A Real-Time Risk Assessment Tool Supporting Wildland Fire Decisionmaking

David E. Calkin, Matthew P. Thompson, Mark A. Finney, and Kevin D. Hyde

ABSTRACT

Development of appropriate management strategies for escaped wildland fires is complex. Fire managers need the ability to identify, in real time, the likelihood that wildfire will affect valuable developed and natural resources (e.g., private structures, public infrastructure, and natural and cultural resources). These determinations help guide where and when aggressive suppression is required to protect values and when fire may be allowed to burn to enhance ecosystem conditions. This article describes the primary components of the Wildland Fire Decision Support System (WFDSS), a geospatial decision support system developed by the US Forest Service. WFDSS provides state-of-the-art wildfire risk analysis, decision documentation, and long-term implementation planning. In particular, we describe how the two primary decision support analysis components of WFDSS, Fire Spread Probability (fire behavior) and Rapid Assessment of Values at Risk (resource assessment), fit into the current state of risk assessment tools for wildfire suppression decisionmaking.

Keywords: wildland fire, decision support systems, fire modeling, economics

Increased wildland fire activity over the last 10 years has had profound effects on budgets and operational priorities of the US Forest Service, Department of Interior (DOI) agencies, and state and local entities with wildland fire responsibilities. For the US Forest Service alone, both the number and the average size of large fires have shown an increasing trend over the last several decades (Calkin et al. 2005). Because of increasing, fire-related expenditures the proportion of the total US Forest Service budget related to fire management has increased from approximately 20% (before 2000) to 43% (US Forest Service 2009a). Meanwhile, the total US Forest Service budget has essentially remained stagnant or decreased, resulting in funds being transferred from nonfire programs to wildfire management. This transfer has created numerous challenges for the agency by disrupting the pursuit of primary agency responsibilities and programs outside the realm of fire management (Stephens and Ruth 2005, Peterson et al. 2008).

Changing fire behavior and budgetary constraints creates a difficult management environment. Improving decisionmaking and promoting effective and efficient wildland fire management are crucial to addressing increased fire management complexities. A major challenge is managing fires that escape initial attack and grow under extreme fire weather conditions, often through heavy fuels. The US Forest Service continues to perform very effective initial attacks of wildland fire ignitions, with approximately 98% of all ignitions between 1970 and 2002 suppressed before fire size exceeded 300 ac. Despite the success of initial attack, the large fires that did escape represented over 97% of the total burned area (Calkin et al. 2005). Numerous reviews by federal oversight agencies and blue ribbon panels sought to identify causal factors influencing the unprecedented cost of fire suppression and to suggest possible modifications to federal fire management policy and strategies (e.g., Strategic Issues Panel on Large Fire Cost 2004, USDA Office of Inspector General 2006, and US Government Accountability Office 2007). The need to adopt risk-based decision frameworks to support wildfire management is recognized by federal agencies with wildland fire management responsibilities (Wildland Fire Leadership Council 2003, USDA and USDOI, Fire Executive Council 2009).

This article describes the primary fire behavior and wildfire impact modules of the Wildland Fire Decision Support System (WFDSS). WFDSS is the result of collaboration between the Rocky Mountain Research Station (RMRS) and the Wildland Fire Research Development and Application (RD&A) Program of the US Forest Ser-

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vice. Recent advances by RMRS scientists in fire behavior modeling and geospatial analysis of values at risk have made sophisticated wildfire decision support possible. WFDSS improves on and has replaced various systems and processes previously used by federal fire management agencies. The development of WFDSS evolved from the need for a more flexible system to fit today's fire management needs. WFDSS is a web-based set of tools that facilitate real-time decisionmaking by improving situational awareness and communication between analysts and decisionmakers. It is used nationwide by the US Forest Service and DOI to inform many events ranging from wildfire starts to complex wildfire occurrences. WFDSS has many advantages over the existing systems and complements the process of risk-based decisionmaking.

We begin this article by briefly discussing the decisionmaking environment and risk assessment in the context of wildland fire management. Next, we describe the development of WFDSS and how the two primary large fire model components, Fire Spread Probability (FSPro; fire behavior) and Rapid Assessment of Values at Risk (RAVAR; resource assessment), fit into the current state of risk-based decision support tools. We review some real-world applications of WFDSS and show the usefulness of the system. To conclude, we discuss research needs and future directions for WFDSS.

Decisionmaking in the Fire Suppression Environment

Development of appropriate management strategies for escaped wildland fires is complex. Fire managers are required to consider and balance threats to multiple socioeconomic and environmental resources. Fire managers need the ability to identify, in real time, the likelihood that wildfire will affect valuable resources. In addition, fire managers need to understand where aggressive fire suppression is required to protect resource values and when fire may be allowed to burn to protect and enhance ecosystem values. Knowledge regarding the effects of fire on private structures, public infrastructure, natural resources, and ecological systems as well as the ability to obtain this information during ongoing wildfires is needed to support risk-informed decisionmaking.

Planning deployment of suppression resources (e.g., ground crews, fire engines, and air tankers, to name a few) to implement suppression strategies requires consideration of multiple decision factors. These factors include things such as likely fire behavior, topography, firefighter safety and exposure, transportation logistics, resource availability, and productivity. This decisionmaking environment is characterized by great uncertainty. The difficulties are especially prevalent with respect to potential fire behavior, the effects of fire on valued resources, relative priorities across valued resources (e.g., protecting recreation sites versus protecting old-growth groves versus protecting aquatic habitat), and suppression efficacy. Because of this uncertainty, attempts at developing standardized decision support tools for wildland fire management have been limited up to this point. Most relevant applications of optimization techniques limit analysis to initial attack and tend to omit or simplify consideration of natural and cultural resources (NCR; e.g., MacLellan and Martell 1996, Donovan and Rideout 2003, Haight and Fried 2007). WFDSS avoids a normative approach by leaving the evaluation of alternative courses of action in the hands of the decisionmaker and instead strives to provide usable, real-time information on likely fire behavior and consequences.

Federal agencies with wildland fire programs have fire management strategies primarily defined by the local agency administrator (AA) and incident management teams (IMTs) are responsible for consulting and implementing the developed strategy. Within the US Forest Service, the AA is typically the District Ranger or Forest Supervisor. Because of the complexities of the fire environment, strategies provided to IMTs are typically fairly general and tactical implementation of the developed strategy is left to the discretion of the IMT. When fire conditions change to such a degree that the initial strategy is no longer feasible, the AA must develop and authorize a new strategy. The primary intent of WFDSS is to assist the local units and AAs in the development of risk-informed fire management strategies. Use of WFDSS also improves communication between AAs and IMTs in testing and developing suppression strategies, improves the understanding of fire management priorities and potential fire behavior, and allows updating of strategies and tactics as fire conditions change.

Wildfire Risk Management

Recognizing the need for improved decisionmaking frameworks, the US Forest Service and other federal fire management agencies have turned to a risk-based paradigm. Working under the expectation that fire must be reintroduced where possible as an essential ecosystem process (Dombeck et al. 2004), risk-based analysis evaluates the potential that fire growth intersects the location of resource values that may be affected by wildfire. Expected value change is assessed as a function of the probability that fire of a given intensity will reach resource values, as well as the associated value change to those resources at that intensity (Finney 2005). Expected value change may be positive in instances where a fire improves ecological conditions or results in reduced future risk due to fuels modification. In these cases aggressive wildfire suppression may not be warranted.

For some resources, such as private structures and commercial timber, risk may be quantitatively estimated using market values and standard economic valuation techniques. Most examples of wildfire risk analysis have focused on timber values and have not addressed more complicated issues associated with expected value change to nonmarket resource values and public infrastructure (e.g., Reed 1984, 1987, Yoder 2004, Amacher et al. 2005, Konoshima et al. 2008).

The significant uncertainty surrounding ecosystem response to fire (and other disturbances) limits our ability to fully make use of an integrated quantitative risk framework (Finney 2005, Sikder et al. 2006, Venn and Calkin 2009). A critical remaining step is risk characterization, the process of pairing fire behavior models with ecosystem response functions to derive an integrated statement of risk to valued nonmarket resources such as habitat and ecosystem processes (Fairbrother and Turnley 2005). Recent and ongoing research is laying the foundation for future applications of risk characterization and assessment. This work entails pairing spatially explicit burn probability maps with expert-defined resource response functions to estimate risk to valued resources. These valued resources include such things as spotted owl habitat (Ager et al. 2007), old-growth trees (Ager et al. 2010), and integrated assessments considering broad categories of resources such as fire-adapted ecosystems, fire-susceptible species, and recreational sites (Calkin et al. 2010). Advanced science integration and data development help improve our ability to manage these nonmarket resources. In lieu of better fire ecology science and supporting spatial data, a reliance on the more intimate knowledge of local resource managers and scientists is common practice. In the following sections we describe how WFDSS integrates wildfire behavior with resource location to assist fire managers in developing risk-based management strategies.

WFDSS: Overview

In the wake of the attacks of Sept. 11, 2001 and the controversial response to the Hurricane Katrina disaster, federal agencies within the US government expanded development of multiple geographical information systems (GIS)–based risk assessment systems (Bell and Dallas 2007). These tools are intended for use by emergency response teams to support rapid, real-time analyses and provide information for protective action recommendations. Development of these systems required the collection and organization of national-scale geospatial data on critical infrastructure (CI) including power transmission lines, oil and gas pipelines, and communication towers. A report from a National Academy of Sciences committee concluded that geospatial data and analytic tools should be considered essential for all aspects of emergency planning, response, and recovery (National Research Council 2007). An important insight driving development of WFDSS was the realization that CI data compiled to support homeland security needs could support other purposes as well, specifically the spatial identification of resources at risk to wildfire. Coincident with the availability of nationally consistent CI data, geospatial cadastral data became available for most counties in the western United States. These mapped tax records were used to systematically identify and map approximate structure locations filling a critical knowledge gap for wildfire management planning and response (Stage et al. 2005)

Recent advances in fire behavior modeling, geospatial analysis, remote sensing biophysical data sets (e.g., LANDFIRE [USDOI Geological Survey 2009]), and weather and climate forecasting coupled with the Internet have made information sharing and decision support possible. In light of these advances, The National Fire and Aviation Executive Board chartered the WFDSS Project in June 2005, "to develop a scalable decision support system for AAs that utilizes appropriate fire behavior modeling, economic principles and information technology to support effective wildland fire decisions consistent with Resource and Fire Management Plans." WFDSS development began in 2004 with initial testing in 2005 and additional testing and prototype applications occurring during 2006 and 2007 fire seasons.

Before the 2007 fire season, the Chief of the US Forest Service, Gail Kimbell, and Undersecretary of Agriculture, Mark Rey, submitted a list of management efficiencies that were to be implemented to address concerns relating to US Forest Service suppression expenditures. Central to these recommendations was a focus on appropriate risk management with requirements to use WFDSS for all fires exceeding defined cost thresholds. Broad use of the tool began during that year's active fire season, when WFDSS products were developed and delivered to several hundred fire events. This included extensive application of WFDSS under the direction of several Area Command operations on fires of "national significance" with expected cost greater than $10 million.

In June and July 2008 WFDSS provided key decision support to the extreme fire events throughout Northern California. Although the prototype application of WFDSS only intended to support wildfires in the western United States, the scientists were able to support large wildfire events in the southeastern United States in the early summer of 2007 and in Minnesota's Boundary Waters Area of the Superior National Forest in 2006 and 2007. During the 2008 season, WFDSS team members worked closely with DOI fire management partners to facilitate the adoption of WFDSS by all federal fire management agencies in the Continental United States and Alaska.

WFDSS Model Components

WFDSS provides a full range of fire modeling and decision support applications. The foundational models of WFDSS include the fire behavior module FSPro (US Forest Service 2009b) and the resource impacts model RAVAR. Together these two models provide the appropriate fire behavior modeling, economic principles, and information technology vital to the functionality of improved decision support. WFDSS supports risk-informed decisionmaking by identifying the likelihood of resources being impacted by fire spread, allowing local managers to evaluate the likely impacts and prioritize accordingly.

Fire Spread Probability

The PSPro model 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. It requires GIS landscape data and data from a representative weather station to develop a historical data set relative to spread component and energy release component. The model simulates the 2D growth of the fire across the landscape (fuels and topography) using a computationally efficient algorithm known as Minimum Travel Time (Finney 2002). FSPro simulates fire growth for thousands of possible weather scenarios using the latest recorded perimeter (or point). Different weather possibilities are developed statistically using the data from the weather station (fuel moisture, wind speed, and direction).

The burn probability for each cell is a calculation of counting how many times a cell burns divided by the total number of simulations. The output probability predictions are ASCII (.asc) files, which can be brought into a GIS application. Although fires and their behavior are heterogeneous with respect to fuels, topography, and weather, in most cases an FSPro burn probability map looks like a series of concentric polygons that represent contours of constant probability. Exterior contours have lower probability of fire occurrence than interior contours, designated with specific colors representing FSPro's. These probability contours inform managers regarding the likelihood of fire impacting valued resources and assist in developing target fire containment perimeters.

An essential component to fire behavior modeling is forecasted weather, particularly wind and moisture. Because of a limited ability to accurately make site-specific fire weather predictions beyond 1–3 days, fire managers need updated information on likely fire spread in response to weather changes. Additionally, updated information on the current fire perimeter is needed to inform fire behavior predictions. FSPro maps are therefore regenerated multiple times over the course of managing an escaped wildfire to provide decisionmakers with up-to-date geospatial information on values at risk. The FSPro maps represent a significant contribution to fire risk assessment for individual fires.

Rapid Assessment of Values at Risk

The RAVAR resource impacts module is a new geospatial modeling tool that identifies the primary resource values threatened by large, ongoing fire events. The RAVAR concept was introduced in 2004 (Calkin and Hyde 2004) to compare suppression costs between two or more fire events relative to values at risk. RAVAR has been typically integrated with the FSPro model to identify the likelihood of different resources being impacted by an ongoing event but it can be linked to any expected fire spread polygon. The RAVAR analytic model produces two distinct map products and associated reports, referred to as CI and NCR.

In the CI reports, private structures, public infrastructure, public reserve areas, and hazardous waste sites are mapped as well as quantified. Public infrastructure includes water supply systems, reservoirs, major power lines, pipelines, communication towers, recreation facilities, and other significant landmarks. CI also identifies designated wilderness areas, roadless areas, wild and scenic river corridors, and national recreation areas. Superfund sites as well as mines are mapped and reported along with other HAZMAT locations. Figure 1 shows a subset of the CI RAVAR map for the Schultz Fire outside Flagstaff, AZ, in 2010. Each RAVAR CI map has a companion report that provides descriptive analysis and tabular data summarizing CI at risk, sorted by probability zones identified by FSPro.

The intent of NCR reports since the inception of RAVAR has been to identify highly valued natural resources and management priorities that may be affected by an ongoing fire event. NCR products focus on regionally identified natural resources and wildland management priorities. In 2007 and 2008 the WFDSS development team coordinated the acquisition and staging of a limited number of the appropriate layers through direct interactions with regional US Forest Service fire and natural resource staff members. Examples of NCR layers include sensitive wildlife habitat, recreation zones, and restoration priority areas.

CI data are generally consistent throughout the nation but NCR data vary substantially across geographic scales and land-management units both in relevant data content and in completeness. Much of the natural resource spatial data are developed and maintained at the local level to meet specific resource management needs and local expertise is required to interpret

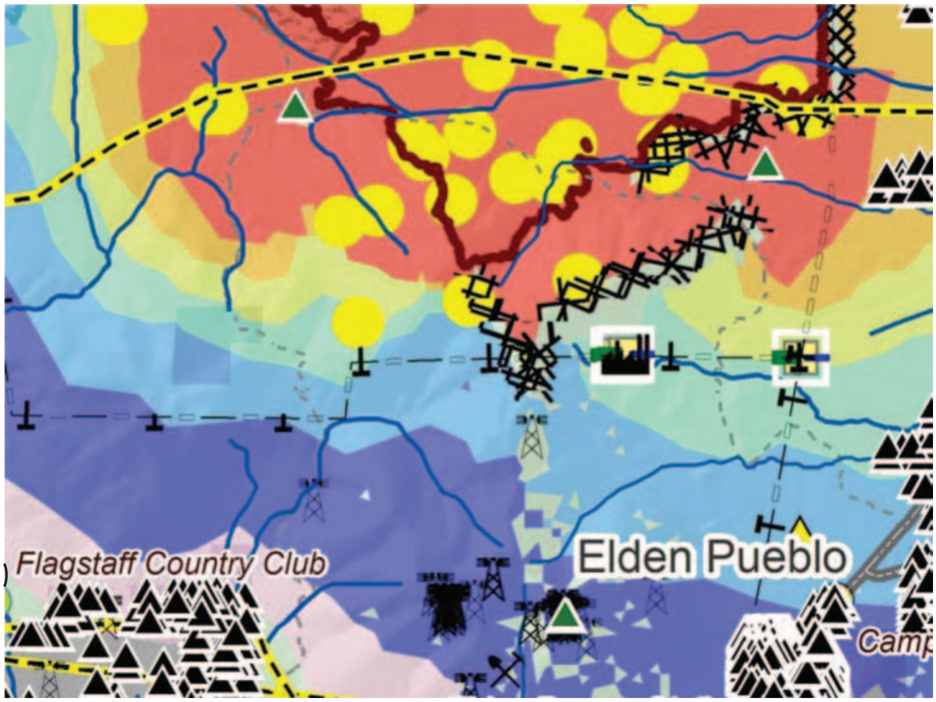

Figure 1. Detail of RAVAR analysis map created for the Shultz Fire, which burned north of Flagstaff, AZ, in June 2010. Image includes oil/gas pipeline (yellow line, black dash), power transmission line (inverted "T," dashed connector), private structures (black triangle with halo), US Forest Service structures (green triangle with halo), communication towers (lower center of map), and mine site (pick and shovel center of bottom edge). FSPro zones radiate from red (more than 80% spread probability) to pink (less than 1%). Yellow dots are "hot" points from satellite images. Lines of "X" represent existing fire line and blue lines are major streams.

these data. This constrains the assessment of wildfire risk to natural resources within a national application such as RAVAR. Successful staging of NCR data requires two challenges be addressed. First, many resource data are highly sensitive, such as nest locations, requiring that these data be carefully protected to prevent adverse impacts. Second, leadership directive may be required to align the resources necessary to compile and improve existing NCR data inventories. Currently, WFDSS development team members are exploring how regional and local users can maintain their own NCR data within WFDSS.

The 2007 Colby Fire in California is a good example of RAVAR NCR analysis (Table 1). This large fire occurred in an area where natural resources on public land were the main concern in developing the fire suppression strategy, while the threat to wildland–urban interface structures was of limited concern. For this NCR report, critical spotted owl, Chinook salmon, and steelhead habitat areas were all covered by agreements with the Quincy Library Group (QLG) re-

Table 1. NCR report for Colby Fire.

Probability zone (%)	Structures (count)	QLG off base (ac)	QLG deferred (ac)	Spotted owl activity centers (ac)	Chinook critical habitat (mi)	Steelhead critical habitat (mi)
>80	0	913	9,109	1	5.2	5.3
60–80	0	1,186	10,551	46	0.6	5.8
40–60	0	1,657	12,160	184	0.2	6.0
20–40	0	2,843	14,768	507	0.5	6.5
5–20	0	6,588	21,475	785	2.3	8.8
1–5	264	28,609	58,022	4,151	24.1	32.9

This information helps managers better understand which resources might be most susceptible to fire and prioritize where suppression resources should be deployed.

garding levels of acceptable management. The QLG is a coalition of stakeholders that started meeting during the early 1990s to create dialogue about national forest management (Davis and King 2000). The QLG negotiations led to several agreements, all of which attempt to incorporate and consider the many diverse interests surrounding national forest land-use decisions (Davis and King 2000). In the NCR report, direct protection areas (DPA) were identified to establish primary suppression responsibilities and recreation opportunity zones were also determined. All these data are important elements of strategy development and are shown with the same fire probability backdrop as CI for consistency. The ability to identify important natural resources at risk to wildland fire can be an important factor in determining suppression resource distribution. In the absence of these data, managers responsible for distributing suppression resources may prioritize those events where human development has been shown to be at risk while not considering important ecological values at risk.

Resource values currently identified within RAVAR are presented in their natural units (e.g., acres of critical habitat) and no information is included regarding the likely value change to these resources caused by fire. Thus, RAVAR NCR maps alone do not provide a clear interpretation of the role of fire as either an unwanted and potentially destructive force or as a natural, beneficial disturbance for the various natural resource and recreation assets. This approach recognizes the complexity and sensitivity of assigning monetary value to natural resources. Recognition of the presence of these resources can trigger involvement of the appropriate resource specialists in the decision-making process that would likely improve fire management decisions. Research is underway that may provide additional information to RAVAR NCR products in relation to the positive and negative effects of fire on specific natural resources and ecosystem processes.

Benefits of WFDSS

Development of WFDSS has facilitated the Wildland Fire Leadership Council's ability to implement fundamental modifications to the 2003 Interagency Strategy for the Implementation of Federal Wildland Fire Management Policy. In 2009 WFDSS officially replaced both the Wildland Fire Situation Analysis for suppression events and the Wildland Fire Implementation Plans for wildland fire-use events. By unifying the reporting and strategic analysis processes, the US Forest Service and the DOI are able to show their commitment to the application of risk-informed decisionmaking. The adoption of WFDSS allowed the Fire Executive Council (USDA and USDOI, Fire Executive Council 2009) to publish "Guidance for the Implementation of Federal Wildland Fire Management Policy," which allowed all wildland fires to be managed for resource benefit objectives where appropriate. Before this, reinterpretation resource benefits could not be considered in evaluating wildland fire suppression strategies. Implementing improved risk-informed management may result in large economic benefits by reducing immediate costs of managing current fires and by increasing fuels treatment, thereby reducing future costs of management.

The web-based integration of fire modeling tools with potential economic effects provides a common framework to share information in real time throughout all levels of federal wildland fire management. Although the application of WFDSS is organized and informative at the incident level, in geographic areas where multiple wildfires are burning, managers responsible for distributing firefighting resources to the individual events may be able to better manage the allocation of resources based on the risk assessments conducted within WFDSS. Similarly, national managers responsible for national level resources and budget oversight may be able to rapidly assess emerging issues at the incident, regional, and national scales. By providing high-end computing resources from a single web-accessible site, field-based wildfire analysts can access, run, and update complex fire behavior assessments that would be otherwise unavailable because of the level of computing resources typically available to IMTs.

By focusing on risk, the intersection of threat (fire spread) and values susceptible to loss, fire managers are more likely to deploy suppression resources where they may most effectively reduce loss. Although quantifying the value of improved decisionmaking due to WFDSS is difficult because we can not observe the outcome of events in the absence of WFDSS, management response has been very positive from those who make strategic decisions. Comments from fire management personnel have been published in *Scientific American* (Andrews et al. 2007), *Predicting Wildfires*, August 2007, and *Wildfire Magazine* (McDaniels 2007, 2009). Referring to use of WFDSS on large fire events in Southern California, Josh McDaniels stated, "When fire behavior modelers worked closely with IMTs to provide information critical for accurate long-term planning on a large, complex fire, the result was a real-time integration of science and practice" (McDaniels 2009, p. 20).

Additionally, WFDSS has improved the US Forest Service's and DOI's ability to show the value of suppression to the public, congress, and government oversight agencies. Consequently, WFDSS has been highlighted in numerous agency reports including the 2008 Fire and Aviation Management Accountability Report (US Forest Service 2009a), the 2009 Quadrennial Fire Review (USDA and USDOI 2009), and each of the annual Forest Service Budget Summaries between 2008 and 2011 (US Forest Service 2010).

Discussion and Concluding Remarks

The linking of spatial fire threat with values at risk in real time is an unprecedented step toward improved wildland fire management. As new information becomes available with respect to weather, fire behavior, or values at risk, WFDSS analyses can be rerun to generate new reports and facilitate adaptive fire management. WFDSS represents a revolution in wildfire decision support. Threats are applied to primary resources at risk, and a summary map and basic report are produced. It is likely the level of complexity will increase as managers become more familiar with WFDSS products and learn over time how best to incorporate this intelligence into operational environments. However, the level of model complexity will need to be carefully weighed against the information capacity of the users who are responding in an emergency management environment. Additionally, training for wildfire managers on risk-based management and agency commitment will be required for achieving the true potential of WFDSS and adopting risk as the basis for federal wildland fire management decision-making.

A primary goal of future research on the RAVAR model is to move beyond resource presence/absence to projections of expected value change. This entails recognition that expected value change not only requires the quantification of negative consequences but also of beneficial effects including improved ecological conditions and reduced future risk to wildfire. An ultimate goal would be that all resource values be assessed in a common currency (i.e., monetary value). However, given the challenges associated with the monetization of the changes to natural resource values, quantification of the likely impacts to the primary resources assessed in their natural units (e.g., temporal impacts to breeding success of an at-risk population) may be all that can be reasonably accomplished in the near term. Research that integrates potential fire severity with spatial and temporal effects on the dynamic systems that support these natural resource values is needed. The authors are also interested in extending the WFDSS system for off-season fire planning to support, revise, or develop land and fire management plans, prioritize fuel treatment opportunities, and support Burned Area Emergency Response. Additional decision support tools are being added to the system, including fire behavior modeling, single-period burn simulation, and smoke dispersal models.

In the span of 4 years WFDSS has transitioned from a conceptual prototype into a fully implemented system adopted across federal land-management agencies for use on large wildland fires. The Wildland Fire Management RD&A Program has built capacity to support WFDSS by investing in extensive training with a staff of devoted analysts able to support fire managers. Additionally, employees at local units are provided with training opportunities for WFDSS and related wildland fire decision support tools.

WFDSS has provided valuable real-time decision support to improve strategic decisionmaking and communication by fire managers and AAs and to improve information sharing across management levels including the Washington Office. Collectively, these advancements have enabled fundamental policy changes to federal fire management policy. Development and application of WFDSS has helped the US Forest Service establish commitment to efficient and effective fire management with a strong focus on wildfire cost containment during a period of unprecedented fire activity. WFDSS supports integrated risk assessment and has improved management of escaped large wildland fires.

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