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Progress towards and barriers to implementation of a risk framework for US federal wildland fire policy and decision making

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ABSTRACT

In this paper we review progress towards the implementation of a risk management framework for US federal wildland fire policy and operations. We first describe new developments in wildfire simulation technology that catalyzed the development of risk-based decision support systems for strategic wildfire management. These systems include new analytical methods to measure wildfire risk to human and ecological values and to inform fuel treatment investment strategies at national, regional, and local scales. Application of the risk management framework to support wildfire incidents has been dramatically advanced with the Wildland Fire Decision Support System and allowed policy modifications that encourage management of incidents for multiple objectives. The new wildfire risk management decision support systems we discuss provide Federal agencies in the US the ability to integrate risk-informed approaches to a wide range of wildfire management responsibilities and decisions. While much progress has been made, there remain several barriers that need to be addressed to fully integrate risk science into current wildfire management practices. We conclude by identifying five primary issues that if properly addressed could help public land management better realize the opportunities and potential payoffs from fully adopting a risk management paradigm.

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1. Introduction

The 2000 fire season began a period of increased wildland fire activity in the United States that has resulted in increased suppression expenditures and significant ecological and financial damage to public and private resources (e.g., Calkin et al., 2008; Prestemon et al., 2008). Federal agencies with wildland fire responsibilities have seen increasing portions of their budgets consumed by fire management expenditures, challenging their ability to fulfill a wide range of other resource management functions. For example, wildland fire management appropriation represented 21% of the Forest Service's discretionary budget in 2000, in 2008 it represented 43% and if trends continue wildland fire will consume over half of the agency's discretionary budget by 2011 (USDA Forest Service, 2009). In a recent joint statement to Congress, five former Forest Service Chiefs stated that the practice of borrowing funds for wildfire management from other programs has disrupted planning and severely impacted accomplishments (Peterson et al., 2008). Numerous reports by budgetary oversight agencies such as the US Government Accountability Office (GAO) and the Office of Inspector General (OIG) have been critical of the US Forest Service (responsible for approximately 70% of federal wildfire suppression expenditures) due to the Agency's inability to justify investments with quantifiable outcomes (see for example OIG 2006, and GAO 2009, which review several previous GAO reports).

In response, the Agency has ramped up investments in tools, technology, and research to implement risk-based wildfire management practices that consider the benefits of management action (or inaction) relative to the impacts on short- and long-term wildfire risks (see for example: http://www.wfmrda.org/NFDSC.html). Current wildland fire management policy states that, "sound risk management is a foundation for all fire management activities" (Fire Executive Council, 2009). Managing fire risk involves analyzing both exposure and effects (i.e., likelihood of wildfire causing potential beneficial or negative effects), and then developing appropriate management response to reduce exposure and/or mitigate adverse effects (Kerns and Ager, 2007; Fairbrother and Turnley 2005; Finney, 2005). Assessing wildfire risk in the US requires the simultaneous consideration of multiple human and ecological values, including public/firefighter safety, homes and other private structures, energy infrastructure, habitat for threatened and endangered species, water quality and quantity, and cultural resources.

As demonstrated by the wildfire risk literature, there have been many attempts to build and apply a variety of risk models in the US and elsewhere (e.g., Calkin et al., 2010; Chuvieco et al., 2010). A systematic review and comparison is lacking, although it is safe to conclude that many of the model formulations excluded important information, or used coarse surrogates to measure difficult parameters including wildfire likelihood (e.g., Vadrevu et al., 2009; Hessburg et al., 2007; Iliadis, 2005).

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The stochastic nature of wildfire occurrence and large-scale spread has frustrated attempts to quantify wildfire likelihood at spatiotemporal scales that are meaningful to planners. Without robust measures of likelihood, many risk models reflected wildfire hazard, or the potential impact given a fire occurs.

Recent advances in wildfire simulation modeling have created opportunities to advance the application of risk management principles for wildfire management (e.g., Ager et al., 2007, 2010; Calkin et al., 2010; Massada et al., 2009; Parisien et al., 2005). These advances have been the result of significant research and development investments by Federal agencies and other entities in the past several years. However, despite the technological advances, there remain several daunting challenges to the adoption of risk-based decision making in the wildland fire environment. These include:

- difficulties and uncertainties associated with implementing the current suite of models,
- a misaligned incentive structure facing land and fire managers in wildland fire situations,
- a lack of clear goals for land and fire management,
- a lack of formal training in risk management,
- and difficulties associated with managing public expectations.

Future progress to fully leverage risk-based management science in wildfire management policy and decision will likely depend on the agencies' ability to grasp and rectify these deficiencies. A first step is to develop the science and tools capable of performing actual risk analysis.

In this paper we first review a suite of risk management tools developed by researchers at the USDA Forest Service's Rocky Mountain Research Station and Pacific Northwest Research Station-Western Wildland Environmental Threat Assessment Center. Although determining the improved efficiency associated with the use of the tools would require counterfactual projections of management actions in the absence of this information, we provide demonstrations and anecdotal evidence of the capabilities of these tools. We then summarize the several important barriers we have identified to continue the adoption and widespread application of risk-based decision making, and offer a series of recommendations to address these barriers.

2. Wildfire risk assessment

Wildfire simulation models are being widely used by fire and fuels specialists in the US to support tactical and strategic decisions related to the mitigation of wildfire risk (Andrews et al., 2007; McDaniels, 2009). Recent advances in fire behavior modeling, geospatial analysis, remote sensed biophysical data sets (e.g., LANDFIRE (Department of Interior Geological Survey, 2009)), weather and climate forecasting, coupled with the internet have made information sharing and decision support more possible. Outputs from wildfire simulation models have been coupled with geospatial identification of human and ecological values to build risk-based decision support systems (Calkin et al., 2010, Calkin et al., in press). The result has been a rapid advance in the application of risk analysis across a full range of wildfire management activities, from the individual fuel treatment project (Ager et al., 2007) to national interagency budgeting (Fire Program Analysis, 2010). Several of the risk-based decision support systems have leveraged the development of a minimum travel time (MTT) fire spread algorithm (Finney, 2002) that makes it computationally feasible to quickly simulate many thousands of large fires[1] and generate relative and absolute burn probability and intensity maps over large areas (10,000–2,000,000 ha). The MTT algorithm is embedded in a number of fire behavior modeling applications including FlamMap (Finney, 2006), FSPro (Finney et al., 2011a), and FSim (Finney et al. 2011b). These models are used for both incident support and strategic landscape planning by Federal land management staff. Extensive application has demonstrated that the MTT algorithm can be effectively used to model large fire spread in the heterogeneous landscapes that typify much of the wildlands in the US (Finney et al., in press). A number of fire effects models are also available (e.g. First Order Fire Effect Model, Reinhardt et al., 1997, Forest Vegetation Simulator (FVS), Havis et al., 2008) that can translate MTT outputs (fire line intensity and flame length) into useful metrics that measure ecological impacts such as loss of habitat, old growth and carbon. The FVS in particular is widely used and well supported in the Federal land management community, although work is needed to update the system to match the usability of the core fire spread programs like FlamMap.

While numerous wildfire risk models have been proposed and applied over the years (Irwin and Wigley, 2005), a formal definition of quantitative wildfire risk assessment incorporates three major elements: 1) Estimation of the probability of fire and intensity through landscape scale fire simulation modeling; 2) Spatial identification of the resources that may experience value change due to fire; and 3) Estimation of resource value change in response to fire intensity level (Finney, 2005). These components are combined to calculate expected net value change (NVC) to a given resource. Eq. (1) presents the mathematical formulation for calculating NVC.

$$E\left(NVC_j\right) = \sum_i p(f_i)RF_j(f_i) \tag{1}$$

where:

$E(NVC_j)$ expected net value change to resource j
$p(f_i)$ probability of a fire at intensity level i
$RF_j(f_i)$ "response function" for resource j as a function of fire intensity level i.

Thus, risk is the product of burn probability at a given fire intensity and the resulting change in resource value, summed over all possible fire intensities. Calculating risk at a given location requires spatially defined estimates of the likelihood and intensity of fire interacted with identified resource values (i.e., exposure analysis). This interaction may be quantified through the use of a response function that estimates expected benefits and losses to the specified resource at the specified fire intensity (i.e., effects analysis). Quantifying wildfire risk to valued resources in this manner allows for an objective risk assessment framework.

Risk analyses appear to hold the most promise to answer a range of strategic and tactical management questions that continues to be debated in the literature, including wildfire management resource and budget allocation (Rideout et al. 2008), tradeoffs between short-term resource impacts of fuel treatments versus long-term benefits of wildfire mitigation (O'Laughlin, 2005; Irwin and Wigley, 2005; Finney et al. 2007), and wildfire impacts to critical habitat and conservation reserves (Agee et al., 2000; Ager et al., 2007a; Hummel and Calkin 2005). Quantitative risk metrics also enable the use of optimization methodologies for a range of applications including commercial timber management (e.g., Konoshima et al., 2010), fuel treatment planning (e.g., Kim et al., 2009), and active fire management (e.g., Dimopoulou and Giannikos, 2004). At present however, computational limitations prevent robust incorporation of fire behavior modeling within optimization algorithms, and so researchers have necessarily turned to simplifications such as piecewise linear approximations of fire occurrence probability (Wei et al., 2008), and consideration of only a few ignitions (Lehmkuhl et al., 2007). As technology advances we can anticipate algorithmic improvements and increased use of risk-based optimization tools.

[1] Within the USDA Forest Service, "large fires" are defined as fires that exceed 300 acres, or ~121 ha. Previously 100 acres (~40 ha) had been the definition.

Recent and projected future development in areas of high wildfire hazard presents significant challenges to federal agencies with wildfire responsibilities (see for example Gude et al., 2008), particularly given anticipated tight future budgets. These factors make the application of risk management concepts more critical to efficiently achieve programmatic goals. Aggressive firefighting adjacent to populated areas deflects the true cost of development placing the burden on the federal taxpayer instead of the developer or homeowner. Insurance companies have made some efforts to incorporate wildfire risk into homeowner premiums (Landkoande et al., 2005). However, the previously high cost of delineating areas of high wildfire potential from areas with low potential has limited the insurers the ability to correctly adjust premiums. Murnane (2006) identified the 3 components of a catastrophe risk model that would be needed for insurance companies to accurately reflect wildfire risk within their premium structure for insured assets at risk to wildfire. The components identified include a hazard module, a damage module and a loss module. The wildfire risk tools described in the paper represent a comprehensive approach addressing the first component with substantial information and methods to address the second; the third module rightly remains in the realm of the insurance industry. The tools described in this paper may substantially lower the cost of information, making it far more likely that the true cost of wildfire risk may be incorporated into insurance premiums thus reducing the moral hazards associated with development in areas with high wildfire potential.

3. Summary of new risk tools

A number of wildfire models have seen wide application for both incident support and strategic planning in the Federal wildfire community (Peterson et al., 2007). However, the emergence of a risk-based approach required the conceptual and programmatic integration of these models into a quantitative framework, along with linkages to data and geospatial systems. In this paper we describe the linkages among three emerging wildfire risk assessment tools that address different aspects of the fire management problem: 1) Wildland Fire Decision Support Systems-Rapid Assessment of Values At Risk (WFDSS-RAVAR) (incident strategic support); 2) ArcFuels (project level fuels management planning); and 3) the National Wildfire Hazard and Risk Assessment (programmatic budgeting). These tools leverage and/or build off of existing tools such as the FVS, Farsite, FSPro, and FlamMap. Table 1 provides a typology that describes the major components and primary differences of the risk assessment tools described in this paper. The tools we review all share a common approach to quantifying wildfire risk based on the actuarial definition described by Finney (2005) and presented above in Eq. (1). Our focus on these three tools should not be taken to suggest that other useful risk-based tools do not exist. For instance, Chuvieco et al. (2010) developed an integrated wildfire risk assessment tool for use in Spain that similarly considered the intersection of fire likelihood and resource response, and the Fire Effects Planning Framework (Black and Opperman, 2005) incorporates ecological response functions.

3.1. WFDSS-RAVAR

When a wildland fire occurs, line officers and fire managers have a broad spectrum of fire management strategies available to them within the parameters of their forest and land management plans. Analytical tools that help managers evaluate various risk factors such as current fire location, adjacent fuel conditions, weather projections and structures and highly valued resources proximate to the fire environment are essential in determining the appropriate fire management strategy to implement. WFDSS is a web-based scalable decision support system that utilizes appropriate fire behavior modeling, economic principles and information technology to support effective wildland fire decisions consistent with resource and fire management plans (Calkin et al., in press). The web-based application provides field-based analysts access to high end computing resources and large database systems that would otherwise be unavailable within the typical wildfire management field setting. Additionally, the web allows for rapid information sharing with managers across the country. The foundational large fire models of the WFDSS comprise the fire behavior module (Fire Spread Probability [FSPro]) and the economic impacts model (Rapid Assessment of Values at Risk [RAVAR])[2]. FSPro is a new fire modeling tool that calculates the probability of fire spread from a current fire perimeter or ignition point for a specified time period (Finney et al. 2011a). The model simulates the 2-D growth of the fire across the landscape (fuels and topography) for thousands of possible weather scenarios. Pairing these modules allows for fire managers to see, in real-time, where fire is likely to spread overlaid with geospatially identified values-at-risk. WFDSS is focused on developing a risk assessment decision support tool that helps agency administrators and wildland fire managers make informed decisions for all wildland fires.

In 2009 WFDSS replaced the two primary existing decision support procedures used by US agencies with wildland fire responsibilities including the Wildland Fire Situation Analysis (for escaped wildland fires) and Wildland Fire Implementation Plan (for wildland fire use fires). The Wildland Fire Situation Analysis (WFSA) process relied upon the judgment of local decision makers to define a set of suppression strategies, associated possible outcomes in terms of fire extent and damage, and the likelihood of the strategy achieving the defined target outcome. The uncertainty associated with making these projections was a critical challenge in providing confidence in the established strategies. For example a survey conducted by Gonzalez-Caban and MacGregor (1998) identified that WFSA users felt they had inadequate experience and information to properly perform the analysis. Donovan and Noordijk (2005) identified errors within the WFSA in terms of estimated probabilities of outcomes, with managers tending to underestimate the likelihood of meeting an established target while overestimating the likelihood of rare events. Field testimonial on the value of the WFDSS in improving fire management decision making has been published in Scientific American (Andrews et al., 2007) and Wildfire Magazine (McDaniel, 2006 and 2007). Additionally, the value of WFDSS in improving wildfire risk management have been highlighted in numerous agency reports including the 2008 Fire and Aviation Management Accountability Report (USDA Forest Service, 2009), the 2009 Quadrennial Fire Review (USDA and USDOI 2009), and each of the annual Forest Service Budget Summaries between 2008 and 2011 (USDA Forest Service, 2010).

RAVAR identifies highly valued resources (HVR) threatened by ongoing large fire events. The RAVAR analytic model produces two distinct map products and associated reports, referred to as Critical Infrastructure (CI) and Natural and Cultural Resources (NCR). In the CI reports private structures, public infrastructure, public reserve areas, and hazardous waste sites are mapped and quantified. Public infrastructure includes water supply systems and reservoirs, major power lines, pipelines, communication towers, recreation facilities, and other significant landmarks. CI also identifies designated wilderness and roadless areas, wild and scenic river corridors, and national recreation areas. Superfund sites and mines are mapped and reported along with other HAZMAT locations. Fig. 1 demonstrates a CI RAVAR report for the Zaca Fire, the second largest fire in modern California fire history, which threatened numerous critical infrastructure elements including private residences, oil and gas pipelines, communication towers, and municipal supply watersheds.

Currently, resource values identified within RAVAR are presented in their natural unit measurements (e.g., number of structures and

[2] RAVAR has been typically integrated with the FSPro model to identify the likelihood of different resources being impacted in the potential fire path of an ongoing event, but can be linked to any expected fire spread polygon.

Table 1
Typology describing the major components and primary differences of the risk assessment tools described in this paper.

	WFDSS-RAVAR	ArcFuels and FlamMap	National wildland fire hazard and risk assessment
Scale	Incident	Watershed, to National forest	State and larger
Fires considered	Individual escaped fire	Typical severe burn event developed from local data	All ignitions
Planning horizon	Days to weeks	1–10 years depending on the fire regime	1–10 years depending on the fire regime
Simulation type	One fire many weather scenarios	Many fires, extreme weather scenarios	Many fires, many weather scenarios
Decisions supported	Suppression strategy, allocation of suppression resources	Fuel treatment prioritization based on local values, decision support for fuel treatment projects	National budget allocation and risk monitoring, strategic decision support

number of nesting sites), and information is not included regarding the likely value change to these resources due to fire. Although for some resources monetization is possible (e.g., structure value and commercial timber value), Boyd (2004) suggested that for planning purposes, natural resource values be presented in natural units, recognizing the complexity and sensitivity of assigning monetary value to natural resources. Venn and Calkin (in press) identified the challenges and limited availability of economic research that are needed to monetarily quantify net-value change to non-market resource values. At present, therefore, RAVAR is limited to exposure analysis, a crucial but not comprehensive step in wildfire risk assessment. Although the lack of monetary valuation for these resources results in subjective decision making compared to traditional benefit cost analysis, tradeoffs among competing strategies (e.g. acres of habitat versus structures impacted by wildfire) may be articulated using concrete quantitative measures. Identifying for fire managers which resources are likely to be impacted by fire reduces uncertainties surrounding suppression decision making, while allowing for flexibility regarding prioritization and local knowledge of resources and their likely response to fire.

Given the national scope of the RAVAR model inclusion of likely resource value change (effects analysis) is not included due to the challenges with identifying nationally consistent measures. However, local scale assessments that evaluate change in resource condition due to wildfire using tools such as the Fire Effects Planning Framework (Black and Opperman, 2005) could easily be incorporated into RAVAR by local analysts. Testing of alternative hypothetical wildfires in the off season through WFDSS could significantly improve fire management plans by allowing managers experience in distinguishing between potentially high risk wildfires and those wildfires that provide opportunities for resource benefit.

Development of the WFDSS-RAVAR system required extensive data acquisition, interpretation and presentation, coordination with fire behavior modelers, and comprehension of decision support needs of the fire management community. WFDSS-RAVAR has revolutionized wildland fire exposure analysis by harnessing state-of-the-art

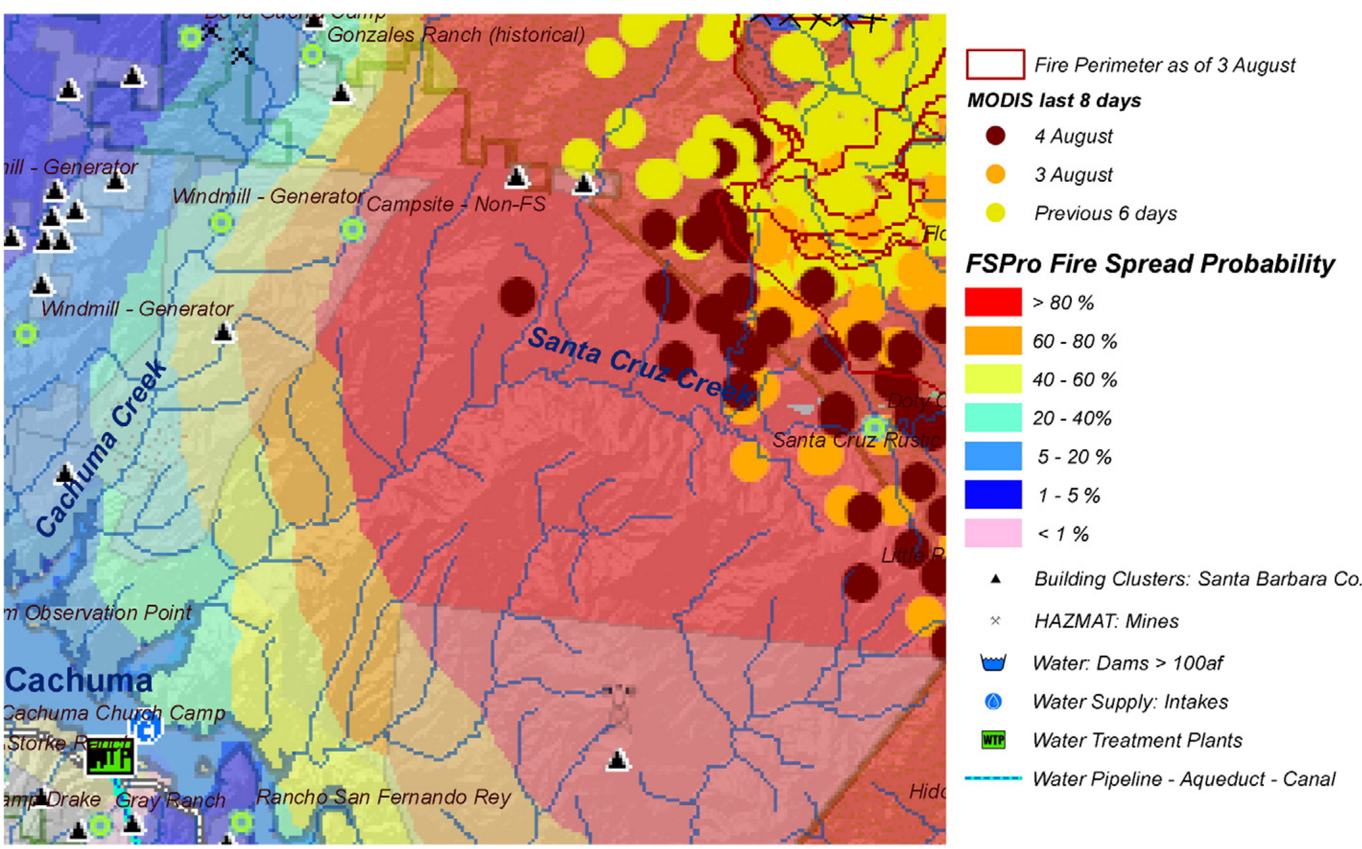

Fig. 1. Critical Infrastructure (CI) RAVAR map from the Zaca Fire, Santa Barbara County, California. The Zaca Fire was a large, long-duration event that threatened many types of critical infrastructure, including private residences, oil and gas pipelines, communication towers, and municipal supply watersheds. This map pairs spatial burn probability estimates with values-at-risk. The third component of risk assessment, resource value change in response to fire, is not yet integrated into RAVAR. Therefore RAVAR is a tool that performs exposure analysis and facilitates effects analysis, in order to provide an overall wildfire risk assessment decision support tool.
Map produced by Kevin Hyde.

tools and data sets. Use of WFDSS within Federal agencies is well established. From October 1, 2009 to September 30, 2010 (Federal fiscal year 2010), 11,579 fires were entered into WFDSS, including all federal initial attack type fires. During the same period, 606 fires evolved in complexity to an extended attack and required more advanced analyses and a published decision (Wildland Fire Management RDA Annual Report 2010). Outputs from the WFDSS-RAVAR have proven very useful in demonstrating risk-informed fire management to the agencies' partners and affected communities. Adoption of WFDSS provides an opportunity to significantly influence social interpretation of fire management policy by demonstrating opportunities to improve the efficiency of wildfire management; both in terms of pecuniary costs to taxpayers and also improved awareness and ability to protect values-at-risk.

3.2. ArcFuels

Fuel reduction activities on Federal lands are generally difficult to plan and implement due to cost, public expectations, limited operating windows, and land management regulations. Fuel reduction programs must balance multiple, and often competing, resource management objectives, and state of the art wildfire modeling is frequently used to analyze the potential benefits of fuel reduction treatments and defend the proposed action. Moreover, the need to develop both stand-specific prescriptions (Keyes and O'Hara, 2002; Stephens et al., 2009) and landscape-scale wildfire behavior requires multiple models and geospatial data sets (Reinhardt et al., 2008).

ArcFuels was developed to streamline fuel treatment planning for federal land management agencies (Ager et al., 2006a,b). The system consists of a customized version of ArcMap (ESRI, Redland CA) that links GIS functionality with vegetation and wildfire behavior models. The system facilitates the development, testing, and refining of landscape fuel treatment designs as well as stand-specific prescriptions. ArcFuels includes (1) interactive linkages between digital imagery, vegetation data, the Forest Vegetation Simulator (FVS, Dixon et al., 2003), and the Stand Visualization System (SVS, McGaughey, 2002), to create a geospatial interface for designing and testing stand-based fuel treatments; (2) tools to scale-up individual stand treatments to build landscape fuel management projects, and (3) data linkages to FlamMap and FARSITE for simulating landscape fire behavior and evaluating fuel treatment scenarios. ArcFuels is used by a number of operational and research units in the Forest Service and other land management agencies to design fuel treatment projects. The system was originally designed specifically for automating geospatial analyses performed in the Fireshed Assessment process (Bahro et al., 2006) where fuel treatments are designed and tested by stakeholders in a collaborative setting.

With respect to risk analysis, ArcFuels streamlines the use of burn probability (BP) modeling with FlamMap (Finney, 2006). Burn probability outputs from FlamMap estimate the likelihood of a pixel burning given a single ignition under burn conditions in the simulation. The likelihood measures are required for quantitative risk assessments. The FlamMap software makes it feasible to rapidly generate BP surfaces for large landscapes and for different management scenarios (Ager et al., 2010). Burn probability represents a major advancement in wildfire behavior modeling compared to previous methods, such as those where fire likelihood was quantified with relatively few (<10) predetermined ignition locations (Stratton, 2004; Roloff et al., 2005; LaCroix et al., 2006; Loureiro et al., 2006; Ryu et al., 2007; Schmidt et al., 2008). The purpose of such analyses is usually to evaluate a problem fire or known problem weather conditions for a single fire and to test the efficacy of fuel treatments in altering fire outcomes. BP estimated with FlamMap represents a conditional probability that can be used to compare fuel treatment alternatives and to quantify change to relative risk. Newer models described below include spatio-temporal probabilities for ignition, escape, and burn conditions to estimate annual burn probabilities (Finney et al., in press).

The use of these planning tools to incorporate risk analysis in fuel treatment project planning on federal lands is slowly increasing following several case studies demonstrating their application. For instance, landscape risk analysis was used to compare treatment alternatives in studies by Ager et al. (2007, 2010). In the former, wildfire risk was calculated for northern spotted owl (*Strix occidentalis caurina*) habitat in central Oregon (Fig. 2). The study demonstrated the feasibility of conducting operational risk analysis for habitat conservation planning and quantified the change in risk from several fuel treatment options (Fig. 2). In the second study (Ager et al., 2010), risk analysis was used to demonstrate tradeoffs between restoration management objectives on wildlands (fire resilient large trees) and the protection of residential structures in the urban interface. The former was quantified using the expected mortality of large trees (Eq. (1), Fig. 3), and the latter with burn probability–intensity profiles (Fig. 4). Structure loss functions from wildfires are difficult to build and implement in landscape fire simulation models (Cohen, 1999), hence both likelihood and intensity were used as surrogates for structure risk. These results quantified relative risk to human and ecological values without detailed loss benefit functions. In subsequent work (Ager unpublished) scatterplots of flame length and burn probability were created for wildland urban interface (WUI) areas adjacent for the national forest lands in the state of Oregon and Washington (Fig. 5). These plots can be used to prioritize fuel management activities to the WUI areas with the highest burn probability and flame length.

In addition to the application of ArcFuels and risk analyses for fuel treatment planning, we envision the use of these tools for developing risk-based resource and fire management plans such that risk from wildfire incidents can be better managed.

3.3. National wildland fire hazard and risk assessment

The Wildland Fire Leadership Council's (WFLC) monitoring strategy posed the following question: "What are the trends and changes in fire hazard on federal lands?" The Assessment includes a process to evaluate fire hazard characterized as likelihood of wildfire by intensity level, but goes further by developing techniques to estimate potential beneficial and negative effects to valued resources from fire at different intensity levels, thereby creating an analytical wildfire risk assessment framework (Calkin et al., 2010; Thompson et al., in press(a)). The research was designed to develop, from a strategic view, a first approximation of how both fire likelihood and fire intensity influence risk to social, economic, and ecological values at the national scale. The approach used a novel quantitative risk framework that approximates expected fire-related losses and benefits to highly valued resources. Burn probabilities and intensities were estimated with a fire simulation model and coupled with spatially explicit data on human and ecological values and fire-effects response functions to estimate the percent loss or benefit.

The burn probabilities and fire behavior were modeled using the FSim program on each of 137 fire planning units (FPU) covering the continental United States (Finney et al., in press). The methods used in this simulation rely on historical weather data from a single weather station in each FPU. The weather data were used for obtaining wind probabilities (speed and direction) and for generating daily National Fire Danger Rating index values of ERC (Energy Release Component) for the past 10 years. ERC reflects the amount of energy released during flaming combustion and is dependent on rainfall, humidity, and air temperature sequences. The sequence of weather conditions is also critically important to the growth and behavior of large fires. To capture the potential variability associated with the limited set of historical weather observations, a time-series analysis of historical ERC was conducted for each FPU. This analysis produced an auto-regressive model of historical seasonal and daily ERC, which was then

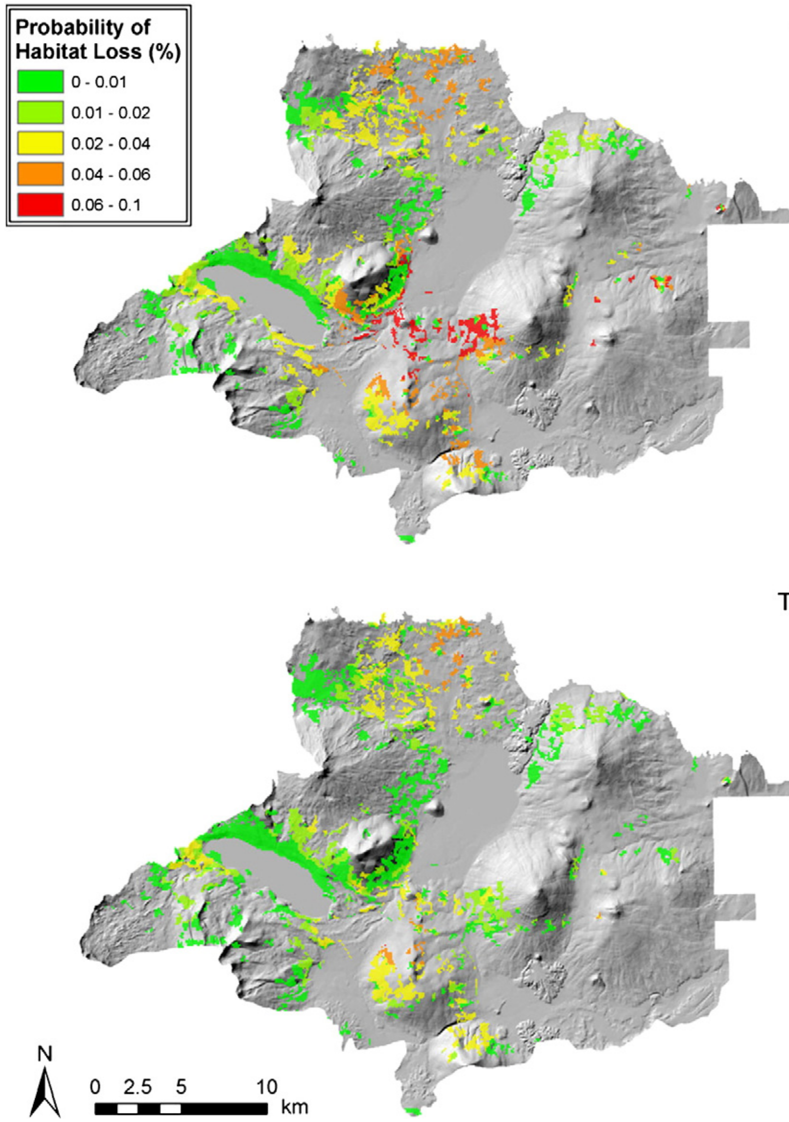

Fig. 2. Map from Ager et al. (2007) of the Five Buttes planning area on the Deschutes National Forest in Oregon US, showing expected habitat loss for the northern spotted owl (*Strix occidentalis*) for two management scenarios (no treatment versus treat 20% of study area). The expected loss is calculated for a single randomly located ignition and severe burn event. The latter was modeled using data from a recent wildfire within the planning area. The expected habitat loss is a subset of the burn probability, and is the probability of a fire with sufficient intensity to eliminate stand structure conditions required for spotted owl habitat. The analyses demonstrated methods to develop quantitative response functions for wildlife habitat that can be applied to other wildlife conservation problems.

used to generate a very large sample of artificial ERC seasons that represent the statistical variability in fire weather. Daily ERC values in these modeled sequences were converted to fuel moisture contents (percentages) required for input to fire behavior models based on the average historical fuel moisture values associated with each ERC percentile. Large fire occurrence was also related to the daily ERC values using logistic regression relationships developed from historical fire occurrence data (Andrews et al., 2003). The simulations were run for 20,000 "years" at a 270 meter resolution and progressed day-by-day, generating artificial weather conditions, and stochastically determining large fire occurrence. When large fires occurred, the origin was determined randomly and fire growth was simulated for the remainder of the season or until suppression action contained the fire (Finney et al., 2009). Recorded at each location was the number of times fires burned (for estimating burn probability) and the intensity (flame length) used to estimate the probability distribution of intensity.

Response functions were used to translate fire intensity into net value change (NVC) to the described resource. In each response function, NVC is based on the flame length of the fire and represents both beneficial and adverse effects to the resource. Although fire outcomes could be related to any fire characteristic, response is typically related to some measure of fire intensity such as flame length (Ager et al., 2007; Finney, 2005). The approach used here quantified NVC to a given resource as the percentage changes in the initial resource value resulting from a fire at a given flame length. That is, response functions address relative rather than absolute change in resource or asset value.

A suite of stylized response functions was defined, after considering the different ways in which the various HVRs under consideration might respond to fire of different intensities. National leaders were engaged in order to assign response functions to specific HVRs. One function was assigned to each HVR. Cumulative hazard and risk ratings for the suite of highly valued resources were evaluated at the FPU and geographic area level for the continental US and Alaska with sensitivity analyses demonstrated in Thompson et al. (in press(b)). For example, Table 2 reports expected loss by highly valued resource category for the continental United States. The availability of

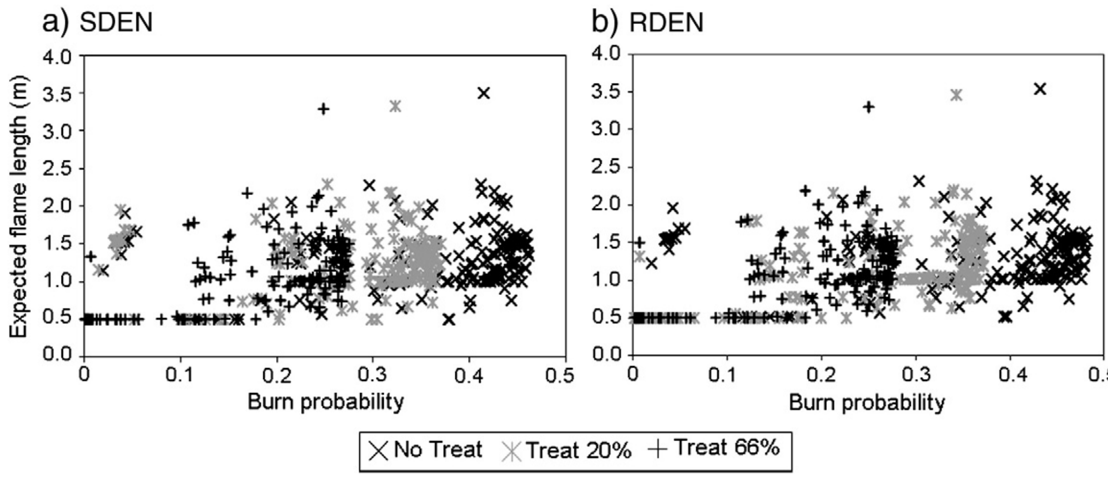

Fig. 3. Example of flame length and annual burn probability scatter plots from Ager et al. (2010) showing values for individual structures for the Mt Emily wildland urban interface in northeastern Oregon. The stand density (SDEN) and residential density (RDEN) scenarios used different spatial treatment priorities that emphasized fire resiliency in the wildlands versus protection of structures in the urban interface. Points are average values for all pixels within a 45.7 m radius around each structure. The figure shows that burn probability, and to a lesser extent flame length, can be reduced around structures when fuel treatments are located outside the interface to address forest restoration and create fire resilient forests.

nationally consistent fire behavior simulation results (generated on high end computing resources) provides researchers and managers opportunities for future comparative fire risk analysis at multiple scales. This research effort demonstrates the feasibility of integrated wildland fire risk assessment at the national scale and has potential applicability informing the Fire Program Analysis and future work to refine the National Cohesive Strategy on Fire and Fuels Management. This work significantly advances the field of effects analysis, to support national scale wildfire risk assessments.

4. Barriers to risk-based decision making

The three new wildfire risk management tools discussed above provide Federal agencies in the US the ability to support a range of management decision with risk-based analyses. However, there are several remaining institutional and socio-political barriers that will need to be addressed to fully realize the power of risk-based wildfire management. We have identified four primary issues that if properly addressed could help the agencies better realize the opportunities and

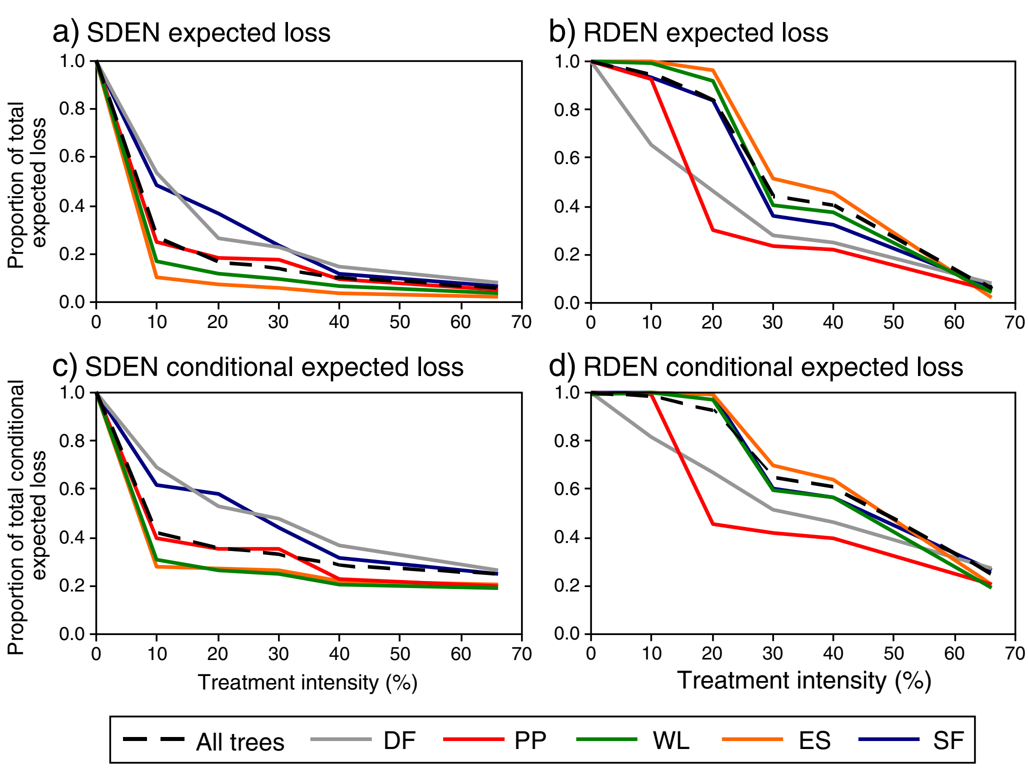

Fig. 4. Graph from Ager et al. (2010) showing the expected loss (Eq. (1)) and conditional loss given a stand burns of old growth trees (>53.3 cm diameter at 137.2 cm above ground) as a function of 6 treatment intensities and 2 spatial treatment scenarios (see Fig. 2). The graphs show that fuel treatments in the urban interface area (RDEN scenario) are relatively ineffective at reducing expected loss of large trees, compared to conducting similar treatments in the wildlands (SDEN scenario) to create a fire resilient landscape. Simulated fuel treatments consisted of thinning from below, site removal of surface fuel, and underburning. Species codes are: DF: Douglas-fir, PP: ponderosa pine, WL: western larch, ES: Engelmann spruce, SF: subalpine fir.

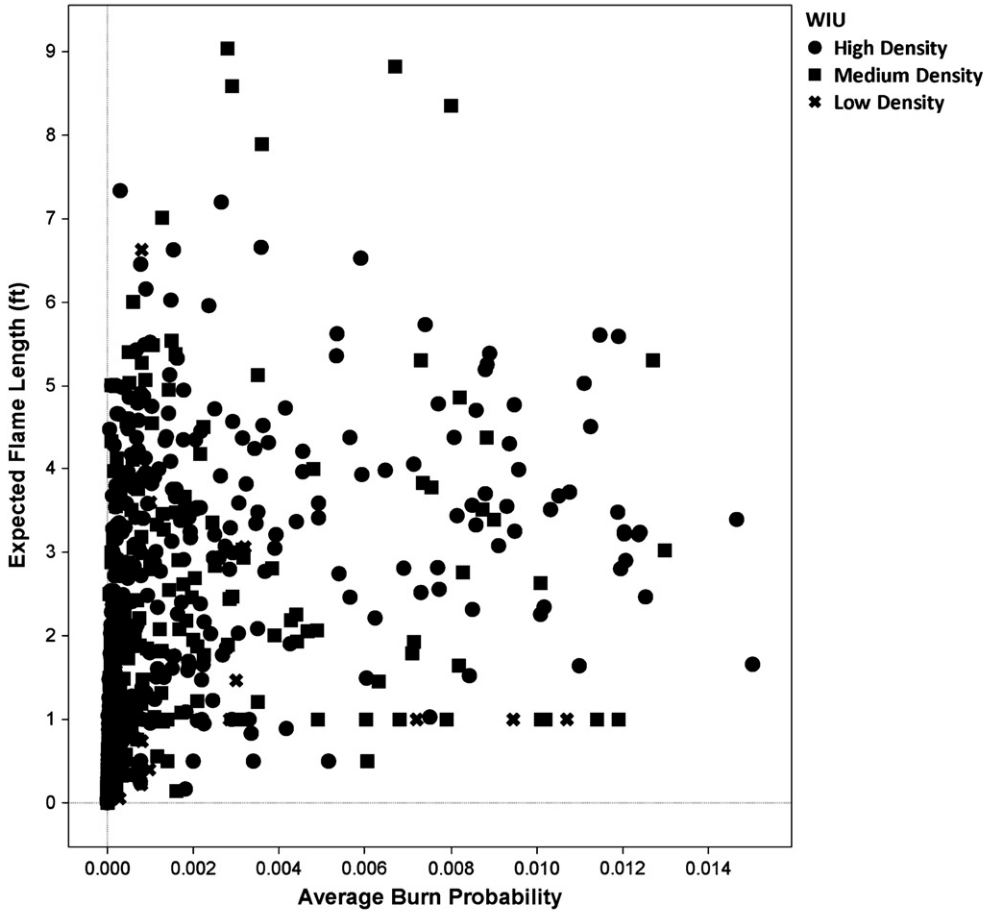

Fig. 5. Scatterplot of the average annual burn probability and expected flame length scatterplot for urban interface and intermix mapped by the Silvis project (http://silvis.forest.wisc.edu/library/wuilibrary.asp) for the state of Oregon and Washington. The plot shows relative risk as measured by wildfire likelihood and intensity for each polygon and can be used to prioritize mitigation efforts. Wildfire simulation outputs were obtained from Calkin et al. (2010).

potential payoffs from fully adopting a risk management paradigm. We conclude each section with a description of existing activities or potential approaches that may help address the identified barrier.

Table 2
Total hectares and expected loss by HVR category/layer at the national scale by value category for the National Wildfire Risk Assessment.
Published in Thompson et al., in press (b).

Value category	HVR category	HVR layer	Total hectares	Exp(loss) hectares
Moderate	Air quality	Class I airsheds	12,463,691	−8819
	Fire-adapted ecosystems	Ecosystems	29,888,286	17,396
	Recreation infrastructure	National trails/camps/sites	1,924,290	−181
	Total		44,276,267	8396
High	Built structures	Low density	16,628,505	−8069
	Energy/infrastructure	Energy/infrastructure	38,173,961	−3953
	Fire-susceptible species	Critical habitat	23,963,834	−35,321
		Sage-grouse key habitat	20,398,842	−51,933
	Recreation infrastructure	Ski area locations	363,071	23
	Total		99,165,142	−99,253
Very high	Air quality	Non-attainment areas	79,065,444	−54,467
	Built structures	Mod/high density	53,405,009	−16,891
	Watersheds	Watersheds	61,804,897	−13,416
	Total		194,275,350	−71,371

4.1. Incentives faced by land and fire managers in wildland fire situations

Donovan and Brown (2005 and 2007) identified the potential misalignment of incentives faced by wildfire managers. Selection of less aggressive wildfire management strategies may be constrained by intense social and political pressures as well as concern regarding the agency's support for managers who experience unintended consequences under less than full suppression strategies. In a series of interviews with Incident Management team command and general staff members (Canton-Thompson et. al. 2008), interviewees point to increased risk aversion and social–political pressure as major factors related to rising suppression costs. Interviewees stated that this increasing tendency towards risk aversion is caused by, among other things, a perceived lack of agency support if things should go wrong, accompanied by risk of personal liability. Emerging research by Donovan et al. (2011) suggests that “manager's cost”, in terms of career consequences or risk of personal liability, may be a significant contributing factor of suppression costs, with managers attempting to minimize these costs. Their results found that the seniority of federal congressional representatives, as well as newspaper coverage of the event both have a positive influence on suppression cost, all other things equal.

Pressures faced by managers to select aggressive, and possibly expensive, strategies do not appear to be counteracted through pressure to avoid unnecessary expenditures of federal taxpayer dollars. That is, the cost of utilizing additional suppression resources is born by the Agency as a whole through the national suppression cost pools with only limited impact to local mangers responsible for developing wildfire strategies. These incentives may encourage suppression expenditures in excess of the social welfare maximizing level for the US public as a whole (Donovan and Brown, 2005, 2007). Furthermore, the beneficial effects of the fuel treatment effect of allowing an existing fire to burn will typically be realized by future fire managers, not the ones engaged in the management of the current event. A recent survey of Forest Service line officers identified loyalty, team work, and achieving targets as the characteristics most rewarded by the Agency while the least rewarded included innovation, taking risks, and independence (Kennedy et al., 2005). These results suggest that implementing a new risk-based decision process will be difficult given the existing Forest Service reward structure.

A number of measures that seek to change the incentives facing the Agency administrator have been proposed. For example, Thompson et al. (in review) suggest an insurance based premium approach to wildland fire, where the individual National Forests contribute to the annual suppression fund based on expected expenditures. The annual premium could then be adjusted based on risk management performance with demonstrated high quality management being rewarded with lower future premium payments, thereby creating additional funds for the unit. Additionally, annual awards could be granted to agency administrators who demonstrate safe, cost-effective, risk-based fire management. Those awards could include individual prizes as well as grants intended to benefit local communities. Making clear that the grant is the result of improved risk management on the part of the agency administrator could serve to reduce sociopolitical pressures.

4.2. Goals within resource and fire management plans

Objectives for managing a single fire and/or fire on the landscape are defined within the land and fire management plans. Limited scientific understanding of how aggressive fire suppression response transfers risk to future periods along with local socio-political influences on fire management decisions may result in land and fire management plans that do not sufficiently consider the role of individual fires in achieving broader scale land management goals (Doane et al., 2006). Additionally, through the planning process we have placed multiple, potentially competing, goals on much of the landscape. When natural processes such as wildland fire conflict with one or more of these goals in the near term, management response tends towards aggressive suppression with limited consideration of the longer term effects to the resource values represented on the landscape. That is, short-term objectives within fire management plans that describe how wildfires under certain conditions should be managed may not align with the long-term desired future conditions described within the land management plans.

Improved risk assessment systems – such as WFDSS for incident management planning and ArcFuels for fuels treatment and resource management plan development – should provide opportunities for managers to explore how certain fire management decisions affect future risk to highly valued resources (both developed and natural resources) and landscape trajectories towards or away from desired future conditions. Further, these tools allow explicit consideration of the relative tradeoffs among competing resource objectives. The implementation of WFDSS will likely encourage future fire management plans to be developed using a more spatially defined framework. WFDSS, along with ArcFuels, provides managers the opportunity to test how alternative fire and fuels management strategies impact future risk to highly valued resources.

4.3. Risk management training

Application of risk management concepts requires training for both those charged with developing and implementing fire management strategies and their supervisors responsible for reviewing major strategies and individuals' performance. To our knowledge there is no formal risk management training offered within existing FS and Interagency fire training programs or for line-officer career development. Leadership will need to recognize that high-impact, hard-to-predict, and rare events will likely occur and those events must be evaluated based on how decision makers evaluated and addressed the risk inherent in the event, not the final outcome. There is also a lack of risk assessment training in the land management staff as well, especially in the fuel treatment planning process.

Appropriate risk management requires considerations of both negative and beneficial consequences to resources. Beneficial consequences could include both resource condition improvement and future risk reduction through reduced fuel levels. Prior to 2009 federal policy reinterpretation (Fire Executive Council, 2009), beneficial effects of wildfires managed under suppression were not allowed to be considered when developing management strategy. Therefore, it would not be surprising for managers to have limited understanding of and ability to quantify beneficial fire effects. Williamson (2007) suggests that Forest Service district rangers who frequently implement wildland fire use strategies do so because they are motivated by a belief that fire can do ecological good. Thus, an important component of risk management training should include procedures to identify and quantify likely benefits associated with wildland fire events.

Formal training for land and fire managers in risk management could be conducted through the National Wildfire Coordination Group (NWCG). The NWCG provides a formal curriculum for wildland firefighters, mangers, and agency administrators within the Unites States. However, currently no course exists that sufficiently addresses how to implement appropriate wildfire risk management concepts in strategic fire management decision making. The NWCG training program provides an established framework in which to conduct such a course with an intended audience of agency line officers and command and general staff of incident management teams (IMT) that are responsible for implementing fire management strategies.

4.3.2. Socio-political influences

Public expectations regarding the role of federal agencies in fire management are evolving; however, there may be a long way to go until a majority of the public understand and accept a risk management paradigm. Recent studies highlight the complexities of dealing with wildfire and the public. Canton-Thompson et al. (2008) found that many of the IMT members interviewed saw themselves as pulled in two ways. They saw residents of the WUI as often not understanding the complexities of firefighting and, therefore, often demanding full suppression of fire events. However, once the fire was over, other entities such as government oversight agencies, want to know why less aggressive strategies weren't used. Black et al. (2010) suggest that the public may not demand more aggressive strategies if adequate communication occurs between the government agencies and the local community regarding possible management alternatives before a fire event actually occurs. Results of the Black et al. (2010) study also suggest that public tolerance for fire impacts diminishes greatly when the fire duration exceeds two or three weeks, as community members' lives are impacted by disruption of normal routines and activities as well as ash and smoke.

Adopting a more risk-based approach to wildfire management is not only constrained by public perceptions, but also the need for federal managers to cooperate with local and state partners. Black et al. (2010) interviewed state and local cooperating fire agencies and county commissioners regarding the Forest Service's use of alternative (less than full suppression) fire management strategies. Most interviewees stated they did not support these actions. All the cooperators interviewed said that their mission included a full suppression mandate, and some were suspicious that anything less than full suppression was simply the federal agencies' way of trying to contain costs under declining budgets. Interviewees stated that differences in fire management mandates were making them increasingly reluctant to engage in cost share agreements with the agency. State and local cooperators do not believe they should have to pay for costs of an escaped resource benefits fire, which they perceive as essentially equivalent to a management ignited prescribed fire. Engaging in risk-based decision making for multi-jurisdictional fire incidents will continue to be problematic unless these issues can be resolved.

Similar to the need to educate federal land and fire managers regarding appropriate risk management, those who exert socio-political pressures on fire managers will need to be educated on risk-informed decision making. Increased transparency regarding the efficacy and cost of various suppression activities, and demonstration of the fuel treatment benefits of wildfire could increase community support for allowing certain wildfires to burn under favorable, low-risk circumstances. These educational efforts should extend to our cooperating state and local fire management agencies. Issues surrounding conflicting fire management mandates may be mitigated with a fuller understanding of why decisions are being made. An important element of this education is that it needs to occur long before the smoke is in the air. As Dombeck et al. (2004) point out, "although changing public attitudes regarding fire will be difficult, it is necessary for the development of effective wildfire policy."

5. Discussion and concluding remarks

In this paper we reviewed three emerging risk-based decision support tools that address a range of fire management issues at a variety of scales using a common actuarial risk framework. Although these tools have been developed with a focus on US federal wildland fire management similar risk-based approaches are evolving in other countries (see for example Chuvieco et al., 2010). Additionally, we discussed several barriers to full adoption of risk-based decision making frameworks within the US. Although we focus on these three tools, a variety of other risk-based models are emerging to address the spectrum of fire and fuels management issues. We believe the tools described here collectively constitute a risk-based decision support system that advances the application of risk science to address growing wildfire issues.

A variety of challenges will need to be addressed to fully realize the potential of risk-based decision making to improve the ecological and financial health of public land agencies. Beyond the institutional and socio-political barriers to broad acceptance of the risk management paradigm, there remain myriad sources of scientific uncertainty challenging wildfire risk analysis. The challenges to fully implementing the current suite of models can be grouped into four categories: 1) temporal considerations are not evaluated within the risk framework upon which these models are based (see Eq. (1)); for example increased future fire risk due to climate change or aggressive suppression that reduces the size of an ongoing fire is not considered within the existing suite of tools, 2) the effects of wildfire on many natural resource values depend on the location and spatial pattern of the values; these highly valued natural resources are defined and managed at local scales, making large scale assessments challenging, 3) estimating expected change in resource condition is difficult due to scientific uncertainty regarding resource response and confounding spatial and temporal considerations (Keane et al., 2008), and 4) substantial uncertainty remains regarding relative social preferences for non-commensurate resources (e.g. the value of a recreation area compared to wildlife habitat), and the state of non-market valuation is ill-equipped to incorporate price-based approaches within wildfire risk analysis (Venn and Calkin, 2009). Though these challenges are substantial, a thorough review of scientific research needs is beyond the scope of this paper (see for example Thompson et al., in press(c)). Resource scientists could in the future synthesize extant challenges and identify opportunities for the wildfire research community. In the preceding chapter we focused specifically on barriers to acceptance of a risk paradigm, not barriers to risk analysis themselves.

Despite these known scientific limitations, the challenges described within this paper primarily focus on the current environment in which fire managers operate; specifically a misaligned incentive structure, a lack of formal education in risk management, and excessive socio-political influence. It is our contention that by thoughtfully considering the recommendations introduced in this paper in order to better our ability to use developing risk-based frameworks, the Forest Service and other US federal agencies will be better able to effectively and efficiently manage wildfire. Improved understanding and management of risk is important across the range of fire management activities. For instance, ArcFuels and the National Wildland Fire Hazard and Risk Assessment provide opportunities to explore risk management concepts within a land management planning environment to develop background knowledge that could translate into better suppression decisions on active wildfires.

The recent development and application of wildfire risk models have been an important step in agencies demonstrating their commitment to improved decision making. In 2009 the GAO published a report titled: "Federal Agencies Have Taken Important Steps Forward, but Additional Action Is Needed to Address Remaining Challenges" (GAO, 2009). One of the important steps highlighted was the success of WFDSS in enhancing the decision making response to wildland fire through improved analytical tools and guidance to managers. Improved information delivery using risk-based frameworks has the potential to improve wildfire response; however, the suppression strategy is ultimately the responsibility of the local line officer and fire manager. It is clear that improved risk assessment across the scale of fire management will not alone 'solve' the problem of escalating costs and increasing threat to human and ecological values. A variety of confounding factors including a changing climate and increased human development into fire-prone areas will continue to challenge Federal agencies' ability to manage wildfire costs. There is a need to consider a broad spectrum of approaches including improved communication with communities (Dombeck et al., 2004), partnerships with insurers to better incorporate wildfire losses into homeowner premiums, and engagement with local planning boards to improve zoning and development standards such as 'fire-wise' in fire prone areas. Achieving the full potential of risk-based management will require that Federal agencies engage in a continuous improvement process with focus on the guidance, training and support for decision makers as well as enhanced communication with partners and the affected community.

We have been given the resources and opportunities to improve risk-based decision support systems; here we offer a call to improve the ability of managers to use them. Risk-based fire management is a concept that can serve to bring fire managers, cooperators, and the public together by providing a common, scientifically-based framework for supporting decisions and for explaining decision rationales.

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References

Agee, J.K., Bahro, B., Finney, M.A., Omi, P.N., Sapsis, D.B., Skinner, C.N., van Wagtendonk, J.W., Weatherspoon, C.P., 2000. The use of shaded fuelbreaks in landscape fire management. Forest Ecology and Management 127, 55–66.

Ager, A.A., Vaillant, N., Finney, M.A., 2010. A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. Forest Ecology and Management 259, 1556–1570.
Ager, A.A., Finney, M.A., Bahro, B., 2006b. Using ArcObjects for automating fireshed assessments and analyzing wildfire risk. Proceedings of the International ESRI Users Conference, San Diego, August 7–11, 2006. http://gis.esri.com/library/userconf/proc06/papers/papers/pap_1547.pdf.
Ager, A.A., Bahro, B., Finney, M.A., 2006a. Automating fireshed assessments and analyzing wildfire risk with ArcObjects and ArcGIS. Forest Ecology and Management 234S, 215.
Ager, A.A., Finney, M.A., Kerns, B.K., Maffei, H., 2007. Modeling wildfire risk to northern spotted owl (*Strix occidentalis* caurina) habitat in Central Oregon, USA. Forest Ecology and Management 246, 45–56.
Andrews, P.L., Loftsgaarden, D.O., Bradshaw, L.S., 2003. Evaluation of fire danger rating indexes using logistic regression and percentile analysis. International Journal of Wildland Fire 12, 213–226.
Andrews, P.L., Finney, M.A., Fischetti, M., 2007. Modeling wildland fires. Scientific American 297 (2), 32–39.
Bahro, B., Barber, K., Perrot, L., Sherlock, J., Taylor, A., Wright, K., Yasuda, D., 2006. Using fireshed assessments to measure landscape performance. 1st Fire Behavior and Fuels Conference Fuels Management — How to Measure Success March 28–30, 2006. Portland, Oregon. Abstract http://www.iawfonline.org/pdf/overview-shtml.pdf.
Black, A., Gebert, K., Steelman, T., McCaffrey, S., Canton-Thompson, J., Stalling, C., 2010. The interplay of AMR, suppression costs, agency–communication interaction, and organizational performance — a multi-disciplinary approach. Joint Fire Science Program Final Report 08-1-4-01.
Black, A., Opperman, T., 2005. Fire Effects Planning Framework: a user's guide. Gen. Tech. Rep.*GTR-RMRS-163WWW*. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO. 63 p.
Boyd, J., 2004. What's nature worth? Using indicators to open the black box of ecological valuation. Resources for Future. Summer 18–22.
Calkin, D., Ager, A., Gilbertson-Day, J., Scott, J., Finney, M., Schrader-Patton, C., Quigley, T., Strittholt, J., Kaiden, J., 2010. Wildland Fire Risk and Hazard: Procedures for the First Approximation. RMRS-GTR-235. 62 p.
Calkin, D.E., Thompson, M.P., Finney, M.A., Hyde, K.D., in press. A real-time risk-assessment tool supporting wildland fire decision-making. Journal of Forestry.
Calkin, D., Jones, G., Hyde, K., 2008. Nonmarket resource valuation in the postfire environment. Journal of Forestry 106 (6), 305–310.
Canton-Thompson, J., Gebert, K.M., Thompson, B., Jones, G., Calkin, D., Donovan, G., 2008. External Human Factors in Incident Management Team Decision making and Their Effect on Large Fire Suppression Expenditures. Journal of Forestry 106 (8), 416–424.
Chuvieco, E., Aguado, I., Yebra, M., Nieto, H., Salas, J., Martín, M.P., Vilar, L., Martínez, J., Martín, S., Ibarra, P., de la Riva, J., Baeza, J., Rodríguez, F., Molina, J.R., Herrera, M.A., Zamora, R., 2010. Development of a framework for fire risk assessment using remote sensing and geographic information system technologies. Ecological Modeling 221, 46–58.
Cohen, J.D., 1999. Reducing the Wildland Fire Threat to Homes: Where and how much? USDA Forest Service General Technical Report PSW-GTR-173. Pp. 189–195 in A. Gonzalez-Caban and P. N. Omi (tech. coords.), Proceedings of the symposium on fire economics, planning, and policy: bottom lines.
Department of Interior Geological Survey, 2009. The National Map LANDFIRE: LANDFIRE National Existing Vegetation Type layer. Retrieved May 5, 2009, http://www.landfire.gov/.
Dimopoulou, M., Giannikos, I., 2004. Towards and integrated framework for forest fire control. European Journal of Operational Research 152, 476–486.
Dombeck, M.P., Williams, J.E., Wood, C.A., 2004. Wildfire policy and public lands: integrating scientific understanding with social concerns across landscapes. Conservation Biology 18 (4), 883–889.
Dixon, G.E., et al., 2003. Essential FVS: a user's guide to the Forest Vegetation Simulator. Internal Rep. Fort Collins, CO: USDA, Forest Service, Forest Management Service Center. 193 p.Dombeck, M.P., Williams, J.E., Wood, C.A., 2004. Wildfire Policy and Public Lands: Integrating Scientific Understanding with Social Concerns across Landscapes. Conservation Biology 18 (4), 883–889.
Doan, D., O'Lauglin, J., Morgan, P., Miller, C., 2006. Barriers to wildland fire use: a preliminary problem analysis. International Journal of Wilderness 12, 36–38.
Donovan, G.H., Brown, T.C., 2005. An alternative incentive structure for wildfire management on national forest land. Forest Science 51 (5), 387–395.
Donovan, G.H., Noordijk, P., 2005. Assessing the Accuracy of Wildland Fire Situation Analysis (WFSA) Fire Size and Suppression Cost Estimates. Journal of Forestry 103 (1), 10–13.
Donovan, G.H., Brown, T.C., 2007. Be careful what you wish for: the legacy of Smokey the Bear. Frontiers in Ecology and the Environment 5 (2), 73–79.
Donovan, G.H., Prestemon, J.P., Gebert, K., 2011. The effect of newspaper coverage and political pressure on wildfire suppression costs. Society and Natural Resources. doi:10.1080/08941921003649482.
Fairbrother, A., Turnley, J.G., 2005. Predicting risks of uncharacteristic wildfires: application of the risk assessment process. Forest Ecology and Management 211, 28–35.
Finney, M.A., 2002. Fire growth using minimum travel time methods. Canadian Journal of Forest Research 32 (8), 1420–1424.
Finney, M.A., 2005. The challenge of quantitative risk assessment for wildland fire. Forest Ecology and Management 211, 97–108.
Finney, M.A., 2006. An overview of FlamMap fire modeling capabilities. USDA Forest Service General Technical Report RMRS-P-41, pp. 213–220.
Finney, M.A., Seli, R.C., McHugh, C.W., Ager, A.A., Barho, B., Agee, J.K., 2007. Simulation of long-term landscape-level fuel treatment effects on large wildfires. International Journal of Wildland Fire 16 (6), 712–727.
Finney, M.A., Grenfell, A.C., McHugh, C.W., Seli, R.C., Trethewey, D., Stratton, R.D., Brittain, S., 2011a. A method for ensemble wildland fire simulation. Environmental Modeling and Assessement 16 (2), 153–167.
Finney, M.A., McHugh, C.W., Grenfell, I.C., Riley, K.L., Short, K.C., 2011b. A simulation of probabilistic wildfire risk components for the continental United States. Stochastic Environmental Research and Risk Assessment. doi:10.1007/s00477-011-0462-z.
Finney, M.A. In press. Simulation of burn probabilities and fire size distributions for the continental United States. Stochastic Environmental Research and Risk Assessment.
Finney, M.A., Grenfell, I.C., McHugh, C.W., 2009. Modeling large fire containment using generalized linear mixed model analysis. Forest Science 55 (3), 249–255.
Fire Executive Council, 2009. Guidance for Implementation of Federal Wildland Fire Management Policy. http://www.nifc.gov/policies/guidance/GIFWFMP.pdf. Last Accessed May 28, 2010.
Fire Program Analysis, 2010. Fire Program Analysis website. http://www.fpa.nifc.gov/2010 Last accessed April 12, 2010.
Government Accountability Office (GAO), 2009. Wildland Fire Management: Federal Agencies Have Taken Important Steps Forward, but Additional Action is Needed to Address Remaining Challenges. GAO-09-906-T. Washington, D.C., July 21, 2009.
Gonzalez-Caban, A., MacGregor, D.G., 1998. Improving decision making process for the Forest Service Wildland Fire Situation Analysis. In Proceedings: Third International Conference on Forest Fire Research. Luso, Portugal, November 16–20.
Gude, P., Rasker, R., Van den Noort, J., 2008. Potential for future development on fire prone lands. Journal of Forestry 106, 198–205.
Hummel, S., Calkin, D.E., 2005. Costs of landscape silviculture for fire and habitat management. Forest Ecology and Management 207 (3), 385–404.
Havis, R.N., Crookston, N.L., et al., 2008. Third forest vegetation simulator conference. 2007 February 13–15; Fort Collins, CO. USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-54. Fort Collins, CO: 234 p.
Hessburg, P.F., Reynolds, K.M., Keane, R.E., James, K.M., Salter, R.B., 2007. Evaluating wildland fire danger and prioritizing vegetation and fuel treatments. Forest Ecology and Management 247, 1–17.
Iliadis, L.S., 2005. A decision support system applying an integrated fuzzy model for long-term forest fire risk estimation. Environmental Modelling and Software 20 (5), 613–621.
Irwin, L.L., Wigley, T.B., 2005. Relative risk assessments for decision-making related to uncharacteristic wildfire. Forest Ecology and Management 211 (1–2), 1–2.
Keane, R.E., Agee, J.K., Fule, P., Keeley, J.E., Key, C., Kitchen, S.G., Miller, R., Schulte, L.A., 2008. Ecological effects of large fires on US landscapes: benefit or catastrophe? International Journal of Wildland Fire 17, 696–712.
Kennedy, J.J., Haynes, R.H., Zhou, X., 2005. Line Officers' Views on Stated USDA Forest Service Values and the Agency Reward System. USDA Forest Service General Technical Report PNW-GTR-632.
Kerns, B., Ager, A.A., 2007. Risk assessment for biodiversity in Pacific Northwest forests. Forest Ecology and Management 246, 38–44.
Keyes, C.R., O'Hara, K.L., 2002. Quantifying stand targets for silvicultural prevention of crown fires. Western Journal of Applied Forestry 17, 101–109.
Kim, Y.-H., Bettinger, P., Finney, M., 2009. Spatial optimization of the pattern of fuel management activities and subsequent effects on simulated wildfires. European Journal of Operational Research. 197, 253–265.
Konoshima, M., Albers, H.J., Montgomery, C.A., Arthur, J.L., 2010. Optimal spatial patterns of fuel management and timber harvest with fire risk. Canadian Journal of Forest Research 40 (1), 95–108.
LaCroix, J.J., Ryu, S.R., Zheng, D., Chen, J., 2006. Simulating fire spread with landscape management scenarios. Forest Science 52, 522–529.
Landkoande, M., Yoder, J., Wandschneider, P., 2005. Optimal wildfire insurance in the wildland-urban interface in the presence of a government subsidy for fire risk mitigation. Available at: http://ideas.repec.org/p/wsu/wpaper/yoder-9.html accessed 1/4/2011.
Lehmkuhl, J.F., Kennedy, M., Ford, D.E., Singleton, P.H., Gaines, W.L., Lind, R.L., 2007. Seeing the forest for the fuel: integrating ecological values and fuels management. Forest Ecology and Management 246, 73–80.
Loureiro, C., Fernandes, P., Botelho, H., Mateus, P., 2006. A simulation test of a landscape fuel management project in the Marao range of northern Portugal. Forest Ecology and Management 234S, S245.
Massada, A.B., Radeloff, V.C., Stewart, S.I., Hawbaker, T.J., 2009. Wildfire risk in the wildland-urban interface: a simulation study in northwestern Wisconsin. Forest Ecology and Management 258, 1990–1999.
McDaniel, J., 2006. When things get busy: FSPro and RAVAR. Wildfire Magazine Fall 2006. Available at: http://www.wildfirelessons.net/Additional.aspx?Page=83.
McDaniel, J., 2007. WFDSS: taking decision support into the 21st century. Wildfire Magazine Fall 2007. Available at: http://www.wildfirelessons.net/Additional.aspx?Page=96.
McDaniel, J., 2009. The emergence and potential of new wildfire risk assessment tools wildfire lessons learned. Fall 2009. Available at: http://www.wildfirelessons.net/Additional.aspx?Page=285. Accessed 12/15/10.
McGaughey, R.J., 2002. Creating visual simulations of fuel conditions predicted by the fire and fuels extension to the Forest Vegetation Simulator. In: Crookston, N.L., Havis, R.N. (Eds.), Second forest vegetation simulator conference. RMRS-P-25. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
Murnane, R.J., 2006. Catastrophe risk models for wildfires in the wildland-urban interface: what insurers need. Natural Hazards Review 7, 150–156.
O'Laughlin, J., 2005. Conceptual model for comparative ecological risk assessment of wildfire effects on fish, with and without hazardous fuel treatment. Forest Ecology and Management 211, 59–72.
Parisien, M-A, Kafka, V., Hirsch, K.G., Todd, J.B., Lavoie, S.G., Maczek, P.D., 2005. Mapping wildfire susceptibility with the BURN-P3 simulation model. Natural Resources

Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton. Northern Forestry Centre Information Report NOR-X-405. 36 pp.

Peterson, D.L., Evers, L., Gravenmier, B., Eberhardt, E., 2007. A consumer guide: tools to manage vegetation and fuels. USDA Forest Service General Technical Report PNW-GTR-690. Pacific Northwest Research Station, Portland, OR.

Peterson, R.M., Robertson, F.D., Thomas, J.W., Dombeck, M.P., Bosworth, D.N., 2008. Statement of R. Max Peterson, F. Dale Robertson, Jack Ward Thomas, Michael P. Dombeck, and Dale N. Bosworth, Retired Chiefs of the Forest Service, on the FY2008 Appropriation for the U.S. Forest Service. Available at: http://www.arborday.org/replanting/firechiefs.cfm. Last accessed 05 November 2009.

Prestemon, J.P., Abt, K., Gebert, K., 2008. Suppression cost forecasts in advance of wildfire seasons. Forest Science 54 (4), 381–396.

Reinhardt, E.D., Keane, R.E., Calkin, D.E., Cohen, J.D., 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Forest Ecology and Management 256, 1997–2006.

Reinhardt, E.D., Keane, R.E., Brown, J.K., 1997. First-order fire effects model:FOFEM 4.0 users guide. General Technical Report INT-GTR-344, USDA Forest Service.

Rideout, D.B., Ziesler, P.S., Kling, R., Loomis, J.B., Botti, S.J., 2008. Estimating rates of substitution for protecting values at risk for initial attack planning and budgeting. Forest Policy and Economics 10, 205–219.

Roloff, G.J., Mealey, S.P., Clay, C., Barry, J., Yanish, C., Neuenschwander, L., 2005. A process for modeling short- and long-term risk in the southern Oregon Cascades. Forest Ecol. Manag. 211, 166–190.

Ryu, S.R., Chen, J., Zheng, D., LaCroix, J.J., 2007. Relating surface fire spread to landscape structure: An application of FARSITE in a managed forest landscape Landscape and Urban Planning 83, 275–283.

Schmidt, D.A., Taylor, A.H., Skinner, C.N., 2008. The influence of fuels treatment and landscape arrangement on simulated fire behavior, Southern Cascade range. California. Forest Ecology and Management 255, 3170–3184.

Stephens, S.L., Moghaddas, J.J., Edminster, C., Fiedler, C.E., Haase, S., Harrington, M., Keeley, J.E., Knapp, E.E., McIver, J.D., Metlen, K., Skinner, C.N., Youngblood, A., 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. Ecological Applications 19, 305–320.

Stratton, R.D., 2004. Assessing the effectiveness of landscape fuel treatments on fire growth and behavior. Journal of Forestry 102, 32–40.

Thompson, M.P., Calkin, D.E., Gilbertson-Day, J.W., Ager, A.A., In Press (a). Advancing effects analysis for integrated, large-scale wildfire risk assessment. Environmental Monitoring and Assessment. Available at: http://www.springerlink.com/content/652j815302ml3x7k/.

Thompson, M.P., Calkin, D.E., Finney, M.A., Ager, A., Gilbertson-Day, J.W., In Press (b). Integrated National-Scale Assessment of Wildfire Risk to Human and Ecological Values. Stochastic Environmental Research and Risk Assessment.

Thompson, M.P., Calkin, D.E., Finney, M.A., In Press (c). Addressing sources of uncertainty in strategic wildland fire planning. Journal of Environmental Management June 3, 2010.

Thompson, M.P., Calkin, D.E., Finney, M.A., Gebert, K., (in review). A risk-based premium approach to wildland fire finance and planning. Forest Science.

USDA Forest Service, 2009. Fire and Aviation Management Fiscal Year 2008 Accountability Report. 45 pp.

USDA Forest Service, 2010. Budget Summaries, Justifications, Overviews for FY2004-2011 for the U.S. Forest Service. Accessed on August 5, 2010 http://www.fs.fed.us/aboutus/budget/.

Vadrevu, K.P., Eaturu, A., Badarinath, K.V.S., 2009. Fire risk evaluation using multi-criteria analysis — a case study. Environmental Modeling and Assessment. doi:10.1007/s10661-009-0997-3.

Venn, T.J., Calkin, D.E., 2009. Challenges of socio-economically evaluating wildfire management on non-industrial private and public forestland in the western United States. Small-scale Forestry 8, 43–61.

Venn, T.J., Calkin, D.E., In Press. Accommodating non-market values in evaluation of wildfire management in the United States: challenges and opportunities. International Journal of Wildland Fire.

Wei, Y., Rideout, D., Kirsch, A., 2008. An optimization model for locating fuel treatments across a landscape to reduce expected fire losses. Canadian Journal of Forest Research 38, 868–877.

Williamson, M.A., 2007. Factors in United States Forest Service district rangers' decision to manage a fire for resource benefit. International Journal of Wildland Fire 16 (6), 755–762.