Fire Science Application and Integration in Support of Decision Making

Thomas Zimmerman
Program Manager
Wildland Fire Management RD&A
Rocky Mountain Research Station
National Interagency Fire Center
3833 South Development Avenue
Boise, Idaho USA 83705
208-387-5871
tomzimmerman@fs.fed.us

Abstract
Wildland fire management in the United States has historically been a challenging and complex program governed by a multitude of factors including situational status, objectives, operational capability, science and technology, and changes and advances in all these factors. The improvement and advancement of risk-informed decision making has the potential to improve natural and community resource protection, reduce firefighter exposure, and potentially, decrease suppression costs. Developing new and improved processes and integrating them in support of risk-informed decision making is an ongoing effort and primary focus of the Wildland Fire Decision Support System (WFDSS). This recently developed application incorporates emerging science in the areas of weather analyses, fire behavior prediction tools, economic assessment tools, and landscape data acquisition processes. It improves overall wildland fire information management and decision making. This paper describes how science application and integration in WFDSS can increase decision makers' ability to acquire information, rapidly analyze that information, and reach more timely and applicable decisions regarding wildland fire management.

Introduction

The wildland fire management program in the United States has historically been subject to dynamic objectives, expanding purpose, adaptive strategies and tactics, evolving policy, rapid growth of scientific and technological bases, and often, inflexible accomplishment expectations. This program has been in existence as a natural resource management discipline for just over 100 years. In its earliest stages, it focused solely on fire control with a principal objective of excluding fire from wildlands to protect and preserve natural resources and human developments. Over time, fire control practices joined with the application of prescribed fire and the management of naturally ignited wildland fires to accomplish resource benefits and became known as fire management.

Fire management policy has been quite responsive to changing situational dynamics and has progressed to a point where decision makers have more flexibility than ever before; wildfires can be suppressed, managed to realize the benefits of natural fire presence and achieve numerous positive resource outcomes, or be managed for both objectives concurrently. Accepted strategies and tactics that fully support these objectives and operational capabilities have become more sophisticated and comprehensive than ever before, although declines in force strength have slightly diminished overall operational capability. During the last 20 years, rapidly changing fire, fuel, and human population dynamics, increasing diversity in land use objectives, and the emergence of multiple strategic objectives and necessary tactics have further compounded fire management program complexity. As a result, wildfire response and management now occupy a major part of the workloads and budgets of U.S. land management agencies, with expectations and costs increasing exponentially. It is becoming alarmingly clear that past practices, processes, and applications cannot effectively support achievement of future program needs and requirements.

In light of such dramatic increases in complexity, ways to improve efficiency are actively being pursued. One very important area deserving attention involves decision making, specifically in terms of information management, decision quality, advances in risk-informed decision making, understanding and use of decision leverage points, role of science application, timeliness of decisions, and operational planning capability. Managers need to be able to actively frame decision space based on relevant information, have as much uncertainty as possible removed from the situation, and reach focused decisions. Improved decision making is viewed as a key component to the improvement of natural and community resource protection and can effect more efficient responses, better use of resources, reduced firefighter exposure, and potentially, decreased firefighting costs.

Fire Management Decision Making

Wildland fire is one of the most important naturally occurring vegetation-shaping factors and likely the highest risk, most complex, and potentially highest consequence program facing natural resource managers. Many decisions must be made pertaining to wildfire and are needed during all phases of management. These decisions frequently occur in settings that place decision makers under considerable time pressure, bring active external attention and scrutiny, involve possible serious consequences, are pervaded with uncertainty because of inadequate information, occur in dynamic conditions, involve complex and seemingly contradictory issues, and are required by decision makers regardless of their range of experience. Best decisions are possible when information is managed and available to address risk and inform decisions. Information management and risk-informed decisions are becoming critical to wildfire management efficiency and success.

Information Management

The beginning of the second decade of the 21st century comes in the midst of a transformative time for wildland fire management. Significant technological innovations and rapid advances in information management are occurring. The completion of routine tasks; establishment of standard procedures, processes, and policy; increases in speed of information acquisition, analysis, application, and archival mechanisms; the influence of information management processes on decision making; and interpersonal and interagency communication processes at local, regional, national, and international levels are all growing areas that influence fire management program effectiveness.

Recent strategic initiatives, studies, and reviews such as the Quadrennial Fire Review (NWCG 2009), the National Cohesive Wildland Fire Management Strategy (DOI-USDA 2011), and Guidance for Implementation of Federal Wildland Fire Management Policy (USDA-USDI 2009) have articulated a need for improved methods to determine what information is of use, to whom, and the best way to achieve the integration of science into management.

In order for decision makers to access and analyze information to frame their decision space and aid in decision making, they must have a firm grasp of overall information management. Managing fire management information in support of decision making and implementation action is a rapidly expanding activity and can be categorized into four areas. These are:

- acquisition – the rapid assimilation of all information relevant to the issue or problem needing a decision and action.
- analysis – the evaluation of all relevant data and information to develop recommendations to support for decision-making.
- application – the process of making a decision, determining the appropriate action(s) to accomplish objectives and resolve issues.
- archival – the creation of permanent record of information acquisition, analysis, and application.

These four components, activities involved, and outcomes are listed in Table 1.

Table 1—*Components of wildland fire information management.*

Component	Activity	Outcome
Acquisition	▪ Obtain situational and directional information ▪ Consolidate program history and current status ▪ Develop shared vision	▪ Accessible information and existing information ▪ Information accuracy validated ▪ Current policies, procedures, and processes reviewed and clarified for a specific situation ▪ Defined program goals, objectives, and management requirements for a specific situation
Analysis	▪ Utilize best analytical tools ▪ Analyze available information ▪ Examine past performance ▪ Establish standards and baselines ▪ Analyze interdependency of all variables ▪ Evaluate relevant information	▪ Improved situational awareness ▪ Identify specific needs and issues ▪ Distinguish between factual information, perceptions, and personal viewpoints ▪ Illuminate relevant situational information ▪ Frame decision space
Application	▪ Apply knowledge, processes, technology, and proven practices ▪ Experiment with new knowledge and technological applications ▪ Incorporate best knowledge and technology into practice ▪ Address problem solving ▪ Transfer knowledge	▪ Continual flow of new ideas, knowledge, and technology into application established ▪ Best practices leading to superior performance and accomplishment identified ▪ Application through the use of a dynamic learning environment improved ▪ Decision making support, facilitation of selection of the appropriate strategy, and development of an operational program of action to accomplish incident objectives
Archival	▪ Document overall processes and results ▪ Document practices, and organizational growth ▪ Ensure the retention of critical information	▪ Information transfer processes improved ▪ New practices, experiences, and knowledge, both positive and negative, documented ▪ All information for future reference and application retained ▪ Knowledge, principles, guidelines, procedures, practices, etc. identified and documented

Wildland Fire Management and Decision Making Models

Under current U.S. fire policy, wildland fire management is comprised of the management of both unplanned and planned ignitions. Unplanned ignitions represent wildfires, regardless of ignition source. While wildfires are unplanned, the overall program for their response and management is actually a very in-depth and well-planned activity.

The initial planning step in the wildfire process begins prior to an ignition. Federal fire policy directs that every unplanned wildland ignition will receive a response developed from the full range of available strategies. Fire Management Plans, created by each land management unit, provide specific fire management objectives which supplement and extend broader comprehensive land and resource management plans and strategic management objectives or land use decisions into action. Strategic objectives and fire management objectives both provide direction on the management of wildfire. They specifically identify where fires can be managed (allowed to burn) for ecological benefit (resource benefit), where they must be suppressed, or where a single incident may be managed under both types of objectives concurrently. Planning at this level represents pre-planned strategic decisions and facilitates more timely decision making and responsiveness once an ignition occurs.

After ignition of a wildland fire, risk-informed decisions are preferred to help optimize firefighter resources, minimize firefighter exposure, develop a high success response option, to minimize social, economic, and ecologic impacts, and respond to concerns over escalating costs. A risk-informed decision is one that utilizes two distinct but linked processes of analysis and deliberation. Analysis involves the use of rigorous, replicable methods to provide information about factual questions. It brings new information into the process. Analysis informs deliberation. Deliberation is the discussion, reflection, and persuasion to communicate, raise, and collectively consider issues, increase understanding, and facilitate substantive decisions. It brings new insights, questions, and problem formulations. Deliberation frames analysis.

Decision making can be categorized by multiple models. Several are very fitting to describe what takes place or is desired to take place in wildland fire management decision making.

The first, the recognition-primed decision model (Klein 1999), couples two processes: the way the situation size-up occurs and the way a course of action is evaluated. Klein (1999) describes this model with three variations that decision makers may follow:

- Recognition of the situation from experience as typical and familiar. Decision makers can realize quickly what will be a typical response. This occurs from understanding and recognition of what goals make sense and the associated priorities, the relevant cues and subsequent sorting of priority information (counters information overload), what to expect (speeds preparations), and how to respond for the situation (Klein 1999). In this variation, the decision maker sees an indicator and takes a rule-based response.
- Unfamiliar situation. Decision makers must spend more time diagnosing the situation. Available information may not match a typical or familiar situation. More information may need to be gathered to support a decision, or the decision maker may have misinterpreted the information and not realized it. This can lead to a breach of expectations and the need to further analyze the situation and determine which response is best suited for the situation. In this variation, the decision maker encounters the problem and then deliberates about the situation to reach the decision.
- Unfamiliar situations with unplanned outcomes. In this situation, the decision maker evaluates single options by imagining how the course of action will play out. Under this variation, if difficulties are anticipated, then course of actions may be adjusted or in some cases, if recurring assessment of actions shows that goals are not being met, that action can be rejected and new strategies and responses selected. In this variation, the decision maker encounters the situation and tries to imagine and clarify possible outcomes of responses before reaching a decision.

Key points of recognition-primed decision making are two-fold: experienced decision makers can size up a situation and judge it as familiar or typical in an almost automatic fashion, leading to a rapid decision and escalating action; and an emphasis is placed on being poised to make a decision and implement this rather than being dependent upon completion of all evaluations.

A second model involves the rational choice decision making model (Klein 1999). In this model, weaknesses in one evaluation criteria can be offset by strengths in other criteria. Occasionally, in this model, decision makers will not try to see if certain criteria strengths compensate for other weaknesses, but will make a decision that is based on a course of action having the best significance in what is perceived as the most important criteria while all others are ignored. In other cases, options are evaluated according to most important criteria, and those that fail to meet it are dropped, remaining ones are evaluated on the next most important criteria, becoming a filtering process that is continued until only one option remains (Tversky 1972).

Decision makers will utilize each of these two models depending on situational status. For example, recognition-primed decisions are more likely to be applied when managers are more experienced, conditions present greater time pressure, situational variables are constantly changing, and unclear or poorly defined goals are present. Rational choice decisions are more likely when there is a need to justify the decision, when the situation involves conflicting priorities that need resolution, when decision makers are trying to find the best decision, and when the situation presents complex information that needs analysis to clarify and define decision space.

A third model involves risk-informed decision making. Definitions of risk-informed decision making models show a progressive process that involves up to eight steps (Stern and Fineberg 1996). These include problem formulation, information gathering, analysis, synthesis, affirmation of analysis results, decision implementation, and documentation. Following this progression for decision making affords an iterative, information-goal directed, analytic–deliberative process that actively engages the decision makers and his/her staff in the process. It provides a risk characterization that is intuitive, logical, relevant, understandable, and accessible. It assembles, consolidates, and presents information to decision makers and makes this information easily shared among approved users.

In addition to applying a decision making model, the use of leverage points, or the identification of small variances that can have substantial effects on the decision and action, are very important to any fire management decision making model. Leverage points can be used to expedite the process, frame decision space, and lead to more rapid and effective decisions. In wildland fire management, information acquisition and analysis serve as significant leverage points for framing decision space and supporting decisions.

In the United States, documentation and analysis of wildland fire management decisions have been required by federal agency policy for over 30 years. An alternative selection decision and documentation process, the Wildland Fire Situation Analysis (WFSA), previously met this requirement for wildfire suppression decisions. While the WFSA supported decision making, it became inadequate over time and its preparation was fraught with limitations constraining product quality. The WFSA process was founded on a comparative process and representative of the rational choice decision making model. However, this process actually reduced managers' decision space and its implementation mixed boundary conditions between this model and the recognition-primed model in a way that did not capitalize on the strengths of either model. The WFSA process was completed under greater time constraints; during periods of highest uncertainty, and rapid workload escalation, heightened stress levels; was associated with poorly defined goals. It also provided justification for the decision; involved high computational complexity, although timely computations could not keep pace with the situation; and decision maker experience was never constant from fire to fire, but varied markedly.

Additional decision documentation processes emerged over time and included the Wildland Fire Implementation Plan (WFIP) for documentation and analysis of selected management alternatives for managing wildland fire for resource benefits; and the Long-Term Implementation Plan (LTIP) for documenting long-term assessment and implementation actions on long duration wildfires. Utilizing these three distinct processes (WFSA, WFIP, and LTIP) resulted in some process redundancy, excess work, and a lack of continual inclusion of emerging and improving technology, fire modeling, and geospatial analysis (Pence and Zimmerman 2011).

The Role for Science Application

Slow and inconsistent transfer of research findings into useable field applications, the lack of an overall comprehensive process for integrating new knowledge and technology into existing wildland fire training curricula, and a limited capacity to implement technology transfer and science application has encumbered the full use of science in fire management. Developing tools and processes to facilitate smart information sharing, communication, and decision making is now the leading challenge for wildland fire management. Tremendous amounts of information are available and rapidly knowing the importance and value of specific sets of information, how to obtain them, how to share them, and how to apply to management actions still has much room for improvement. In order to keep pace with these challenges and increasing complexity, wildland fire management needs to become a true knowledge management program. Fire management must find ways to rapidly acquire information, manage that information, analyze that information, and build and maintain a greater knowledge base to support more timely and complex decisions.

Emerging scientific and technological developments have the potential to dramatically advance and modernize the practice of wildland fire management; these tools can provide more complete information involving the situation than previously available, afford faster data acquisition and analysis, and offer enhanced ease of use. Incorporating these tools and capabilities into applications useable by fire practitioners and managers is of primary importance.

The deliberate application of science to fire management can serve to achieve greater capability. Building blocks of decision making are shown in Figure 1. From this figure it can be seen that there are several driving factors that form the foundation for decision making. Decision support, incorporating the latest scientific tools, then builds on the driving factors to link the situation to land and resource and fire management objectives and provide the most detailed situational information and analysis. This information is then available to the decision maker to help frame the decision space and ensure that the most applicable information is used by the decision maker to help reach a decision.

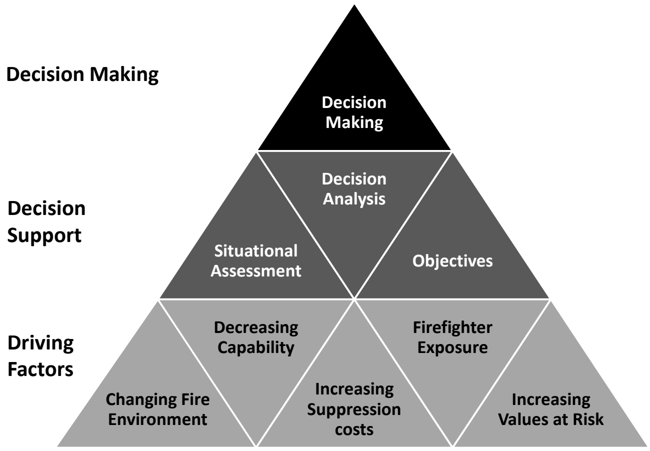

Figure 1—Building blocks of wildland fire management decision making.

Wildland Fire Decision Support System (WFDSS)

As a result of the emergence of disparate documentation and analysis processes with applicability limited to specific fire types and situations, a new method for wildfire decision documentation and analysis became an urgent goal for the U.S. fire management program. A new system, the Wildland Fire Decision Support System (WFDSS), was initiated to be a single system to replace all previous processes, to integrate science and technology, and to streamline and improve wildland fire decision-making.

Integrating emerging science and technology in support of risk-informed decision making is the primary focus of WFDSS. This system possesses many attributes that exclusively differentiate it from other wildland fire decision systems (Pence and Zimmerman 2010). It is a web based system for documenting decisions, supporting analyses, and completing operational plans applicable to and used for all wildland fires. It promotes access to numerous information analysis tools in the areas of fire behavior modeling, fire weather information, economic principles, air quality and smoke management, and information technology to support effective wildland fire decisions consistent with Land and Resource Management Plans and Fire Management Plans. WFDSS greatly reduces text input requirements by using spatially oriented and graphically displayed information. The system incorporates a progressive decision documentation and analysis process that can be scaled and adapted to match situational changes. Through WFDSS, information is assembled, consolidated, and processed for decision makers in a way that fosters collaboration and, ultimately, provides better opportunities to improve large wildland fire strategic decision making.

The design of WFDSS improves existing documentation capabilities and makes the decision process accessible, consistent, flexible, and geospatial. Accessibility for users is controlled but promoted through authorized access privileges. Authorized users require an internet connection and logon for access to the system and have access capability dependent upon their authorized roles. Consistency of inputs and outputs is ensured by the system. Basic incident information and minimal text requirements are entered while analysis display outputs improve fire managers' ability to focus on pertinent fire issues. Maps and other spatial information of values, assets, and the fire environment that offer support to information synthesis are available. Collectively, these attributes improve the documentation and analysis from previous methods and consolidate them into a single process that is intuitive and easy to use.

WFDSS presents a linear decision support structure that includes seven different components to guide a fire manager through the information acquisition and decision process. These components are:

- **Incident Information**. This is where a fire start is documented. Location, size, date, and responsible agency are documented here for administrative fire reporting purposes.
- **Situation Assessment**. Maps, reference data layers, and applicable assessments are collected here for use by decision makers. Values, fire potential, and hazards help develop a relative risk

for the incident. If fire complexity is high or escalates, managers can move from a relative risk assessment to a very quantitative risk assessment process and obtain a more complete overview of the fire situation to better focus decisions. Decision analysis tools are available in WFDSS which help managers understand specific components of the values, hazards, and probabilities of impacts and their effects on the situation. Decision analysis tools included in WFDSS are described in Table 2. A complete description of tools and example uses is available in Noonan-Wright et al. (*In Press).*

Table 2—*WFDSS decision analysis tools; informational area, available models or information source, and use.*

Informational Area	Model or source	Use
Fire weather	Tabular data from Weather Information Management System (WIMS) using hourly data from Remote Automated Weather Stations (RAWS)	Create fire danger products, provide weather data for fire behavior analyses, and provide data for air quality analyses
Fire danger	National Fire Danger Rating System (NFDRS)	Establish fire danger trend information, provide managers with indications of relative fire danger and provide input to relative risk assessments
Fire behavior	*See below*	Project fire size probabilities, forecast fire progression, predict fire behavior characteristics such as rate of spread, crown or surface fire occurrence, and fire intensity, and spotting distances from torching trees
	Basic Fire Behavior	Provides basic fire behavior characteristics of the flaming front (spread rate and flame length) for short term situations - up to one week
	Short Term Fire Behavior	Simulates fire growth for a particular ignition source and forecasted weather using the Minimum Travel Time method (Finney 2002).
	Near Term Fire Behavior	Fire growth simulation up to 7 days using hourly forecasted weather (Finney 1998).
	Long Term Fire Behavior	Address fire growth beyond time-frames of reliable weather forecasts as probabilities. The Fire Spread Probability simulator (FSPro) is used to produce these probabilities (Finney et al., 2010).
Fire economics	*See below*	Provide information on historical costs, tabular displays of economic values at risk, and a risk assessment of important values overlaid on a fire spread probability map.
	Stratified Cost Index (SCI)	Provides a historical comparison of the costs of a current fire to ones with similar characteristics and potential (Gebert et al., 2007).
	Short Term, Near Term, and FSPro simulations	Provides immediate estimates of values at risk as a simple, qualitative inventory of values within a planning area encompassing the simulated perimeter (Calkin et al., *In Press*). FSPro outputs show a values inventory summarized by probability zones as well as the expected quantity of each threatened value.
	Rapid Assessment of Values-At-Risk (RAVAR)	Produces tabular and spatial information combined with fire spread probability prediction in two groups: (Calkin et al., *In Press)* • Critical Infrastructure • Natural and Cultural Resources
	Values inventory	Produces information similar to that from RAVAR, but auto-generated.

	Values at Risk	Tabular value information produced in combination with FSPro outputs.
Air quality and emissions	WFDSS air quality portal, WFDSS-AQ (Larkin et al. 2010)	Provides access to historic, real-time and forecasted air quality information using a stand-alone web portal Eight air quality and emissions tools provide information about the current smoke situation, climatological statistics, and forecasts. Five tools are available for immediate and short term smoke assessments. Two Smoke Guidance tools provide fire-specific tabular point forecasts and regional maps of air quality metrics.

- **Objectives**. This area automatically populates pre-loaded, spatially relevant, fire management objectives from land, resource, and fire management plans to help managers develop and refine specific incident objectives.
- **Course of Action.** Managers define operational actions here to meet specific incident objectives. These actions can be short or long-term, depending on the fire situation. Actual locations of planned operational tactical actions and contingency actions can be established using the geospatial data and maps. Also, costs, operational resources, and an organization necessary to manage the fire are described here.
- **Validation.** This allows managers to review the Situation Assessment, Incident Objectives, and Course of Action and confirm that the objectives and actions are achievable and comply with land management guidance. If managers are unable to confirm this, the COA Validation page direst them to the development of a new course of action.
- **Decision.** Managers document the decision, rationale for it, stipulate a timeframe for reassessing the decision, and approve the decision with an electronic signature.
- **Periodic Assessment.** This component provides a process for a recurring review of the current decision to evaluate effectiveness of selected strategies and tactics, and, if warranted, initiate a new decision.

These components have been designed to keep WFDSS consistent with the eight steps used to define risk-informed decision making. WFDSS components are also fully inclusive of all phases of information management (Figure 2). The structure and function of this system helps decision makers reach deliberative, risk-informed decisions on how to manage wildland fires. It recognizes the importance of consolidating program examination, facilitates new and relevant information acquisition, provides access to the best procedures for conducting analyses, promotes the application of knowledge, processes, technology, and proven practices, and archives the overall processes and results using the information to improve program effectiveness (Figure 2).

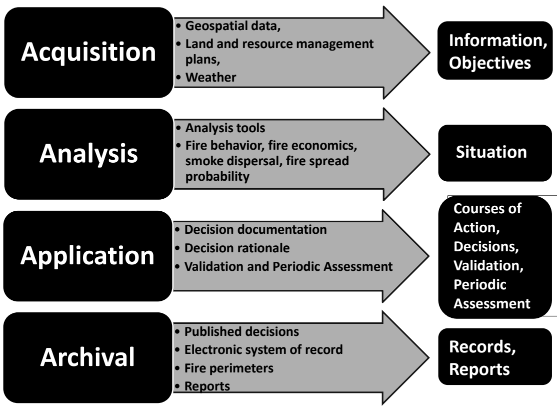

Figure 2—Comparison of WFDSS component areas and information management phases.

Once a wildland fire starts, a progressive process of assessment, risk-characterization, analysis and deliberation begins in order to make a risk-informed decision in WFDSS. Maps of forest, brush, and grass fuel types with other geospatial data such as values at risk (infrastructure and natural resources) are viewable and can be displayed with fire behavior and smoke modeling tools to visually project risk. Other assessment information available during the initial phase includes local, regional, and national fire situations; a quick, qualitative risk assessment; and the pre-planned strategy defined in a Fire Management Plan. The initial stage closely follows the first variation of the recognition-primed decision making model where initial response situations are somewhat familiar with less variation in objectives and managers can implement pre-planned decisions. If the pre-planned strategy is accomplished, no further documentation is needed in WFDSS.

When pre-planned actions are not successful or the situation significantly changes, additional or new decisions are needed. WFDSS facilitates this process by providing more information and improving access to analysis tools. As the situation escalates, WFDSS actually incorporates the best aspects of both the recognition-primed and rational choice decision models to support risk-informed decisions. WFDSS does not place high emphasis on comparative analysis but has a goal of full deliberate use of decision analysis support tools to provide the best available information. When this information and process are fully embraced and applied, decisions can be optimized without additional work, time, and computational support associated with comparisons of multiple options. Managers can fully document their decisions, including rationale for those decisions with all supporting analysis information as they proceed through the system.

The last area of substance in WFDSS is its ability to facilitate long-term implementation action planning. Fire managers can develop implementation actions in the Course of Action section which can include short- or long-term tactical response information. Long-term actions can be designed around a Planning Area representing the desired management area for the fire which creates a reference for all analysis, planning, and implementation activities. Management Action Points that identify where defined actions will be taken in response to changes in fire temporal or spatial extent, or other situational changes can be spatially developed and displayed. Contingency actions for implementation during unplanned situations can also be developed here.

Summary

The wildland fire management program in the United States is based on the best available science, incorporates up-to-date knowledge, and is more responsive to land and resource management needs and increasing complexity and risks than ever before. As fire management moves into the future, focus will be needed on improving program efficiency while accomplishing both protection and resource management objectives. Improved decision making capability will continue to be particularly important.

The Wildland Fire Decision Support System possesses many attributes that make it uniquely different from other decision systems that have been used in wildland fire management. These differences, along with implementation swiftness, represent a significant change in fire management practices. WFDSS fully utilizes all aspects of information management, facilitates the application of the latest science and technology, incorporates the most applicable attributes of accepted decision making models, and modernizes fire management by advancing decision making capability.

WFDSS development to date has resulted in delivery of a viable decision support system for use in post-ignition wildfire situations. However, since this system offers considerable potential power, many opportunities for future enhancements and growth exist. As research models and technological advancements emerge, these will be added to WFDSS. Potential decision support growth areas include pre-ignition project situations such as planning, optimization of, and placement of fuel treatments; and for both pre- and post-ignition situations: risk quantification refinement and improvement, and additional air quality tools. Information archival in WFDSS is already generating valuable databases for future reference, reporting, and knowledge learning. Strong possibilities exist to make this system a more comprehensive documentation and reporting system and reduce process redundancy with other systems. Examples include storage of geospatial information, fire summary statistics, strategic and tactical knowledge and applications, and outcomes. System enhancements involving user friendliness and responsiveness such as better user interfaces, more adapted graphics, greater response speed, greater data acquisition and transmission capabilities, and more intuitive and logical process sequencing are areas of consideration. WFDSS development and enhancement will continue to improve with the goal of providing and maintaining a state of the art wildland fire management decision support system responsive to changing program complexity and social, economic, and ecologic needs.

References

Calkin, D.E., M. P. Thompson, M. A. Finney and K. D. Hyde, (*In press).* A real-time risk-assessment tool supporting wildland fire decision-making, *J. Forestry.*

DOI-USDA. (2011). A national cohesive wildland fire management strategy. http://www.forestsandrangelands.gov/strategy/documents/reports/1_CohesiveStrategy03172011.pdf. *U.S. Department of the Interior, U.S. Department of Agriculture*, Washington, D.C., USA.

Finney, Mark A. (1998). *FARSITE*: Fire Area Simulator – model development and evaluation, U.S. Department of Agriculture, Forest Service, Research Paper, RMRS-RP-4, p. 47.

Finney, Mark A. (2002). Fire growth using minimum travel time methods, *Canadian Journal of Forest Research*, **32**(8):1420-1424.

Finney, M. A., I. C. Grenfell, C. W. McHugh, R. D. Stratton, D. Trethewey, and S. Brittain, (2010). An ensemble method for wildland fire simulation. *Environmental Modeling and Assessment,* Published online Nov. 6.

Gebert, K. M., D. E. Calkin, and J. Yoder, (2007). Estimating suppression expenditures for individual large wildland fire. *Western Journal of Applied Forestry*, **22**(3):188-196.

Klein, Gary. (1999). Sources of power: how people make decisions. The MIT Press. Cambridge, MA.330 p.

Larkin, **N**.S., T. Brown, P. Lahm, and T. Zimmerman. (2010). Wildland Fire Decision Support System Air Quality Tools, *Fire Management Today* **70**(2), 36-40.

Noonan-Wright, Erin, T.S. Opperman, M. A. Finney, G.T. Zimmerman, R.C. Seli, L.M. Elenz, D. E. Calkin, and J.R. Fiedler. (*In Press)*. Developing the U.S. wildland fire decision support system (WFDSS). *J. Combustion*.

NWCG 2009. Quadrennial Fire Review (2009). Final Report. http://www.nifc.gov/QFR/QFR2009Final.pdf. National Wildfire Coordinating Group, National Interagency Fire Center. Boise, ID. 52 p.

Pence, Morgan, and Thomas Zimmerman. (2011). The wildland fire decision support system: Integrating science, technology, and fire management. *Fire Management Today* **71**(1), 22-26.

Stern, Paul C., and Harvey V. Fineberg, eds. (1996). Understanding risk: informing decisions in a democratic society. Committee on Risk Characterization, Commission on Behavioral and Social Scienes and Education, National Research Council. The National Academies Press, Washington, D.C. 249 p.

Tversky, A. (1972). Elimination by aspects: a theory of choice. *Psychological Review* 79(4):281-289.

USDA-USDI, (2009). Guidance for Implementation of Federal Wildland Fire Management Policy (February 2009), http://www.nifc.gov/policies.htm. U.S. Department of Agriculture, U.S. Department of Interior, Boise, Idaho, USA.