread of fire according to Fermat's principle, producing fire growth by searching for the fastest straight-line travel paths from burning to unburned nodes. FSim uses the minimum travel time fire spread algorithm (Finney 2002), which is optimized for processing large numbers of fires. FSim was initially developed for the Fire Program Analysis system, a common interagency strategic decision support tool for wildland fire planning and budgeting (Fire Program Analysis 2009), although the model is now being used for other purposes such as the Hazardous Fuels Prioritization and Allocation System and national risk assessments (Calkin et al. 2010, Thompson et al. 2011). Fire Program Analysis system analyses divide the landscape into forest planning units (FPUs). Thousands of years of simulations were performed in each FPU using artificial weather sequences generated by time-series analysis of the fire danger rating index (Deeming et al. 1977) energy release component calculated from daily weather records. FSim results were calibrated for each FPU using historical records of annualized burn probability and the slope of fire size distributions (Finney et al. 2011). Our simulations were run on a bank of computers located at the US Geological Survey Earth Resources Observation and Science Data Center (Sioux Falls, SD). From these simulations, we were able to obtain the ignition location and final fire size for tens of thousands (10,000–50,000, depending on FPU) of simulated fire seasons (using constant, or current, fuel conditions; the model is effectively simulating possible realizations of the next fire season without dynamic updating).

Suppression Cost Estimates

Estimating the suppression costs of a given fire is relatively straightforward using current deterministic cost models. Key data necessary are final fire size and some geographic characteristics of the fire. These can be characteristics at the ignition point (as in Gebert et al. 2007, Liang et al. 2008, Hesseln et al. 2010), summary characteristics of the fire area polygon (Liang et al. 2008), or summary characteristics for a fixed geographic area associated with the fire (e.g., a grid cell as in Preisler et al. 2011). These models appear to perform reasonably well; in a linear regression, burned area and selected geographic characteristics tend to explain between 40 and 80% of variation in suppression costs. We used the regression cost model currently used by the Forest Service and other federal agencies for performance review and for decision support on active fires (Gebert et al. 2007). The output of the model is the natural log of cost per acre, which we transformed into cost per fire. Table 1 details the independent variables for the model along with our data sources for these inputs.

Deriving Expected Annual Suppression Costs

To demonstrate proof of concept, we generated annual suppression cost distributions for two national forest regions, Region 3 (Southwest) and Region 5 (Pacific Southwest). The regions, although geographically close, differ in timing and duration of the fire season, predominant fire management concerns, and, importantly, suppression expenditures. Region 5 (average cost per fire = $2,772,378 in 2004 dollars) is significantly more expensive than Region 3 (average cost per fire = $983,434 in 2004 dollars) (Gebert et al. 2007). In the updated version of the suppression expenditure model[3], regression coefficients indicate Region 5 as the most costly and Region 3 as the second least costly region of the western model (Regions 1–6).

Figure 1 delineates the major steps in our modeling approach to estimate annual suppression cost distributions. In the first step, we estimated the occurrence and size of large fires across the landscape (for FPUs in Regions 3 and 5) using output from FSim. Next, we applied a mask to filter out all fires that did not ignite within national forest borders. For all remaining fires we queried a US Geological Survey (2009) LANDFIRE database using the ignition location to derive other information needed for the cost model, such as fuel type, slope, aspect, and distance to the nearest town, and queried US Census data to derive total housing value within a 20-mile radius. With all relevant independent variables obtained, we were then able to estimate suppression expenditures for all simulated fires, in turn, enabling the estimation of probability cost distributions for each national forest.

Modeling Results

As a validation exercise, we compared estimated suppression expenditures with observed historic expenditures for the years 2000–2009 (Foundation Financial Information System). In particular, we are comparing expected costs to P-code expenditures, which are the accounting codes the Forest Service uses to track wildfire expenditures (see Gebert et al. 2007). Definitively ascribing suppression expenditures to a specific national forest is problematic. First, nearly all of the national forests charged suppression dollars for every year in question, even in years in which no large fires were reported (National Interagency Fire Management Integrated Database). This apparent disconnect results in part from dispatching firefighting resources to other forests/regions while charging the home forest's suppression account, which is the way the accounting system tracked expenditures before 2007. We handled this issue by merging cost data with large fire history (large fire defined as ≥300 acres) and reallocating costs accordingly; for years in which a forest had zero large fires, charged suppression expenditures were reassigned to forests that did experience large fires proportionally to overall expenditures. Second, expenditures charged to more general accounts (e.g., "Aerial Fire Depot" or "Regional Office") are not easily decomposed into forest-specific expenditures. For this preliminary analysis, we excluded the latter category of costs. In all, we found that Regions 3 and 5 were responsible for 10.60 and

Table 1. Variables used in regression model [dependent variable = ln(wildland fire suppression expenditures/acre)].

Fire characteristics	Variable definition	Source
Size		
ln(Total acres burned)	Natural log of total acres within the wildfire perimeter	FSim
Fire environment		
Aspect	Sine and cosine of aspect at point of origin in 45° increments	LANDFIRE
Slope	Slope percentage at point of origin	LANDFIRE
Elevation	Elevation at point of origin	LANDFIRE
Fuel type	Dummy variables representing fuel type at point of origin: Brush = NFDRS fuel models F and Q; Brush4 = NFDRS fuel models B and O; Slash = NFDRS fuel models J, K, and I; Timber = NFDRS fuel models H, R, E, P, U, and G; Grass (reference category) = NFDRS fuel models A, L, S, C, T, and N	LANDFIRE
ERC	ERC calculated from ignition point using nearest weather station information (cumulative frequency)	FSim
Values at risk		
ln(Distance to nearest town)	Natural log of distance from ignition to nearest census designated place	LANDFIRE
ln(Total housing value 20)	Natural log of total housing value in 20-mile radius from point of origin (census data)/100,000	Census
Wilderness area	Dummy variables indicating whether fire was in a wilderness area	LANDFIRE
ln(Distance to wilderness boundary)	If in a wilderness area, natural log of distance to area boundary	LANDFIRE
Region	Dummy variables for National Forest system region (reference category for western model = Region 1)	FSim

NFDRS, National Forest Danger Rating System; ERC, energy release component.

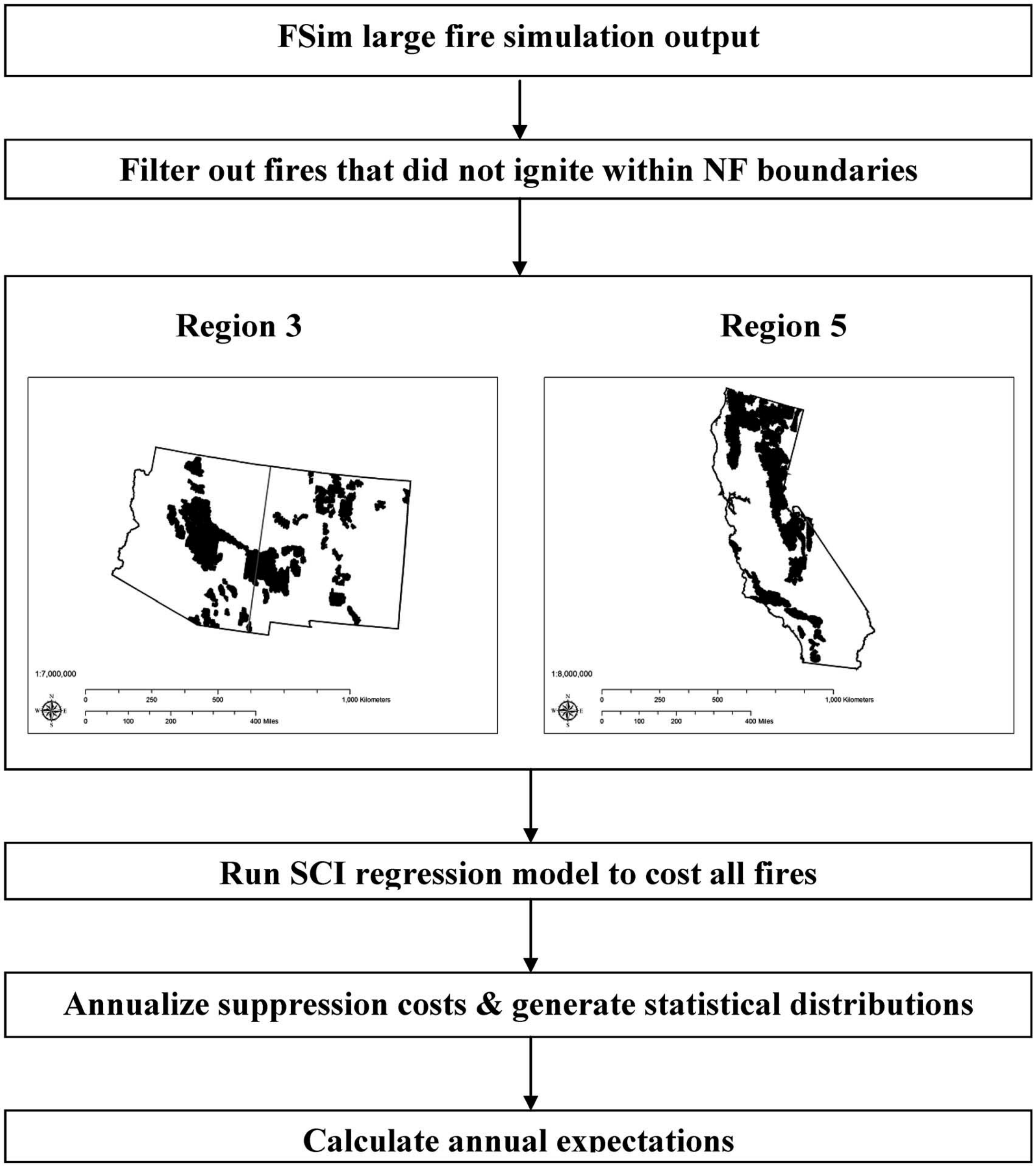

Figure 1. Flow chart of fire simulation and suppression cost estimation process, for Forest Service Regions 3 and 5. NF, national forest; SCI, Stratified Cost Index.

36.29% of overall historic suppression expenditures for 2000–2009, respectively (exclusive of Forest Service Region 10 [Alaska Region]).

Our simulated suppression costs were considerably lower than observed costs (as quantified by a 10-year average for 2000–2009). Numerous explanations exist for this result, including the following: (1) the last 10 years have been exceptionally active and expensive fire years relative to the historic record on which the cost model is based, (2) the FSim model assumes uniform distributions of fire starts, when, in fact, because of human-caused ignitions there may be more escaped fires proximate to populated areas in which per unit expenses are higher than those in remote (e.g., wilderness) areas, (3) we only evaluated fires that started within national forest boundaries whereas the Forest Service incurs significant costs for fires that start outside boundaries and burn onto federal lands, (4) the Forest Service often provides assistance and resources to other federal agencies, and these fires are not included in evaluation, and (5) very large fires are observed within the data set that are outside of the sample used to develop the historic per area cost model, and the total cost of these very large fires may be underrepresented because of the current cost model specification.

We therefore compared in relative terms the percentage of overall regional expenses ascribed to each national forest from simulated and historic expenditures. Our simulation model appears to assign a high percentage of total suppression costs to identified high-cost forests (Figures 2 and 3). That is, we find good model agreement on relative terms, often the most appropriate use of simulation results anyway. In comparison with the 10-year average costs over 2000–2009, simulation results yield correlation coefficients of 0.88 and 0.63 for Region 3 and Region 5, respectively.

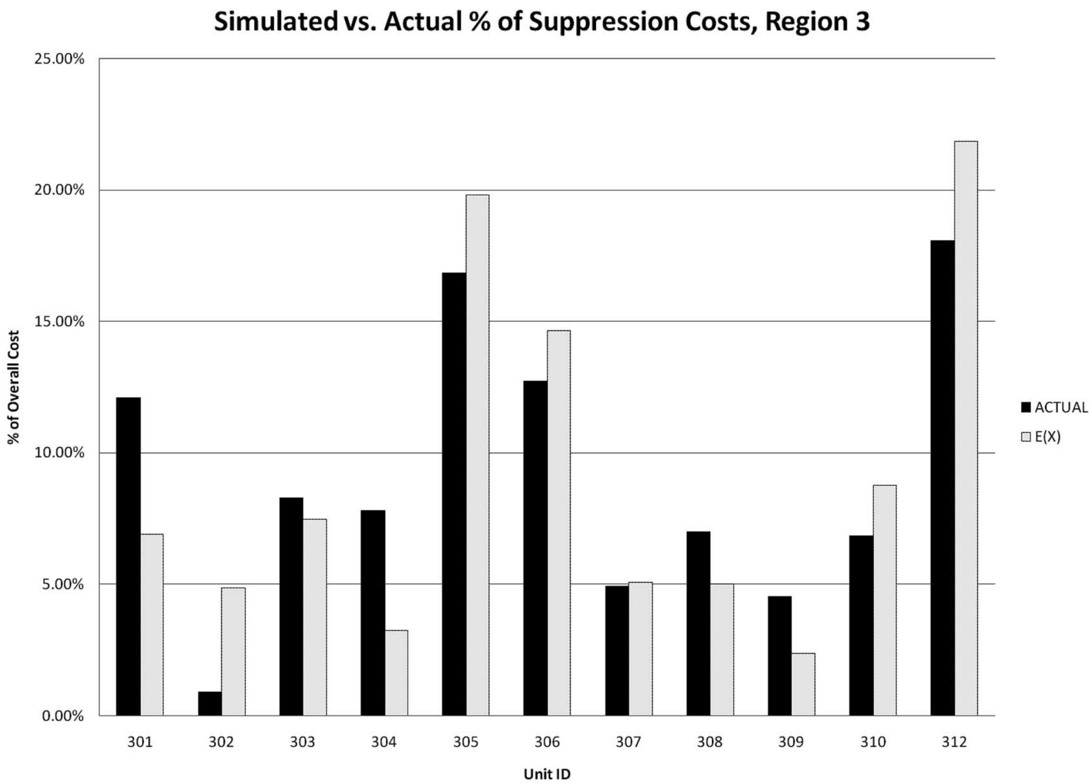

Figure 2. Comparison of simulated versus actual percentage of regional suppression expenditures, Region 3.

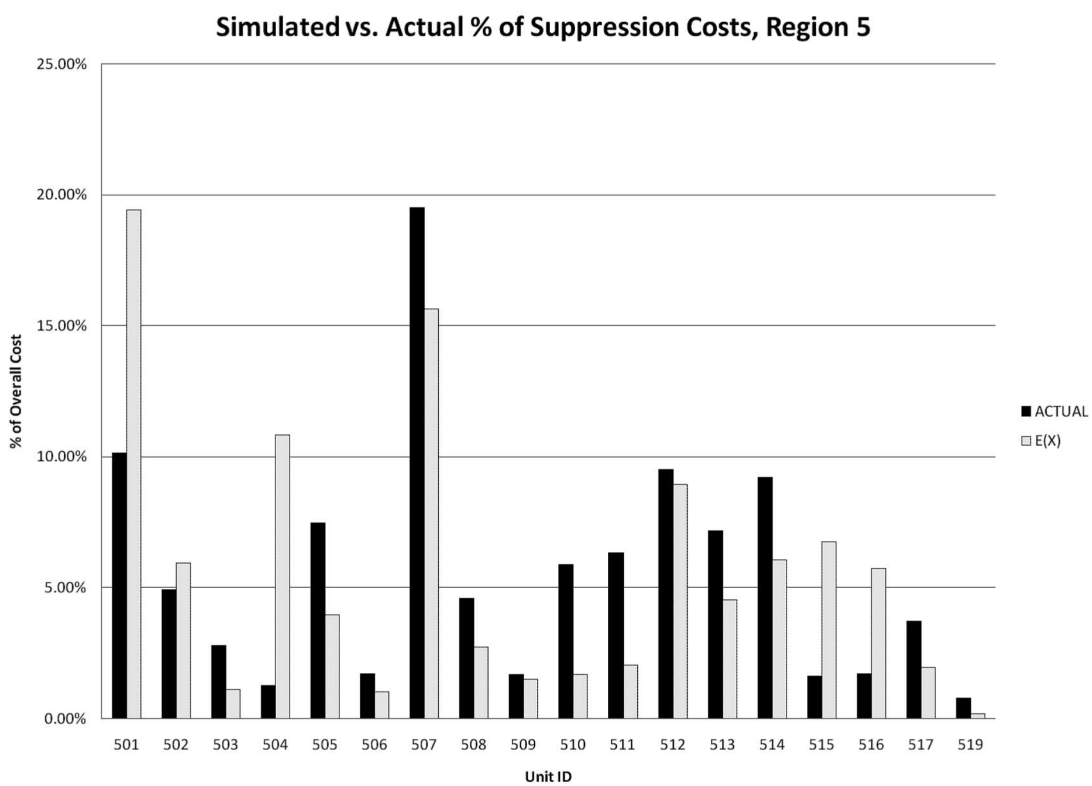

Figure 3. Comparison of simulated versus actual percentage of regional suppression expenditures, Region 5.

Table 2 presents values for percentage of regional expenditures along with unit rank (high-cost → low-cost). Simulations for Region 3 correctly identified, in order, the top three high-cost forests (Units 312, 305, and 306). Simulations for Region 5 identified in reverse order the top two high-cost forests (Units 507 and 501). We expect that more in-depth

Table 2. Comparison of percentage of regional suppression costs and rank (high-cost → low-cost) for actual and simulated suppression, for Forest Service Regions 3 and 5.

Region 3					Region 5				
	Historic		Simulated			Historic		Simulated	
Unit	%	Rank	%	Rank	Unit	%	Rank	%	Rank
301	12.08	6	6.90	4	501	10.15	1	19.41	2
302	0.91	9	4.85	11	502	4.92	7	5.94	9
303	8.29	5	7.48	5	503	2.80	16	1.11	12
304	7.79	10	3.24	6	504	1.27	3	10.83	17
305	16.84	2	19.80	2	505	7.48	10	3.96	5
306	12.72	3	14.65	3	506	1.72	17	1.01	13
307	4.91	7	5.08	9	507	19.51	2	15.63	1
308	6.98	8	5.02	7	508	4.58	11	2.74	10
309	4.54	11	2.37	10	509	1.67	15	1.51	15
310	6.86	4	8.76	8	510	5.87	14	1.67	8
312	18.08	1	21.86	1	511	6.33	12	2.04	7
					512	9.51	4	8.94	3
					513	7.16	9	4.52	6
					514	9.23	6	6.06	4
					515	1.63	5	6.76	16
					516	1.70	8	5.74	14
					517	3.71	13	1.94	11
					519	0.78	18	0.19	18

analyses addressing the issues identified in the previous paragraph could further refine estimates of annual suppression costs.

Figure 4 presents simulation results for conditional annual suppression cost distributions, that is, cost distributions given that at least one large fire occurs. We compare cost distributions for Unit 507 and Unit 519, the (actual) high- and low-cost forests in Region 5, respectively. Our simulation results indicate that the distribution for Unit 507 is skewed to the right of Unit 519 and, in particular, has a long right tail. These results reflect variability in the factors that drive suppression cost (fire growth potential, proximity to values-at-risk, and others). Of course, the frequency of occurrence and number of large fires will also significantly influence overall suppression cost distributions, and these values exhibit substantial variability both within and across

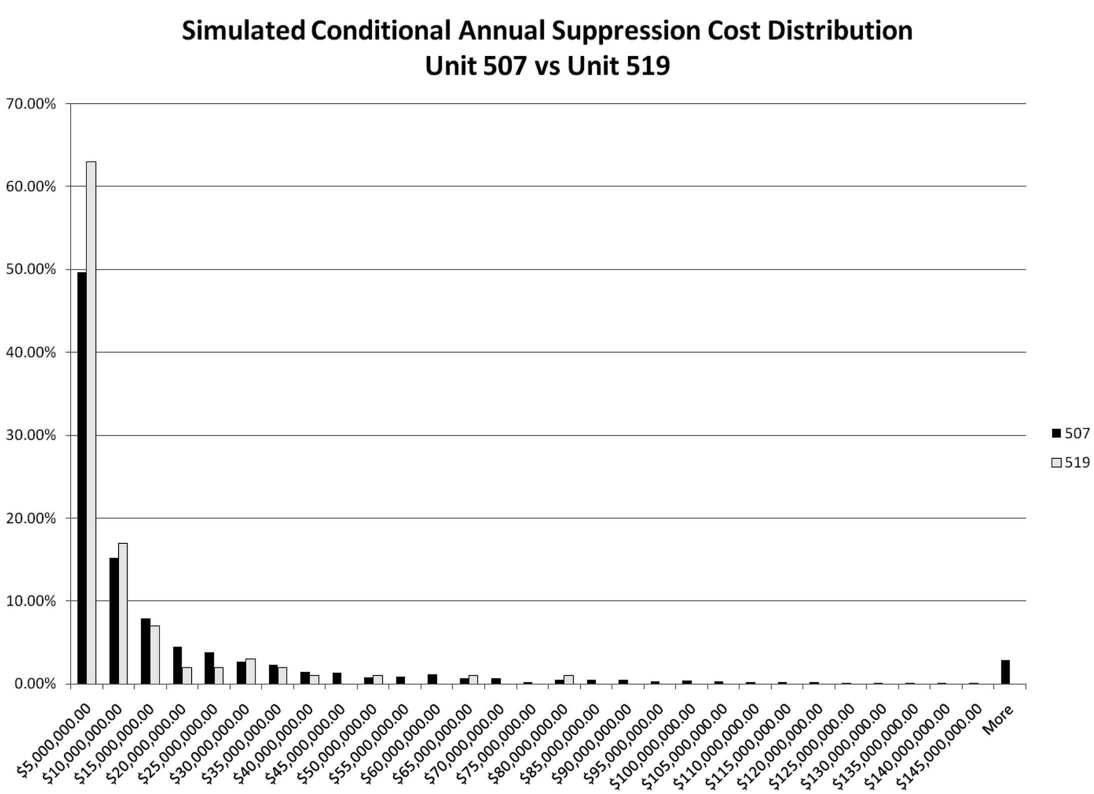

Figure 4. Comparison of simulated, conditional annual suppression cost distributions for Unit 507 (high cost in Region 5) and Unit 519 (low cost in Region 5).

Forest Service regions. For instance, across 2000–2009 Unit 519 experienced a total of two large fires that occurred in separate years, whereas Unit 507 experienced a total of 20 large fires occurring over 7 years. Region 3 similarly exhibits variability in large fire occurrence over 2000–2009, from a low of 2 fires (Unit 302) to a high of 75 large fires (Unit 306.) Modeled fire occurrence is also highly variable, and spatially explicit simulation results for large fire burn probability differ by orders of magnitude (Finney et al. 2011).

Critiquing and Improving Suppression Cost Estimates

Although our intent is to merely illustrate the process of estimating of suppression cost distributions rather than definitively offer statistical results, it would nevertheless be useful to highlight some of the limitations of our modeling approach. There is large variability in the costs of individual fires, and a correspondingly large confidence interval surrounding per acre suppression cost estimates within the suppression model (Gebert et al. 2007). Modeling fire occurrence and behavior is similarly subject to variability and a degree of imprecision. The rarity of large fires in the historical record means that comparisons can only be made for large land areas from which sample sizes are sufficient to estimate burn probabilities and fire size distributions. Fire activity is also highly variable year-to-year, contributing to wide confidence intervals from only 20–30 years of records. Nevertheless, modeled burn probabilities compared well against averages for 134 fire planning units over 4 orders of magnitude (0.00001–0.01) (Finney et al. 2011). Similarly, modeled fire size distributions were statistically comparable with observed distributions.

With regard to improving our use of fire models, spatial information on fire perimeters for all simulated fires would allow assessment of financial impacts remote from ignition locations. In particular, this information would enable us to identify those fires that did not ignite within but eventually spread to national forests and would therefore improve cost estimates for a more realistic set of fires. Improvements could also stem from increasing the resolution of weather information driving the simulation models by incorporating additional information from more weather stations and historical large-fire densities.

Continued data acquisition and econometric analysis may allow for more refined cost models in the future. One avenue for improving cost estimates may be identification of omitted variables that explain some of the remaining variation in costs. These may include additional or refined geographic data that better describe differences in fire conditions that affect costs; data collection along these lines is currently underway. It could also include variables representing constraints to available suppression resources, for example, the number of contemporaneous fires or national/regional preparedness levels to proxy for resource availability. Resource availability may be important in simulation applications when changes in conditions result in a change in demand for suppression resources. In addition, including previously omitted variables may avoid bias in parameter estimates for geographic characteristics that could be correlated with how managers use resources under constraints.

For example, suppose fire simulations are run for two forest units (A and B) under two different situations: the status quo simulation in which occurrence and size of fires are simulated in units A and B under current conditions, and a run in which unit A has received fuel treatments that alter the probability of large fire occurrence on unit A but not on unit B. Suppression costs are estimated for both units under both situations using a standard regression cost model. In unit A, changes in average costs per acre and total costs per fire would be determined by whether and how the reduced probability of large fire occurrence alters the average characteristics of remaining fires. In unit B, in which there is no change in fire occurrence, the cost model would predict no change in costs. However, if the reduced fire occurrence in unit A frees up resources to be used on remaining fires (in either unit), then average costs may change in both units after the fuel treatment. Understanding whether and how costs in one forest unit may be related to those in other units would be an important feature of an actuarial approach to wildfire budgeting.

One way to incorporate the effects of changing probability of large fire occurrence may be with a censored regression estimate of costs. Costs are currently estimated ignoring the fact that cost observations are censored for fires less than 300 acres (an artifact of the accounting system that does not report costs for small fires). Estimating a censored model is less important in a static scenario in which we are only interested in the relationship between fire characteristics and costs conditional on large fire occurrence, but ignoring censoring when simulations incorporate policies or actions that change the probability of large fire occurrence would bias cost estimates. For example, a risk-based performance evaluation may create incentives to reduce hazardous fuel loads and thus reduce the probability that a large fire is observed for cost estimates. An advantage of censored regressions is that they can be estimated with little additional data; it is possible to create more sophisticated models that condition the censoring process on specific characteristics that may be generated from simulations. There are no known examples of censored cost regressions for wildfire suppression.

It may also be necessary to directly estimate a suppression cost function, in which total costs are a function of output (e.g., total fire size or fire line production), input prices, and exogenous cost shifters. This would be a more intensive modeling effort. Efficiency of fire line production has been estimated using observations of actual fire line production (Calkin et al. 2011c). However, it may be necessary to gather daily production data, which is currently gathered for only a small selection of fires each year. A difficulty in this regard will be connecting cost function estimates (using observed fire line production from historical fires) to simulated fires or fire seasons. In addition to fire frequency and size, the simulations would need to be modified to generate simulated fire line production along a modeled perimeter.

In addition, it may be possible to tighten confidence intervals around cost estimates by dropping the pairing of fire simulation and fire cost models and instead focusing on scaling down existing suppression cost forecasting models (e.g., Prestemon et al. 2008, Abt et al. 2009). Currently, these approaches are applied at regional or larger scales, but in theory, they could be refined to the forestwide forecasts. An advantage to such approaches is the use of more broad-scale climate indicators (e.g., Pacific Decadal Oscillation) and drought, which is more amenable to forecasting future costs. However, these models would also need modification to account for altered conditions stemming from prevention planning, fuels management, increased development, and so on. Ultimately, we believe our simulation exercise yielded reasonable results, and these types of simulations could generate improved estimates of forest-level expected suppression expenditures with more intensive data collection and modeling efforts.

Extending the Actuarial Approach to Wildfire Budgetary Planning

Extending risk-based analyses of wildfire management to incorporate actuarial principles of insurance management could more comprehensively incentivize cost containment across the fire and fuels management continuum. Insurance is essentially a form of risk management, wherein the insured pay a statistically derived premium to be protected against financial loss. Updating of premium payments in response to changing conditions and observed behavior provides the incentive to invest in loss reduction and related risk mitigation efforts.

In the wildfire context, financial loss corresponds to suppression expenditures incurred as a result of unpredictable large wildfire occurrence. Exogenous environmental conditions (that is, conditions outside of the fire manager's control) that influence premium rates include topography, climate/weather, proximity to human development, existing plant communities, and others. Variables influencing premium calculations that the fire manager does exert control over include investments in prevention programs, fuel treatments, how active fires are managed, and how the local community is engaged to facilitate acceptance of less aggressive wildfire management.

For such a strategy to work effectively in the wildfire management environment, the risk being managed should be insurable. Again, in this context the insurable risk is financial loss associated with large fire suppression expenditures. An insurable risk generally satisfies most of a set of seven criteria. Below we enumerate these criteria and argue why, in our estimation, financial loss associated with suppression expenditures is an insurable risk.

1. *Numerous and homogeneous.* The nature of the risk must be such that there are many risks that are largely similar. Financial losses associated with wildfires appear to satisfy this criterion, in that wildfires frequently occur throughout the United States and present common perils to safety, property, and resource values, requiring suppression activities with associated expenditures.
2. *Determinable losses.* When actualized risk results in a loss, the degree and extent of loss should be quantifiable and determinable. Financial losses (i.e., suppression expenditures) associated with wildfire management are maintained by the Forest Service (see Calkin et al. 2005a) and are therefore determinable.
3. *Calculable.* To price the risk, the likelihood and magnitude of potential loss must be calculable. Until recently, estimation of the probabilities associated with financial losses was a major challenge. However, with the emergence of significantly improved wildfire simulation models and nationally consistent geospatial fuel models, analysts are able to assess wildfire risk at the national scale. When paired with existing suppression cost models currently used by federal agencies, probability distributions for financial losses can be derived.
4. *Accidental.* The occurrence of the loss must be subject to chance and not under the control of the insured. In the context of wildfire, the occurrence of loss is only partially accidental. Clearly the agency administrator does not control the occurrence of wildfire (ignoring escaped prescribed fires), but suppression decisions resulting in expenditures are related to financial loss.
5. *Information symmetry.* The assessment of the likely amount of loss must be reasonably close between the insurer and the insured to reach an agreement to transfer risk. It is assumed that agency administrators have a sufficient knowledge of wildfire management practices, relative wildfire hazard, and values to be protected within their scope of management. A transparent process of evaluating wildfire hazard and establishing financial loss probability distributions should enhance information symmetry.
6. *Independence.* Each occurrence of loss should be independent. We consider wildfire suppression expenditures to be largely independent, assuming that expenditures on a given fire do not influence or correlate to expenditures on other fires. For a single forest, climatic cycles such as El Niño could induce some correlation across a single fire season (temporal nonindependence). Across forests, some correlation could be induced by similar weather systems driving fire occurrence and behavior or by competition for scarce firefighting resources (spatial nonindependence).
7. *Unpredictability.* Losses that are highly predictable are not suitable for insurance. Wildfires are unpredictable events, making financial losses associated with wildfire suppression unpredictable.

As with home or auto insurance, each national forest would pay a "premium" commensurate with the wildfire risk and associated risk of financial loss (suppression expenditures). The national suppression pool would be distributed to the field, and then each national forest would pay a premium to be protected against significant financial losses from a high-cost fire season. By design, premium rates would be adjusted periodically to reflect observed changes in landscape conditions and agency administrator behavior.

Updating premiums provides the feedback loop necessary to holistically incentivize risk management. Managers who effectively manage risk and suppression costs may see their premiums decrease in subsequent years, with savings eligible for investment into other programs. Unlike the current environment in which agency administrators see only diffusely (if at all), the economic impacts to other programs from their suppression decisions, this premium-based approach provides a direct tie between suppression decisions and available fiscal resources for other programs. Managers of forests with high present or future risk would have a greater incentive to mitigate risks by active management than those of areas with low risk. This system is similar to the budgetary approach proposed by Donovan and Brown (2005) in that it concentrates the costs of overutilization and excessive suppression effort, but it would be risk-based and would better buffer all interannual variability in costs associated with unexpectedly high or low fire seasons.

Premium rates could be calculated as shown below in Equation 2:

$$E(X) * \mathrm{AF} \tag{2}$$

The adjustment factor (AF) increases the premium above the statistical expectation (Equation 1) to account for administrative costs and to buffer risk. Premiums could be increased where the distribution of costs has a long right tail, indicating the possibility of very high-cost fire seasons. Here, premium rates could be increased according to established probabilistic rules, such as "increase the premium rate by $X\%$ if there is $\geq Y\%$ chance that the forest will incur $\geq \$Z$ in suppression expenditures." In more general terms, AF could also be used as a mechanism to provide feedback with respect to other performance measures, such as firefighter exposure, public health and safety, and damage to ecological/cultural values.

There are three primary ways in which an agency administrator could work to reduce their effective premium: first, change the shape of the suppression cost distribution, $p(x)$; second, reduce the magnitude of the AF; and third, encourage "hardening" of high-value assets to reduce their sensitivity to fire damage (e.g., Firewise Communities, National Fire Protection Agency 2009). By investing in fuel treatments and by allowing nondamaging fires[4] to treat fuels across the landscape, the agency administrator is reducing the future likelihood of burning as well as the susceptibility of various resources to fire (Finney 2005). Fuel treatments and fire patterns at landscape scales can alter the movement of fires, thereby reducing probability of impact far from the treatment units (van Wagtendonk 2004, Ager et al. 2007, 2010, Finney et al. 2007, Collins et al. 2009). Treatments also affect local fire behavior, and, thus, susceptibility of a particular value or resource to damage (Graham et al. 2004). All other things being equal, this would have the effect of reducing expected suppression expenditures as well as considerable long-term rehabilitation costs (Lynch 2004). Further, by engaging in cost-effective suppression responses, an agency administrator can also expect to change the shape of his or her fire cost function. To reiterate, this feedback loop is a fundamental purpose of the insurance approach: to incentivize investments in loss reduction, whether through engaging in fuel treatments or by allowing nondamaging fires to treat more acres. Reducing the sensitivity to fire damages, all else held equal, would decrease suppression requirements for the fire because the fire behavior and occurrence would cause less damage.

Given that large fire suppression expenditures are an insurable risk, it is conceivable, if not immediately feasible, that the Forest Service could adopt a wildfire budgetary planning framework premised on actuarial risk management principles. Payment of the premiums would allow national forests access to a common pool filled by premium payments from all other insured national forests. Financial resources would be drawn from the suppression pool as needed to fight large wildfires. A critical step in establishing the wildfire suppression insurance system would involve setting up a public-private partnership with an insurance firm or establishing a pseudogovernmental agency to manage the money for annual premiums, annual savings, claims and payments, premium adjustments, and incentives. All money must be safe from Congressional borrowing, because insurance and risk management is a long-term strategy for which annual costs and savings must balance over the long term. That is, surplus money in the premium pool would be retained to buffer against future high-cost years.

If the Forest Service were to consider broadly applying an insurance system to wildland fire, it would clearly precipitate a real revolution in fire and forest management—all the way from funding, staffing, and budgeting to on-the-ground management. Full accomplishment could take, perhaps, a decade. Designing the appropriate mechanisms to manage budgets and premium payments is a not trivial undertaking and would require significant planning and policy modifications. Adopting an actuarial approach would require risk-management training for agency administrators, development of approved actuarial methods, and intensive data mining efforts to sufficiently characterize past fire behavior, suppression efforts, and expenditures. Nevertheless, precedents for fundamental changes to fire management and budgeting do exist, with two major examples being the removal of the artificial, mutually exclusive distinctions for wildland fire use (recognizing wildfire benefits) and suppression (benefits not allowed to be considered) to allow consideration of beneficial fire effects within broader wildfire suppression strategy development and legislative action to pass the FLAME Act, designed in part to reduce harmful impacts of borrowing from nonfire programs by establishing a separate fund to finance suppression efforts for wildfires deemed to be a "catastrophic emergency" (although we note that the existence of this fund does nothing to directly address incentive issues and in theory could exacerbate incentive issues[5]).

Discussion

In this article, we sought opportunities to leverage wildfire risk assessment methods to improve performance measurement and incentive modification. Use of the best available wildfire behavior and suppression expenditure data and models meets the call of Bruins et al. (2010) for analytical planning and budgeting systems commensurate with the challenge of efficient wildfire management. The technique of fire growth simulation that we used is being increasingly used for producing burn probability surfaces and wildfire risk analyses (e.g., Bar Massada et al. 2009, Ager et al. 2010, Braun et al. 2010), and related risk assessment tools are now embedded within the Wildland Fire Decision Support System (Calkin et al. 2011d, Noonan-Wright et al. 2011). In concert with deployment of improved decision support tools, the agency could provide training for fire managers that focuses on risk-based scenario analysis, in the ideal, leading to improved wildfire management and decreased risk aversion (Calkin et al. 2011b).

In the near term, offering positive incentives for cost containment could also be pursued. The agency could provide recognition to agency administrators (and incident commanders) for a few fires each year that have been particularly well managed from the risk perspective. In addition to the recognition, there could be an award of some sort; for instance, there could be a lump-sum budgetary award provided to the unit for use in local recreation facilities enhancement that the community could use. This award would provide learning opportunities by highlighting the characteristics, decisions, and community relationships that promoted outcomes that are determined to be excellent examples of managing a challenging fire event while realizing good results from a resource and cost perspective. By provision of enhanced recreation facilities to the local community, the importance of community interactions and tolerance of new fire management approaches will be recognized and rewarded. That is, this reward approach not only creates a positive incentive for cost containment on the part of the fire manager, but also creates a positive incentive for the local community to accept less aggressive suppression strategies (which decreases the sociopolitical pressures the agency administrator feels). A further step would be to create the ability to use a portion of surplus suppression funds (FY2010 had approximately $200 million in surplus because of a relatively calm fire season), when available, to be distributed as grants that reward cost containment, encourage improved community relations, and encourage monitoring and exertion of peer pressure across fire managers to enhance the likelihood availability of surplus funding.

Ultimately, the agency administrator's decision space has effectively no opportunity cost for suppression expenditures (Donovan and Brown 2005). Thus, even with the complementary measures of risk training and the advent of positive incentives for cost containment, it is likely that more comprehensive changes to the incentive structure are warranted. We introduced risk-based measures for retrospective performance analysis, explained their relation to derivation of effective premiums that would concentrate overutilization of suppression resources by affecting local rather than national budgets, and proposed the conceptual foundations for transition to an insurance scheme.

Implementation of the insurance system would put some agency administrators in a position to gain (or lose) more than others. Those who stand the most to gain, in terms of premium savings that could be reinvested, are those managing high-cost forests with risk factors that can be mitigated. Managers of those forests with low risk and relatively low historic suppression expenditures, which have seen budgets for other programs reduced, may not have as much opportunity for additional funds for investment in nonfire programs. Managers of other forests may have little potential for reducing their premium reductions due to nonmanagerial factors such as a changing climate and increased human development. However, programwide redistribution of cost savings (in addition to or in lieu of the grants described above) could encourage those working in low-risk forests to pressure colleagues in high-risk forests to emphasize cost containment.

A number of factors would need to be weighed before adoption of the new frameworks proposed here. The administrative costs of such a system should be considered to examine whether the benefits of the new policy warrant the change. Time in position of agency administrators is another factor to consider; agency administrators who may be leaving their current position may not care about how their actions affect premiums in future years.

Beyond restructuring the incentive structure facing the agency administrator, broader issues relating to wildfire occurrence and behavior, suppression expenditures, and damages clearly must be addressed. The effectiveness of suppression activities on large fires is poorly understood (Finney et al. 2009), offering economists little information with which to analyze the cost effectiveness of suppression actions. Perhaps more pressing, human development continues in fire-prone areas, and the Forest Service and other federal and state agencies retain responsibility for protecting private structures from harm, in effect creating a moral hazard. This raises the question of shifting the burden of investing in loss reduction to property owners. As Dombeck et al. (2004, p. 887) state, "communities need to shoulder greater responsibility for regulating sprawl and for encouraging proactive efforts by homeowners to reduce the risk of home ignition during wildfire." The public needs to be better educated that fire exclusion is neither desirable nor possible in many regions of the country. Land use restrictions, fire insurance requirements, and investments in Firewise Communities are all possible remedies that could be explored further.

Summary and Conclusions

Turning to risk-based principles for wildland fire budgetary planning, performance measurement, and incentive modification is attractive for a number of reasons. First, the approach is consistent with the Forest Service's transition to risk-based frameworks for decisionmaking. Consideration of the probabilities of different outcomes and their associated costs is a clear improvement over current practices using rolling average cost data. Second, the approach allows for a more holistic approach to fire risk management, including actions taken before, during, and after fire incidents. Agency administrators would see clearly that performance is evaluated quantitatively based on investments in loss reduction as well as past fire management.

An extension to an insurance scheme further incentivizes risk management and cost containment. The insurance-based system would transfer risk to the party that controls the risk, and would demonstrate clearly an opportunity cost associated with additional investments in suppression activities. Agency administrators who demonstrate effective and efficient wildland fire management would be rewarded with reduced effective premiums and would be better achieving their objectives as land managers. Savings in premiums could be fed back into land and fuel management activities. Fuel treatment money and efforts would be directed to places where the treatment opportunity was rewarded by reduced risk. Further, ecologically complementary fire management activities, for example, under-burning of ponderosa pine and mixed conifer forests, would be rewarded within the system because more activity would lower the local risk and consequently lead to rebates of the locally assigned premiums. The application of insurance principles and premiums may, thus, allow modern fire management to finally break the positive feedback loop of the fire paradox.

For illustrative purposes, we demonstrated how risk-based performance measures could be derived, using readily available data and existing tools. Our approach entailed estimating statistical distributions for annual suppression expenditures for selected national forests by pairing a probabilistic wildfire simulation model with a regression cost model. Preliminary results suggested that our simulation approach performs well in a relative sense and can identify high- and low-cost forests. The modeling used as a demonstration here can be greatly improved for use in estimating statistically derived performance measures.

Fire managers are most likely to change their behavior in response to a change in incentives, and perhaps through proper management of risk and incentives, we can exit the positive feedback cycle of the fire paradox and better manage escalating large fire expenses that are currently challenging the fiscal health of the agency.

Endnotes

1. Although we focus on the US Forest Service, the issue of misaligned incentives may apply to other federal agencies with fire management responsibilities, and we expect that the incentive structure facing incident commanders may share many characteristics with that facing agency administrators. We are most familiar with the literature pertinent to and the management practices of the Forest Service.
2. One could further look to theories of public choice to better understand bureaucratic decisionmaking or to human factor engineering to better understand cognitive limitations in complex decisionmaking environments, although we do not pursue those angles here.
3. The cost model we used was provided by Krista Gebert (coauthor and Regional Economist, Northern Region, US Forest Service, 2009) and is an updated version of the cost model described in Gebert et al. (2007).
4. The definition of a nondamaging fire will vary by locale and circumstance, but generally here we refer to fires that do not measurably threaten human life, property, or other fire-susceptible resources and where allowing a fire to burn (perhaps to enhance fire-adapted ecosystems) is consistent with land and fire management plans.
5. The FLAME Act changes the fire management picture, funding suppression expenditures for fires that meet certain criteria (size and complexity) from an entirely separate pool. The Act's intent in part is to preserve funding for nonfire programs, thereby alleviating problems of interagency borrowing. In reality, borrowing is only eliminated under conditions in which suppression forecasts used to inform appropriations for the Flame Fund are sufficient. Because fire and weather are stochastic, appropriation based on forecasts is inherently subject to the possibility of insufficient funds. Using an extremely wide confidence interval and budgeting at the upper bound could significantly reduce the likelihood of insufficient funds, but this amount of funding is unlikely to be appropriated. Beyond borrowing, funding suppression from a different pool does little to solve the problem of overutilization. In fact, this change would have the effect of eliminating the primary, if weak, signal that agency administrators now see relating to excessive suppression expenditures: reduced future budgets for other programs. Therefore, we anticipate continued problems of misaligned incentives in the absence of other measures.

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