Integrated Environmental Assessment and Management — Volume 6, Number 3—pp. 469–483
© 2009 SETAC

A New Process for Organizing Assessments of Social, Economic, and Environmental Outcomes: Case Study of Wildland Fire Management in the USA

Randall JF Bruins,† Wayne R Munns Jr.,‡ Stephen J Botti,§ Steve Brink,|| David Cleland,# Larry Kapustka,†† Danny Lee,‡‡ Valerie Luzadis,§§ Laura Falk McCarthy,|||| Naureen Rana,## Douglas B Rideout,††† Matt Rollins,‡‡‡ Peter Woodbury,§§§ and Mike Zupko||||||*

†US Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment, 26 W. Martin Luther King Drive, Cincinnati, Ohio 45268, USA
‡US Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory, 27 Tarzwell Drive, Narragansett, Rhode Island 02882, USA
§US National Park Service, Ret., National Interagency Fire Center, 3833 S. Development Avenue, Boise, Idaho 83705-5354, USA
||California Forestry Association, Suite 1830, 1215 K Street, Sacramento, California 95814, USA
#US Forest Service, Eastern Regional Office, 68 South Stevens, Rhinelander, Wisconsin 54501, USA
††LK Consultancy, 8 Coach Gate Place SW, Calgary, Alberta T3H 1G2, Canada
‡‡US Forest Service, Southern Research Station, Eastern Forest Environmental Threat Assessment Center, 200 WT Weaver Blvd., Asheville, North Carolina 28804, USA
§§State University of New York, College of Environmental Science and Forestry, Forest and Natural Resources Management Department, 307 Bray Hall, One Forestry Drive, Syracuse, New York 13210, USA
||||The Nature Conservancy, Global Fire Initiative, 212 East Marcy Street, Santa Fe, New Mexico 87501, USA
##Great Lakes Protection Fund, 1560 Sherman Avenue, Suite 880, Evanston, Illinois 60201,USA
†††Colorado State University, Warner College of Natural Resources, Department of Forest, Rangeland, and Watershed Stewardship, Fort Collins, Colorado 80523, USA
‡‡‡US Geological Survey, Center for Earth Resources Observation and Science (EROS), Sioux Falls, South Dakota 57198, USA
§§§Cornell University, Crop and Soil Sciences Department, Ithaca, New York 14853, USA
||||||Southern Group of State Forester, PO Box 93, Winder, Georgia 30680, USA

(Submitted 30 July 2009; Returned for Revision 6 October 2009; Accepted 2 December 2009)

ABSTRACT

Ecological risk assessments typically are organized using the processes of *planning* (a discussion among managers, stakeholders, and analysts to clarify ecosystem management goals and assessment scope) and *problem formulation* (evaluation of existing information to generate hypotheses about adverse ecological effects, select assessment endpoints, and develop an analysis plan). These processes require modification to be applicable for integrated assessments that evaluate ecosystem management alternatives in terms of their ecological, economic, and social consequences. We present 8 questions that define the steps of a new process we term *integrated problem formulation* (IPF), and we illustrate the use of IPF through a retrospective case study comparing 2 recent phases of development of the Fire Program Analysis (FPA) system, a planning and budgeting system for the management of wildland fire throughout publicly managed lands in the United States. IPF extends traditional planning and problem formulation by including the explicit comparison of management alternatives, the valuation of ecological, economic and social endpoints, and the combination or integration of those endpoints. The phase 1, limited-prototype FPA system used a set of assessment endpoints of common form (i.e., probabilities of given flame heights over acres of selected land-resource types), which were specified and assigned relative weights at the local level in relation to a uniform national standard. This approach was chosen to permit system-wide optimization of fire management budget allocations according to a cost-effectiveness criterion. Before full development, however, the agencies abandoned this approach in favor of a phase 2 system that examined locally specified (rather than system-optimized) allocation alternatives and was more permissive as to endpoint form. We demonstrate how the IPF process illuminates the nature, rationale, and consequences of these differences, and argue that its early use for the FPA system may have enabled a smoother development path. Integr Environ Assess Manag 2010;6:469–483. © 2009 SETAC

Keywords: Integrated assessment Integrated problem formulation Valuation Wildland fire Decision making

Case Study

INTRODUCTION

Integrated assessment requires an integrated problem formulation process

Human societies derive an array of services from inherently complex ecological systems (Millennium Ecosystem Assessment 2005). Consequently, environmental problems and the actions intended to address them have complex ramifications

* To whom correspondence may be addressed: bruins.randy@epa.gov
Published on the Web 3 December 2009.
DOI: 10.1897/IEAM_2009-075.1

for societal well-being. Therefore, decision makers should be informed by analyses that integrate (i.e., bring together to form a coherent whole) the social, economic, and ecological outcomes of management alternatives. Interdisciplinary integration has been defined as ''the activity of critically evaluating and creatively combining ideas and knowledge to form a new whole or cognitive advancement'' (Repko 2008). It contributes to solving complex problems by providing a systematic approach to combining and interrelating insights grounded in commonalities while taking into account differences (Klein and Newell 1997) and providing opportunity for ''nonlinear thinking'' (Nikitina 2002).

Early risk-assessment approaches stressed the necessity of isolating the scientific processes of risk analysis from any discussion of technical feasibility, economics, or policy (NRC 1983). More recent assessment frameworks have urged that analyses be multidisciplinary and procedures more open and inclusive (UNEP 1996; PCCRARM 1997; USEPA-SAB 2000; Stahl et al. 2001). In this regard, the approaches that are now recommended for assessing environmental risks have much in common with the planning processes used to manage US water resources (USACE 2000) or federal lands (USFS 2002), which tend to be concerned with both environmental risks and resource utilization; they tend to be multidisciplinary, to recognize multiple objectives, and to acknowledge the need for public involvement. Industries complying with environmentally relevant standards of the International Organization of Standardization (e.g., the families of ISO 9000, ISO 14000, and ISO 18000) have also recognized that environmental analyses should be broadly based: stakeholders must help craft the compromises that are inevitable with any substantive environmental management action (ASTM-I 2006), and social and economic values must be taken into account.

However, even as the frameworks have been broadened to encourage assessments to be more fully integrated, many technical barriers to integration still exist. For example, a comprehensive analysis of economic benefits of US Clean Air Act regulations from 1990–2010 (USEPA 1999) was able to estimate only a few kinds of ecological benefits, such as those stemming from improved visibility in national parks, from improved recreational fishing in areas impacted by acid deposition, and from improvements in timber and agriculture due to tropospheric ozone reductions. The analysis was unable to value other ecological changes, including reductions in acid-induced forest ecosystem damage or nitrogen-induced eutrophication of US estuaries. Similarly, the US National Research Council's critique of ''Superfund and Mining Megasites'' (NRC 2005) concluded that one major deficiency of the Superfund program is a general lack of ''ability to address socioeconomic as well as health and environmental aspects of remediation, including the need for economic assistance for low-income communities and provision of health support services for communities living with health risks.''

Various factors contribute to this seeming lack of completeness. Some ecological or social processes require basic research before analyses can proceed routinely. Collection of primary data about economic benefits can be costly and time-consuming. Substantial effort may be required to develop and evaluate models capable of linking sources, exposures, effects, and benefits. Decision processes also vary in their valuation requirements, posing differing demands on analysis. Most significant US regulatory decisions require benefit-cost analysis (BCA) (USEPA 2000; OMB 2003). Although BCA enjoys wide acceptance, its requirements can also be cumbersome and limiting (Boyd 2004). Some environmental management programs have made effective use of multicriteria decision analytic techniques for the joint evaluation of multiple values and objectives (McDaniels et al. 1999; Larichev and Olson 2001; Linkov et al. 2006). The US Environmental Protection Agency's (USEPA) Science Advisory Board (USEPA-SAB 2009) recently reviewed and summarized the range of valuation systems that have been used to inform environmental decisions, categorizing them as either preference-based (including attitudes or judgments, economic values, community-based values and constructed preferences) or biophysically based (including bio-ecological values and energy-based values). The Board stressed that, due to this wide variety, the appropriateness of any given valuation system will vary with the decision problem and that therefore selection criteria should be established.

Thus, an integrated environmental analysis typically requires some combination of basic research, data collection, and model development, as well as the adoption of 1 or more valuation techniques. Because these elements are interdependent, it is imperative that they be approached in a coordinated manner. A systematic process is needed for examining all of these requirements and formulating an integrated assessment approach. The USEPA's Guidelines for Ecological Risk Assessment (USEPA 1998) describe 2 processes, respectively referred to as *planning* and *problem formulation*, that are used to plan the steps of an assessment. Planning is a discussion among managers, stakeholders, and analysts to clarify the goals and objectives of ecosystem management and the scope of assessment. Problem formulation is carried out by risk analysts, ideally interacting iteratively with stakeholders, and produces a plan for ecological data collection, analysis and use to inform decisions. These processes, as previously described (and as further elaborated in USEPA 2001), do not fully meet the needs of integrated assessment because they do not provide guidance for including social and economic assessment or comparisons of management alternatives.

In this study, we describe a process that we term *integrated problem formulation* (IPF). IPF combines the planning and problem formulation processes and expands them as needed to meet the demands of integrated assessment. We present a set of 8 questions that guide IPF, and we illustrate their use by means of a case study. We believe that this procedure will be useful as a front-end process for organizing integrated assessments in various environmental decision settings, and that it will benefit from further use and refinement.

An integrated problem formulation exercise

In October 2003, the Society of Environmental Toxicology and Chemistry sponsored an expert workshop, held in Pensacola, Florida, to examine integration of ecological risk assessment and socioeconomic valuation. The workshop's findings (Stahl et al. 2007) included a set of general principles for organizing and integrating the valuation process (Heninger et al. 2007). The 2003 workshop organizers determined that a second workshop should apply those principles to the design of an IPF process, and that this could best be accomplished through a detailed case study. Allocation of federal funding for wildland fire management in the US was selected as a problem appropriate for this exercise for 3 reasons. First, the scope of the wildfire problem is large and rapidly growing. Second, as wildland fire presents both risks and benefits to society, effective funding allocation requires the collection and integration of information on social, economic, and ecological risks and benefits. Third, an analytic system currently being developed by the US Forest Service and Department of Interior to address this need, the Fire Program Analysis (FPA) system, could serve as a model for case study evaluation. An initial version of the FPA system had just been completed in early 2006, and following reviews this phase 1 system was being replaced by a phase 2 system that differed substantially in approach. The contrast between these 2 approaches could serve to illustrate the choices involved in design of an integrated assessment.

Using the complex issues pertaining to wildland fire management as a case study, the IPF approach was refined and evaluated in a protracted series of discussions punctuated by a workshop held October 22–25, 2006, at the Wingspread Conference Center in Racine, Wisconsin. Over the course of these interactions, the 8 guiding questions were evaluated and a conceptual model of the environmental system and decision problem was developed. In IPF, a conceptual model represents the relationships of stressors and ecological entities to societal values and impacts, and also depicts how management alternatives are expected to alter stressors or their effects (Bruins et al. 2005). The conceptual model developed for wildland fire management enhanced understanding of the decision problem and complemented the process of IPF refinement. Participants included professionals from governmental and nongovernmental organizations concerned with wildland management and conservation, environmental protection, the interests of rural communities, and the interests of the forest industry. Expertise represented included ecological risk assessment and management, wildfire risk assessment and management, forest ecology and management, economics and the social impacts of wildfire.

CASE STUDY: WILDLAND FIRE MANAGEMENT IN THE UNITED STATES

Integrated problem formulation is intended as an approach for planning an integrated assessment, so that assessment steps (data gathering, analysis, etc.) can proceed in a coordinated manner. IPF is guided by a series of questions that establish environmental issues to be addressed, and the management objectives and alternatives salient to the decisions that the assessment addresses (Table 1). These questions also are used to identify endpoints for the assessment and their measurement, and to frame analyses important to the decisions and their effectiveness. This section is organized according to the guiding questions. We introduce our conceptual model of the wildland fire management problem in the discussion of questions 1 and 2, referring to it as needed in the process of addressing the remaining questions.

Questions 1 and 2: What is the problem or decision being addressed? What is the management context of the problem or decision?

Management of an environmental problem can be effective and efficient only to the extent that it addresses all contributing stressors, as well as the sources and driving forces that produce them. Therefore, the problem and its decision context must be clearly defined. In most cases, those who plan an assessment have sufficient understanding to adopt preliminary definitions of the problem before analyzing its context, even though these definitions may require revision once the situation has been evaluated more fully. Here, we have combined the discussion of these topics. Consideration of context should include: geographic and ecological setting; social setting, including institutions, regulatory and legal requirements, decision makers, other affected parties and social values; and available management options. It also involves the temporal setting, which can include historical development of the problem, past management strategies, and the rates of relevant natural processes both past and future (USEPA 2001).

Ecological context and problem history. Fire is a natural part of forest ecology throughout most of the US and plays an important ecological function within forest ecosystems (DellaSala et al. 2004). Indeed, ecosystems throughout the western US have been shaped by fire for millions of years (Noss et al. 2006). Different types of forests can vary in their characteristic fire regimes (Schoennagel et al. 2004). Some forest types have frequent low-intensity fires that kill undergrowth, but do not kill most mature trees (Veblen et al. 2000). For example, ponderosa pine forests in much of the southwestern US have low-intensity natural fire regimes, which result in an open canopy and widely spaced mature trees. Other forest types have infrequent, high-intensity fires that kill nearly all trees, such as occurred in the famous Yellowstone fires of 1988 (Turner et al. 2003). Such fires are often extremely difficult to extinguish and can burn until there is a substantial change in weather conditions and rainfall (Dombeck et al. 2004; Kauffman 2004).

The number of large (>400 ha) fires occurring in the western US increased sharply in the 1980s and continues to exceed historic trends (Westerling et al. 2006). Fire management costs tripled during the period 1998 to 2006, becoming the largest budget items in the US Department of Agriculture (USDA) Forest Service (USFS) and the Department of the Interior (DOI) (Public Lands Council 2007). The severity of the current wildfire management crisis is best understood as a convergence of several decades-long trends involving historic fire management practices, climatic conditions, and land use change related to population growth.

In some common forest types, such as ponderosa pine, fire suppression during the past 50 y has significantly altered the natural regime of low intensity fires. Additionally, logging, livestock grazing, road building and other land uses have changed these forests (Dombeck et al. 2004). Many small trees have matured, making the forests much denser than they were historically. Dense forests have ''fuel ladders'' that connect ground vegetation to tree canopies, allowing ground fires to access the upper canopy. Such forests are now susceptible to uncharacteristic (i.e., outside the range of historical variation; Hardy 2005), high intensity ''stand-replacing'' fires that often kill nearly all trees, even fire-adapted mature trees. As stated by the federal bureaus, ''while the policy of aggressive suppression appeared to be successful, it set the stage for the intense fires that we see today'' (USDA and DOI 2000).

The long-term, average area of the western US experiencing drought has trended upward from 18% in 1900 to 40% in

Table 1. Questions to guide integrated problem formulation. All main and supporting questions should be asked in a problem formulation setting that includes managers and stakeholders, although as noted, some are more technical and likely will be answered subsequently by analysts

Nr	Main question	Supporting questions	Comments
1	What is the environmental problem or decision being addressed?	What decision (or decisions) needs to be made?	Question 1 is answered when a succinct problem statement has been adopted.
		What problem does the decision address?	
		What environmental stressors, sources of stressors or adverse effects are of primary concern?	
		What spatial and temporal scales and boundaries apply to the problem and the decision, respectively?	
2	What is the management context of the problem or decision?	Who are the decision-makers, and what is the nature and scope of their authority?	Development should begin of a conceptual model of the environmental problem and its management, comprising the information from this and all subsequent planning activities.
		What is the historical context, both social and ecological, within which the problem has developed and the decision must be implemented?	
		Who are the interested or affected parties (stakeholders)?	
3	What are the management objectives?	What are the key concerns of the stakeholders (including the decision-makers), including goals to achieve and values to protect?	Question 3 is answered when a succinct statement of objectives has been adopted.
		What are the social, economic and environmental objectives and constraints?	
		What are the fundamental objectives, their specificity and goal conflicts?	
4	What are the management alternatives?	What are the various actions or suites of actions that can be taken by the decision-makers to reduce the stressors or their sources, or to ameliorate their effects?	
		What are the temporal and spatial scales of these actions?	
		What tractable subset of possible management alternatives should be used for purposes of integrated analysis?	Likely will be answered by analysts.
5	Given the management objectives and alternatives, what are the assessment endpoints?	Of the management goals and values identified earlier, which ones are at risk due to the environmental problem or likely to be otherwise affected by the management alternatives?	
		Of those at risk or otherwise affected, which ones can feasibly be operationalized to serve as analytic endpoints? Should any be grouped or lumped for analytical purposes?	Likely will be answered by analysts.

6	How should expected changes in the social, economic, and ecological endpoints be characterized?	How (by what pathways or mechanisms) are the endpoints believed to be affected by the environmental problem (i.e., what are the risk hypotheses)?	
		How (by what pathways or mechanisms) are the endpoints believed to be affected by the management actions (i.e., what are the risk management hypotheses)?	
		What data or models are needed to characterize these relationships?	Likely will be answered by analysts.
		Of these data or models, which are available and which need to be developed?	Likely will be answered by analysts.
		Which endpoints can be quantified, and which can only be characterized more qualitatively (e.g., by ordinal ranking, high-medium-low rating, or direction of change)?	Likely will be answered by analysts.
		How will uncertainties be characterized?	Likely will be answered by analysts.
7	How will the expected changes in social, economic, and ecological endpoints be valued and integrated for use in making decisions?	Do decision-makers have established requirements or preferences for the valuation/integration approach?	
		What limitations on valuation approach, if any, are imposed by the nature of the endpoints or their manner of characterization?	
		What valuation and/or integration approach is feasible and will be most useful to decision-makers? What additional data or modeling requirements would this approach impose? What data quality objectives follow?	
8	How will the outcomes and effectiveness of the management actions be	What opportunities exist to revisit or adjust management actions? What is their nature and timeframe?	
		What implementation actions can be measured to indicate the progress of implementation?	Likely will be answered by analysts.
		What assessment endpoints or surrogates can be measured to provide data to verify or falsify the management hypotheses or to calibrate the assessment models?	Likely will be answered by analysts.

2003 (Cook et al. 2004), and especially severe conditions prevailed from 1999 to 2004. Recent analysis shows a close correspondence between western large-fire frequency and mean spring-summer temperature (Westerling et al. 2006). Furthermore, increased population and changes in urban and rural development patterns have contributed to exacerbating growth of the wildland-urban interface (WUI), both in area and numbers of housing units contained (e.g., Hammer et al. 2007). The WUI infers both *interface*, where populated areas abut wild land, and *intermix*, where structures are built in wildland at a density of at least 1 per 16 ha (66 FR 751).

United States agencies use the Fire Regime Condition Class (FRCC) system established by Hann and Bunnell (2001) to define degrees of ''departure from the historical natural regimes, possibly resulting in alterations of key ecosystem components such as species composition, structural stage, stand age, canopy closure, and fuel loadings.'' While not an evaluation of fire risk per se, FRCC serves as a metric for reporting the number of wildland acres in need of hazardous fuels reduction and for evaluating the level of efficacy of fuel treatment projects. In the Interagency FRCC Guidebook (Hann et al. 2004), low departure (FRCC 1) describes fire regimes and succession status considered to be within the historical range of variability, while moderate and high departures (FRCC 2 and 3, respectively) characterize conditions outside of this historical range (Hann and Bunnell 2001; Hardy et al. 2001; Schmidt et al. 2002).

Recent management initiatives. Review of the severe fires of 1988 (which included the Yellowstone fires) and 1994 (which resulted in numerous firefighter fatalities) prompted the Clinton administration to initiate a comprehensive review of wildland fire policy. This led to what is now known as the 1995 Federal Interagency Fire Policy (DOI and USDA 1995). Key features of this policy were calls for a more integrated approach to wildland fire management and for the recognition and management of fire as a central feature of natural systems. This was soon followed by the unprecedented severe fire year of 2000, which generated a further sequence of government actions. A National Fire Plan was prepared (see http://www.forestsandrangelands.gov/NFP/ as accessed 25 June 2009), and an interagency team consisting of representatives from the USFS, Bureau of Land Management (BLM), US Fish and Wildlife Service (USFWS), Bureau of Indian Affairs (BIA) and National Park Service (NPS) was organized to provide the vision for a new integrated fire management and planning system (Rideout and Botti 2002). In January 2002, the team produced a report entitled ''Developing an Interagency Landscape-scale Fire Planning Analysis and Budget Tool'' (USDA and DOI 2002), which became known as the Hubbard Report. Other important measures included passage of the Healthy Forests Restoration Act of 2003, which included key provisions for facilitating fuels treatments (removing brush and other fuels) on USFS and BLM lands, and the Ten Year Comprehensive Strategy (DOI and USDA 2001), which outlined the need for cooperation among citizens and all levels of government.

The Hubbard Report described current management and planning approaches as inadequate, and established a development roadmap that included performance criteria. Desired attributes of this system were given as follows:

- **Be objective driven and performance based**—meaning that it would have clear ties to land management goals,
- **Address the full scope of fire management activities**—meaning it should provide an integrated analysis of all components of the fire program, in contrast to the old systems that analyzed preparedness, fuels management and so on as separate programs,
- **Model the effects of different management strategies over time**,
- **Identify fire-management resources**—meaning identify the type, number and location of resources that would best meet management objectives,
- **Contain a cost-effectiveness analysis**—meaning that any set of defined objectives would be produced at least cost and that a menu of cost effective alternatives would be produced for budget analysis, and
- **Provide analysis over a range of scales**—meaning that the planning and budget analysis would be scalable from the interagency planning unit through the national system.

Achieving these objectives also required recognizing and overcoming adverse incentive structures. The uncertainty and threat surrounding fire events provide an incentive for managers to use any available resources to aggressively suppress fires. Because much of the expense of fighting large fires is funded from a separate national account, local officials have little disincentive to call for increased levels of fire-fighting resources. They may also be hesitant to call a fire *contained* (full line perimeter) or *controlled* (no longer a threat to escape), because fire-fighting resources might then be released or reassigned elsewhere. By contrast, the potential benefits of permitting a specific wildland fire to burn are hard to ascertain and may not substantively affect a fire incident commander's decisions (Donovan et al. 2008). While such decisions can seem rational from a local perspective, they can have unintended consequences at larger scales, contributing to both economic inefficiencies and potential shortages at other fires as they arise. Successful planning requires an institutional willingness to identify desired conditions over broad landscapes and time scales, to accept responsibility for managing long term risk, and to share budgets and resources. Such planning also requires an analytical planning and budgeting system commensurate with the challenge.

Development of the FPA System was therefore seen as a critical step. An initial, Phase 1 version of the FPA system was begun in 2002. Chartered as a limited prototype to address preparedness planning only, the phase 1 system estimated wildfire risks across all US federally owned lands, and it estimated optimally efficient deployment of fire management resources within each of 139 Fire Planning Units (FPUs) covering the conterminous US, as well as at the national level. Following reviews (DOI and USDA 2006b), a second and more complete phase of FPA system development was undertaken in 2006, and as of this writing is still in the process of being implemented. The phase 2 system differs in its approach to identification of management alternatives, evaluation of alternatives and identification of preferred outcomes.

Problem definition and issues of scale. Given this context, we initially stated the decision problem for this IPF exercise to be: ''How should limited public resources be allocated to minimize the risks to social welfare posed by wildfires in the US?'' Here, *public resources* referred to federal, state, and local governmental resources potentially applied to wildland fire management and included funds, equipment and personnel; *social welfare* included any social, economic, or ecological contributions to human well-being. In use, however, we found this statement to be vague in several key aspects, causing some confusion during our discussions. The federal agencies conduct planning at multiple scales, ranging from local districts and units to the agency and department level. The formation of landscape-perspective, interagency Fire Planning Units (FPUs) was a central feature of FPA development, reducing their number from approximately 1500 to 139 (each current FPU encompasses an area ranging in size from a few thousand to several million ha). However, the federal government is concerned with cost-effective management of risks both within and across FPUs. Similarly, decisions are made annually corresponding to the budgeting process, but this can obscure crucial tradeoffs between short- and long-term risk reduction (i.e., aggressive suppression causes fuels to accumulate). A more explicit decision statement would be: ''How should limited public resources be allocated, among and within Fire Planning Units, to minimize both short- and long-term risks to social welfare posed by wildfires in the US?'' This refined statement still leaves unclear the politically sensitive question of whether state and local resources should be accounted for in the federal allocation exercise, but that can be regarded as a problem of application rather than of assessment tool design.

Conceptual model and related terminology. After much modification and refinement, our conceptual model (Figure 1) views wildland fire management planning decisions as the means by which public and private *resources* are applied to various combinations of management actions, which vary by location and year (*management options*). Wildfire management consists of activities taken before, during and after the occurrence of fire (*pre-fire*, *fire response*, and *post-fire options* in Figure 1). The specific combination used depends on local conditions and management objectives. Although these details are not depicted, fire managers can affect the occurrence, severity, and extent of wildland fires through a long-term strategy of *fuels treatment*, including mechanically removing fuel (involving brush removal and/or timber harvest), igniting fires to reduce fuels (*controlled burning*), and allowing natural ignitions to burn within specific prescriptions (*wildland fire use*). Pre-fire strategic management also involves actions by homeowners and communities to reduce the ignitability of structures, and education to reduce ignitions. Tactical response to a fire begins with *initial response*, which includes assessment and, when suppression is indicated, *initial attack*. Initial attack can evolve into *extended*

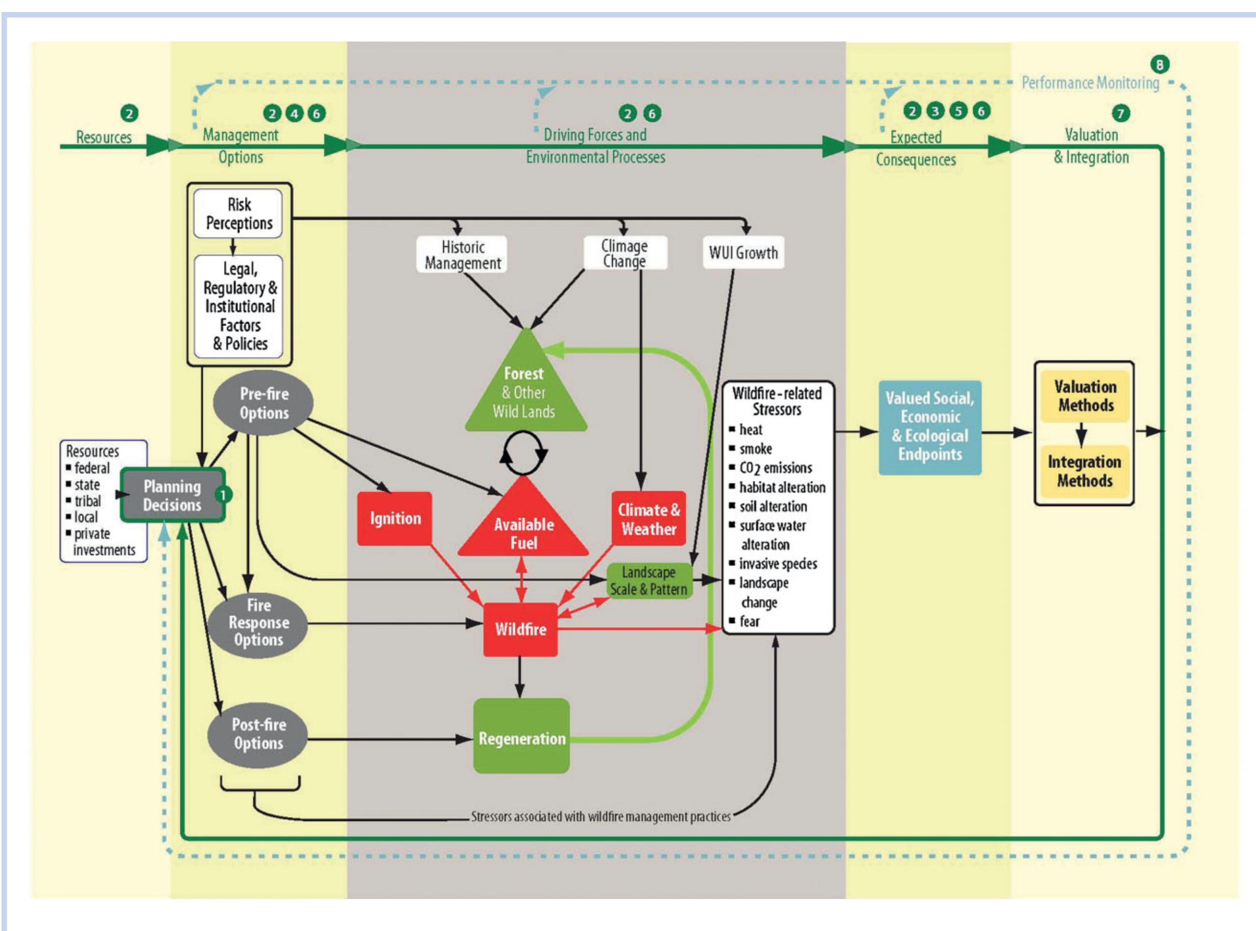

Figure 1. Conceptual model of wildland fire management on public lands throughout the USA. Vertical shading shows different portions of the analysis. Circled numbers indicate the 8 main questions of the Integrated Problem Formulation process (see Table 1) and their relevance to each portion. WUI means wildland-urban interface.

attack when additional time and resources are required for containment. If full suppression is not selected as the appropriate strategy, initial response can evolve into long-term monitoring of wildland fires and localized actions to prevent such fires from burning outside designated management areas. After a fire is extinguished, managers can rehabilitate areas of unstable soil or severe vegetation mortality using mechanical erosion control methods and by replanting vegetation.

Wildfire occurs in dynamic relationship with management actions and sources of ignition, vegetation condition (especially fuel availability) and pattern, and climate (*environmental processes*). These are affected by driving forces that include historic management practices, climate change and growth of the WUI. Wildfire and some wildfire management practices produce environmental stressors that affect social, economic, and ecological entities valued by society. Analytic processes seek to identify discrete endpoints reflective of those values and to predict how planning decisions will affect them (*socioeconomic and ecological consequences*). Analysis must determine how to value those predicted changes (*valuation*) and how to synthesize those values meaningfully for purposes of making optimal planning decisions (*integration*). An integrated assessment process entails modeling all of these relationships, a priori, in a manner that will enable effective planning decisions. It also should involve *performance monitoring* (dashed line), a posteriori, and use of that information to improve future decisions.

Question 3: What are the management objectives?

Management objectives should be established based on an in-depth understanding of the values and concerns of decision-makers and other stakeholders. Once these have been enumerated, fundamental objectives should be determined and potential conflicts noted (McDaniels 2000; USEPA 2001). Representatives of various stakeholder sectors who attended our workshop articulated their interest groups' concerns as follows:

- **Congress**—Expanding fire management costs are crowding out other programs that the public values, posing a management challenge for the US Congress (Public Lands Council 2007). Congressional oversight concerns can be summarized in 3 themes: cost (containment and cost-effectiveness), cohesion (comprehensiveness, system integration, and geographic comparability), and accountability (transparency and optimization). The performance measures currently reported by the agencies (e.g., acres receiving fuel treatment) do not address these themes. A budget allocation procedure using an optimization approach based on explicit valuations of economic, social, and ecological outcomes would be viewed favorably because of the transparency it would provide. Deviations from optimization (as are sometimes needed by managers on-the-ground) can be documented and used to improve future budgeting.
- **States**—Most US states are legally required to follow a specific hierarchy for allocating resources and responding to wildfire. This hierarchy reflects key values and includes firefighter safety, public life safety (including minimizing health problems associated with smoke), property protection, and ecological protection. States also share many other values of federal agencies, but must act in the context of state laws and priorities.
- **Forest Industry**—The forest industry values life, property, and healthy vegetation, and believes these are best protected by categorizing wild lands according to population density (WUI or non-WUI), value and defensibility of property, and fire condition class of vegetation. Within a given land category, fuels treatment priorities should be to: a) maintain those areas in FRCC 1 condition, b) treat all FRCC 3 lands to achieve FRCC 1, and c) treat all FRCC 2 lands to achieve FRCC 1. Resources should be applied with order of priority to: 1) WUI vegetation treatment, 2) establishment of strategically located fuel breaks, 3) non-WUI forestlands vegetation treatment, 4) shrub lands vegetation treatment, 5) grasslands vegetation treatment, 6) creation of adequate defensible space around all structures, and 7) containment of 98% of fires during initial attack. State and federal policies should acknowledge that climate change and population increases will challenge our ability to achieve the above goals. The industry favors government incentives for the use of harvested biomass (such as woodchips from fuels reduction to generate electricity), and legislation requiring defensible space around properties and the use of fire resistant building materials.
- **Rural Communities**—While national policy focuses resources on the relatively populated areas that constitute the WUI (NASF 2003; DOI 2003), communities in less densely populated areas also need the resources and capability to defend themselves, including stationary equipment, trained crews, and development of escape routes (which both help control fire spread and serve as anchor points for suppression activities). In many areas the federal agencies are heavily dependent on local resources for initial attack on wildfires. Under the National Fire Plan, the federal agencies have funded these collaborators through State and Local Fire Assistance programs. Hazardous fuels mitigation treatments and projects identified in Community Wildfire Protection Plans (CWPPs) receive priority for federal funding in WUI areas (SAF 2004). However, many rural communities may lack the capacity to develop CWPPs. Although CWPPs designate some lands as habitat for threatened and endangered species, very little funding is available for fuels reduction, restoration and fire suppression on these lands. When rural lands are damaged by fire, the local economy is adversely affected; loss of homes is also especially devastating for those rural residents who own little else (Lynn and Gerlitz 2005).
- **Environmental Groups**—These organizations often emphasize that fire is a natural and necessary part of many ecosystems, whereas uncharacteristic wildfires are among the many compounding stresses that threaten these ecosystems. Ecological values to be protected include: natural biodiversity, soil integrity, air quality and water quality, timing and storage. Therefore, fire management should address five key ecological goals: 1) where ecologically and socially appropriate, restore natural fire regimes to fire-dependent ecosystems to maintain forest, shrub, and grassland conditions at landscape scales, 2) prevent damage to soils, streams and biodiversity from uncharacteristic wildfires, 3) manage smoke effects of wildfire and prescribed burning, 4) control the spread of invasive species after wildfire, and 5) in areas where it would be

impossible to restore natural fire regimes, such as fragmented landscapes or those in which high-intensity, large-scale fires are part of the natural regime, find manageable ways to mimic wildland fire's ecological role.

Federal agencies, fundamental objectives, and the management task. In view of the concerns listed above, US federal agencies responsible for wildfire management face multiple and sometimes conflicting mandates and goals. Differences among agencies' particular missions and management cultures also complicate any narrowing of objectives. In particular, the historic focus on economic utilization within the missions of the USFS, BLM, and BIA contrasts with the focus on ecological preservation within the missions of the NPS and USFWS. Protection objectives also vary geographically; a compilation and synthesis of land and resource values identified during Phase 1 as important to land managers in 1 or more FPUs is identified in Table 2. Given the heterogeneity of the wildfire management problem, it is clear that a relatively broad list of protection objectives must be retained.

Table 2. Compilation of fire protection attributes elicited in phase 1 of development of the Fire Program Analysis system (adapted from NIFC 2006)

Wildland-urban interface values: residential areas ($\geq$1 structure/16 ha) at risk due to wildland proximity (interface or intermix)
Commercial values: grazing, utility rights-of-way, oil/gas infrastructure, commercial timber, commercial trust timber, agriculture, and mineral leases
Cultural/historic values: cultural resources, historic properties, Native American interests, paleontological sites, and heritage sites
Environmental quality: air quality, water quality, watershed values, hydrologic function, riparian systems, and invasive species
Legislated or policy restrictions: designated wilderness, wilderness study areas, research natural areas, roadless areas and other areas that have either legislated or policy restrictions
Natural resource values: critical wildlife habitat (other than for threatened & endangered species), high value habitats, sensitive habitats/species, noncommercial woodlands, fire-dependent plant communities, and representative plant and animal communities of special significance
Other special concerns: improvements, special uses, nonfederal improvements, non-WUI[a] improvements, nonurban development, and wildland industrial interface
Recreation: developed recreation, dispersed recreation, high public use, and travel corridors
Threatened & endangered species and critical habitat: identified critical habitat for federally listed threatened and endangered species, and state listed species
Ecosystem restoration: restoring ecosystems to desired conditions that are sustainable and healthy
Ecosystem maintenance: maintaining desired ecosystem conditions that are sustainable and healthy

[a]Wildland–urban interface.

Based on the foregoing discussion, a succinct statement of the objective for public wildfire management in the United States could be advanced as follows:

''Human life and valued ecological, economic, and social assets are protected cost effectively from the short- and long-term risk of wildfires—as well as from adverse after-effects of wildfires and fire-fighting activities—and wildland ecological conditions are improved.''

In this example, human life, a varied set of valued assets, and the management of public funds are each recognized as fundamental. It is implicit that conflicts among the protection of ecological, economic, and social assets will be addressed according to some assessment of relative value, whereas human life is in a special category. Finally, the notion that ecological condition is both compatible with and ultimately necessary for achieving the objective is acknowledged. This statement does not represent the policy of any specific agency or group but was adopted for purposes of this exercise.

Question 4: What are the management alternatives?

Management alternatives are sets of actions or policies that could be put in place to achieve the management objective. Clearly, the suite of management options that may be considered occur within the legal frameworks of federal, state, and local jurisdictions. And as noted above, the tone of the management alternatives should reflect the interests of affected stakeholders and resonate with their perspectives on social welfare (including social, economic, or ecological benefits and offsets) provided by the system. The goal of this stage of IPF is to identify a set of plausible alternatives for further consideration. As described earlier, wildland fire management involves combinations of actions taken before, during and after fires, which vary from place to place and from year to year. In a planning system, however, management alternatives to be evaluated emphasize pre-fire actions (and their costs); responses (and their costs) during and after fires are then simulated as outcomes. An effective budget allocation system must have the capacity to represent these kinds of actions over space and time.

There are 2 major differences between FPA phases 1 and 2 with respect to the representation of alternatives. First, because phase 1 was chartered as a limited prototype, the scope of management alternatives in each FPU to be evaluated in the phase 1 system was limited by design to the preplacement of preparedness resources (local staff and equipment such as firefighters, fire engines and aircraft) with a focus on initial attack. By contrast, phase 2 is expanding the scope of analysis to include fuels treatments. Second, in phase 1 local managers did not specify discrete preplacement alternatives. Rather, the phase 1 system evaluated how different kinds and levels of preparedness investments change probabilities of harm to various types of valued resources (discussed below) and generated preplacement prescriptions that were estimated to optimize cost-effective protection within and across FPUs. This feature of phase 1 later was flagged as a source of concern by reviewers who worried that these synthetic prescriptions could violate policy (DOI and USDA 2006b). By contrast, phase 2 requires the planning units to generate respective lists of preparedness alternatives and fuels treatment alternatives. The fuels treatment component consists of identifying high priority treatment areas to reduce threats to highly valued resources, along with areas in which fire should be used to restore and maintain ecosystem values. Combinations consisting of 1 option from each list constitute alternatives for simulation of outcomes.

Question 5: Given the management objectives and alternatives, what are the assessment endpoints?

Endpoints for an integrated assessment should be specific and measurable expressions of the management objectives identified in response to question 3. Endpoint form will therefore depend on the objectives, but it will also depend on modeling capability as well; therefore, questions 5 and 6 might be addressed iteratively. Social and economic endpoints are not necessarily distinct; social scientists tend to evaluate community-based context, not simply utility to individuals, when evaluating a change (Turnley et al. 2007). Endpoint expressions typically identify a valued entity and some characteristic of that entity (USEPA 1998). Endpoint forms corresponding to the wildfire management objective stated above could vary widely. In the preliminary list compiled in Table 3, valued entities could include WUI and WUI-resident populations, firefighters, and the various land-based resource types identified in Table 2. Uncharacteristic fires themselves could be thought of as negatively valued entities, as could program costs. The characteristics of those entities to be quantified could fall into different categories that vary as to their difficulty of estimation. Completion of a procedural requirement (such as the completion of a CWPP) or the attainment of a condition (such as an FRCC class) are simplest to estimate, whereas determination of risks (probability of exposure to fire of unacceptable intensity) or event magnitudes (fires contained) require modeling of fire behavior in response to weather, terrain and containment efforts.

Differences in endpoint selection approach between phases 1 and 2 are indicated by footnotes in Table 3. In phase 1, endpoints were locally tailored but identical in form. All areas were categorized and mapped according to a set of resource types that was selected for each FPU in a consensus process involving local fire managers. Endpoints were then the probabilities of exceeding certain flame heights in each resource type. An example of this process, conducted with officials of the Southern Sierra FPU in California and described in Rideout et al. (2008), yielded the endpoint table shown in Table 4. This similarity in form facilitated

Table 3. Possible and selected approaches to assessment endpoint definition for wildland fire management

Valued entity (extent expression)	Characteristic	Category of characteristic
WUI (area, population, economically vulnerable population, number or value of structures)	Having (not having) CWPPs, fire safety codes or adequate response capacity	Completion of a management procedure
	Meeting (not meeting) fuels management objectives[a]	Completion of a management procedure
	In a given FRCC (or, where FRCC does not reflect fire risk factors, some substitute classification)	Ecological condition
	Exceeding a given probability of fire of unacceptable intensity[a,b]	Risk to valued entity
	Exceeding a given probability of smoke exposure	Risk to valued entity
Firefighters (number)	At risk of injury or death	Risk to valued entity
Resource type, as listed in Table 2 (area)	Meeting (not meeting) fuels management objectives	Completion of a management procedure
	In a given FRCC (or substitute classification)	Ecological condition
	Exceeding a given probability of fire of unacceptable intensity[a,b]	Risk to valued entity
	At given levels of risk from secondary effects of fire (invasive species, water quality impacts)	Risk to valued entity
Uncharacteristic fires (number, area burned)	Prevented[a]	Event magnitude
	Contained in (escaping) initial attack[a]	Event magnitude
	Exceeding a given size, or exceeding a given cost	Event magnitude
	Allowed to burn for fuels reduction[a]	Event magnitude
Costs (dollars)	Of whole program[b]	Program expenditure
	Of program component[a]	Program expenditure

[a]Endpoint of this general form used in FPA phase 2 system.
[b]Endpoint of this general form used in FPA phase 1 system.

Table 4. Relative value of land attributes as meriting initial-attack protection from wildfire, for the Southern Sierra Fire Protection Unit. Implicit attribute price varies as a function of flame length (adapted from Rideout et al. 2008)

	Flame length (feet)			
Attribute list	**>6**	**4–6**	**2–4**	**0–2**
WUI[a]	1.00	1.00	1.00	1.00
Sequoia groves	0.75	0.75	0.75	0.40
Commercial timber	0.60	0.60	0.60	0.60
Forested area (noncommercial)	0.40	0.35	0.35	0.20
Rangeland	0.30	0.30	0.30	0.30
Roadless area	0.20	0.10	0.10	0.10

[a]Wildland–urban interface.

the use of cross-program cost optimization, as elaborated below. By contrast, in phase 2, five assessment endpoints (termed *performance measures*) are applied within and across all FPUs:

- Expected total suppression costs associated with unplanned fires,
- Expected acres burned within the WUI,
- Expected acres trending toward objectives, defined as the sum of acres receiving fuels treatment and acres burned by wildfire below an acceptable intensity level, minus the acres burned at undesirable intensities,
- Expected acres burned at undesirable intensities in areas with highly valued natural, historical, or infrastructure resources,
- Expected number of fires contained in initial response or prevented through fire prevention programs.

These measures, which correspond to a varied set of management concerns, are more various in form. It may also be noticed that the fourth phase 2 measure combines acreages across resource types that were differentiated in phase 1. In endpoint selection processes, questions often arise as to whether given endpoints should be differentiated or bundled for analysis. For example, should an endpoint be defined with respect to the critical habitat of a particular endangered species, or more broadly to reflect a general set of habitat conditions and species? We suggest 2 sets of conditions in which bundling is appropriate: the first being when the endpoints covary (such as when 2 species' habitats frequently overlap, and their responses to fire are similar), and the second being when the endpoints are similarly valued and tradeoffs between them are not considered important. Thus, valuation issues, which will be addressed under question 7, can influence endpoint identification as well.

Question 6: How should expected changes in risks to the endpoints (resulting from management actions) be characterized?

At this stage of IPF it is necessary to state clear hypotheses about the specific causal mechanisms by which the assessment endpoints are affected by the problem under evaluation, and the mechanisms by which the endpoints would respond to the management alternatives being considered (i.e., *risk hypotheses* and *risk management hypotheses*, respectively; see Bruins et al. 2005). Then, the availability or feasibility of obtaining data and models necessary to estimate those endpoint changes must be considered. Given the hypothesized relationships that are diagrammed in Figure 1, risk estimation procedures used in a budgeting process should account for both short- and long-term effects of budgeting decisions. Over short time scales they should model fire spread across heterogeneous landscapes, fire response to suppression or management efforts, risks to firefighters, and potential for impacts to valued resources of various kinds (with special attention to WUI). They should also address effects of secondary stressors such as smoke and watershed pollution. Over longer time scales they should account for vegetation change as affected by fuels management or rehabilitation efforts. If the system also is to be used for long-range strategic planning, models projecting changes in driving forces (WUI growth and climate change) also should be incorporated.

National data resources are available to assist the characterization of wildland fire risks in the US. LANDFIRE is a joint, USFS and DOI mapping project to characterize landscape condition with regard to wildland fire risk for the entire United States. LANDFIRE incorporates field and remote sensing data, gradient modeling, predictive landscape modeling and vegetation disturbance dynamics to provide spatial data layers including FRCC and all layers required to run fire modeling applications (Rollins 2009). FPA uses LANDFIRE data to identify priorities for fuels treatment and for preplacement of preparedness resources.

WUI has been mapped nationally (Radeloff et al. 2005). The National Association of State Foresters (NASF) regularly surveys states to determine progress in identifying communities-at-risk (i.e., communities located within the WUI), developing CWPPs, and reducing risk through increasing local capacity, enacting local ordinances or treating hazardous fuels (NASF 2003, 2007). In 2007, for example, only 9.2% of communities-at-risk had CWPPs and 7.3% had taken actions to reduce risk. However, most of this information, which in many cases reflects rural poverty (Lynn and Gerlitz 2005), is not taken into account in FPA. A national project to map wildfire risk and rural communities' capacity to adequately address such risk has not yet been carried out.

In both phase 1 and phase 2 of FPA, an Initial Response Simulator, based on an algorithm by Fried and Fried (1996), is used to estimate the expected effectiveness of initial response, identify suppression costs for contained fires, and identify fires that exceed simulation limits (i.e., escapes). From a set of ignition events, the Initial Response Simulator simulates fire spread and response to the building of a containment line. In FPA phase 1, fire spread was modeled for a 1-yr sequence of ignitions, taking into account both the placement of preparedness resources and wildland fire use. In phase 2, FPU-specific preparedness and fuels treatment alternatives, as well as the effects of wildland fire use, are modeled in the Initial Response Simulator using 200 annual sequences of stochastically generated ignition events. Escapes are passed to a Large Fire Simulator for a series of simulations (10 000 or more simulated fire seasons) in which fuel treatments vary by management alternative, while weather and fire location vary randomly. The Large Fire Simulator (Finney 2007) is a series of simulation and statistical models that are used to estimate the distribution of fire sizes expected, the probability of burning from escaped fire for each 7.3 ha pixel in the FPU, the conditional probability of burning at 1 of 6 flame intensity levels (by pixel), and the expected annual large-fire suppression costs. Suppression is not modeled directly; rather, a containment algorithm developed by Finney et al. (2009) is used to select the number of days each fire burned, which is used in turn to estimate final fire size. Suppression costs are estimated using the stratified cost index developed by Gebert et al. (2007). Statistical analysis of the results of these simulations generates performance measures for the management alternatives in terms of the five phase 2 endpoints given above.

These risk estimation procedures clearly cover many, but not all of the relationships described in Figure 1. Additional procedures that have been considered but are not currently implemented include modeling the effects of fuels treatment on vegetation change and modeling large fire responses to different management techniques, including wildland fire use. Secondary stressors and changes in driving forces currently are not considered.

Question 7: How will the expected changes in social, economic, and ecological endpoints be valued and integrated for use in making decisions?

In addition to estimates of how each endpoint is expected to change under each of the management alternatives, decision makers typically need some way to integrate this multivariate information into condensed forms that provide insight as to the preference of one alternative over another. Economic analysis would typically approach this as a problem of maximizing overall utility subject to an income constraint. However, analytical difficulties (as referred to in the *Introduction*), complicating factors related to the legality or public acceptability of certain alternatives, and the uncertain preferences of future generations lead to the consideration of a broader menu of methods.

Participants in the Racine workshop suggested the following considerations in the selection of valuation/integration methods:

- Able to accommodate multiple endpoints,
- Flexible with respect to the sorts of goals it reflects (i.e., narrow or broad),
- Transparent, accessible, based on assumptions that are readily understood,
- Accurate (valid and reliable) and robust,
- Producing values that can be integrated across endpoints,
- Does not require monetization of endpoints,
- Place and scale independent,
- Comprehensive, and
- Accepted by the scientists and nonscientists who will use it.

The 2 phases of FPA have used different methods of valuation and integration. As pointed out earlier, all phase 1 endpoints were similar in form (i.e., risks to WUI or other areally measured resources). The local fire managers who identified these endpoints also assigned relative weights to their importance of protection at each flame height (as illustrated in Table 4). In all FPUs, the relative value of WUI was set at 1.0. This WUI ''common currency'' allowed for direct comparison of all of the values by the technique of marginal rates of substitution (MRS). A traditional approach to understanding tradeoffs based on utility theory, MRS is the rate at which consumers are willing to give up units of one good in exchange for more units of another (Rideout et al. 2008). This approach is useful for understanding interactions among management options that are substitutes or complements for one another, allowing for the application of optimization analyses. After fire-spread modeling of phase 1 management alternatives, endpoint outcomes were evaluated at the FPU scale by an MRS-based optimization routine which synthesized the unique set of preparedness measures estimated to afford the most cost-effective protection across all resources at risk (subject, of course, to all of the data and computational limitations of the phase 1 system). This information was then aggregated nationally for optimal allocation of preparedness funds.

By contrast, the phase 2 performance measures differ from one another in form (Table 3), making relative value among them hard to assess. Instead, estimated outcomes for the 5 measures are placed into a goal program for exploratory analysis. This technique treats each of the performance measures as a goal with defined target and weight. Targets are generally assigned as the maximum (or minimum) value observed among the alternatives, depending on the measure; weights can be changed in the program to observe alternative solutions to the problem. By varying the weights systematically, analysts can examine the sensitivity of solutions to different weighting schemes (and implicit value judgments), and identify robust solutions (i.e., combinations of the locally-developed management alternatives) that perform well from multiple perspectives. The complete set of alternatives can be used in further analysis to better understand how, where, and why different combinations of preparedness and fuel treatments perform best.

Question 8: How will the outcomes and effectiveness of the management actions be evaluated?

Management effectiveness should be gauged by measuring the accomplishment of the management objective. Therefore effectiveness measures, like assessment endpoints, should mirror the objective, but because modeling and monitoring procedures may differ fundamentally, it cannot be assumed that effectiveness measures will be identical to the endpoints.

A set of implementation measures for the National Fire Plan was developed, and later updated, by the Western Governors Association (DOI and USDA 2001, DOI and USDA 2006a); some of these are also in use by the White House Office of Management and Budget to evaluate program effectiveness (Table 5). They include both short term (e.g., treatment of hazardous fuels) and long term measures (e.g., achievement of desired wildland conditions) that correspond well to most of the performance measures established in phase 2. However, they make no distinctions, beyond the WUI or non-WUI distinction, regarding populations protected or the value of assets protected.

DISCUSSION AND CONCLUSIONS

The Hubbard Report (USDA and DOI 2002) laid out a detailed roadmap for creation of an FPA system. Would the use of an IPF process, as introduced in this study, have added anything? Specifically, could it have simplified the

Table 5. Performance measures established for evaluating implementation of National Fire Plan (DOI and USDA 2006a)

Implementation goal	Specific performance measures address
Improve fire prevention and suppression	Ignitions[a]
	Containment during initial attack[a]
	Costly escapes[a]
Reduce hazardous fuels	Treatment of acres with hazardous fuels (WUI, non-WUI)[a]
	Costs of treatment[a]
	Treatment in which fire management objectives are achieved
Restoration of fire-adapted ecosystems	Treatment of acres with hazardous fuels, by treatment category (i.e., prescribed fire, mechanical, and wildland fire use)[a]
	Natural ignitions which are allowed to burn (consistent with wildland fire use strategies)
	Treated acres which are moved toward, or maintained in, desired conditions[a]
Post-fire recovery of fire-adapted ecosystems	Burned acres identified as needing treatments that do receive treatments
	Burned acres treated for post-wildfire recovery that are trending toward desired conditions
Promote community assistance	Communities-at-risk covered by a Community Wildfire Protection Plan (CWPP) or equivalent that are acting to reduce their risk from wildland fire
	Communities-at-risk who report increased local suppression capacity
	Woody biomass from hazardous fuel reduction and restoration treatments that is made available for utilization

[a]Performance measures also used by Office of Management and Budget (http://www.whitehouse.gov/omb/expectmore/detail/10000448.2006.html).

development path and helped avoid the scrapping of an initial (phase 1) approach, in favor of a very different one (phase 2)? Although this IPF case study entailed substantial effort, before and following our 2006 workshop, several participants who had been part of the development of FPA expressed the opinion that FPA development could have benefited from the systematic and analytic nature of IPF. At least from the perspective of this retrospective case study, it is apparent that the respective phases of FPA development diverged significantly in their approach to the step we have referred to in question 7 as ''valuation and integration.'' This key difference resulted in other differences that emerge in responses to questions 4 and 5.

The Hubbard Report had directed that the new system ''contain a cost-effectiveness analysis.'' While acknowledging that traditional BCA would not be feasible (because some endpoints, such as those related to ecosystem health, would not easily be monetized), it assumed that relative importance of different objectives could be established, allowing the overall effectiveness of different management plans to be compared. Through use of a WUI common-currency metric and the MRS technique, the phase 1 approach took pains to ground the evaluation of relative importance in economic welfare theory. Phase 1 system assessment endpoints (question 5) were commensurate within and across FPUs, based on relative weights obtained in a transparent process. Not only could different plans be compared, but the phase 1 optimization routine (question 7) afforded the ability to synthesize the unique, most cost-effective management alternative (question 4) for any given set of constraints—a capability that exceeded the Hubbard Report criterion.

The teams of scientists and managers who reviewed the phase 1 system (DOI and USDA 2006b) worried that the MRS-based metric by which alternatives were compared in phase 1 would be considered counterintuitive and that the synthetic, optimized management prescriptions for each FPU might prove less workable, and less congruent with agency policies, than alternatives prepared by local managers on the ground. The commensurability requirements of the phase 1 approach also complicated the use of other performance goals of interest to agency managers, such as acres burned and initial-attack success rate. By contrast, the phase 2 system compares discrete, locally determined management alternatives, is more amenable to iterative runs and is more flexible with respect to performance objectives. Because these objectives differ from one another in form, however, they lack a basis of commensurability, and there is no objective way to establish weights and compare effectiveness among alternative plans. Arguably, the early use of an IPF process could have exposed and clarified these issues for agency decision-makers.

Another important goal in IPF is to ensure that assessment scope is broad enough to encompass all significant drivers of the environmental problem being addressed. Our exploration of the wildfire management context, depicted in Figure 1, shows climate change and WUI growth as additional drivers of critical importance that currently are inadequately linked to wildfire management decision-making. This suggests that, for effective management, the scope of assessment must be broadened to encompass these dependencies as well. The long-term consequences of recurring, uncharacteristic fires also are poorly understood. These may include changes in ecosystem stability, and functional components such as habitat, species distribution, ecotones and vegetative communities. Uncharacteristic fires could also induce changes in economic utilization of lands, recreational use patterns, and water runoff and storage. Given that FPA is primarily designed to aid near-term budget planning processes, it may be unreasonable to expect FPA to directly address these longer-term concerns. Nevertheless, the analytical machinery developed by the FPA system provides a substantive platform from which to begin exploring these issues in depth.

Based on the success of this case study analysis, we believe that the 8-question sequence given in Table 1 provides an effective framework for an integrated problem formulation process, including both stakeholder group sessions and follow-up efforts by risk analysts. We encourage further use and refinement of this approach.

Acknowledgment—The ideas and integrated problem formulation process communicated in this study resulted from the Society of Environmental Toxicology and Chemistry Technical Workshop on Integrating Ecological and Economic Risks and Values in Wildfire Management, held 22–25 October 2006 at the Wingspread Conference Center in Racine, WI. We thank R. Stahl, C. Joy, G. Schiefer, D. Reagan and the staff of the Wingspread Conference Center for their assistance with planning and coordinating the workshop. Constructive reviews of this study and its concepts were provided by Brian Heninger, Anne Sergeant, and several anonymous reviewers.

Disclaimer—The views expressed in this study are those of the individual authors and do not necessarily reflect the views and policies of any US Government agency and no official endorsement should be inferred. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. This article has been reviewed in accordance with the USEPA's peer and administrative review policies and approved for publication.

REFERENCES

[ASTMI] ASTM-International. 2006. Standard guide for a framework for a consensus-based environmental decision-making process. In: ASTM-I Annual Book of Standards. West Conshohocken (PA): ASTM-International, E 2348-06.

Boyd J. 2004. What's nature worth? Using indicators to open the black box of ecological valuation. *Resources* 154: 18–22.

Bruins RJF, Heberling MT, Maddock TM. 2005. Conceptual approach for integrated watershed management. In: Bruins RJF, Heberling MT, editors. Economics and ecological risk assessment: Applications to watershed management. Boca Raton (FL): CRC Press, p 185–226.

Cook ER, Woodhouse CA, Eakin CM, Meko DM, Stahle DW. 2004. Long-term aridity changes in the western United States. *Science* 306: 1015–1018.

DellaSala DA, Williams JE, Williams CD, Franklin JE. 2004. Beyond smoke and mirrors: A synthesis of fire policy and science. *Conserv Biol* 18: 976–986.

[DOI] US Department of the Interior. 2003. Identifying and prioritizing communities at risk. Washington (DC): DOI. Memorandum from the Assistant Secretary for Policy, Management and Budget.

[DOI and USDA] US Department of the Interior and US Department of Agriculture. 1995. Federal wildland fire management policy & program review, final report. Washington (DC): DOI and USDA. 45 p. [cited 2009 January 9]. Available from: http://www.nifc.gov/fire_policy/mission/1995_fed_wildland_fire_policy_program_report.pdf

[DOI and USDA] US Department of the Interior and US Department of Agriculture. 2001. A collaborative approach for reducing wildland fire risks to communities and the environment: Ten year comprehensive strategy. Washington (DC): DOI and USDA. 24 p. [cited 2009 January 9]. Available from: http://www.forestsandrangelands.gov/plan/documents/7-19-en.pdf

[DOI and USDA] US Department of the Interior and US Department of Agriculture. 2006a. A collaborative approach for reducing wildland fire risks to communities and the environment: Ten year strategy implementation plan. Washington (DC): DOI and USDA. 35 p. [cited 2009 January 9]. Available from: http://www.forestsandrangelands.gov/plan/documents/7-19-en.pdf

[DOI and USDA] US Department of the Interior and US Department of Agriculture. 2006b. Management review team report of the fire program analysis (FPA) preparedness module. Washington (DC): DOI and USDA. 41 p. [cited 2009 April 21]. Available from: http://www.fpa.nifc.gov/Library/Docs/FPA_Review_Report_Final_March.2006.pdf

Dombeck MP, Williams JE, Wood CA. 2004. Wildfire policy and public lands: Integrating scientific understanding with social concerns across landscapes. *Conserv Biol* 18: 883–889.

Donovan GH, Brown TC, Dale L. 2008. Incentives and wildfire management in the United Sates. In Holmes TP, Prestemon JP, Abt KL, editors. The economics of forest disturbances: Wildfires, storms, and invasive species. New York (NY): Springer, p 323–340.

Finney MA. 2007. A prototype simulation system for large fire planning in FPA. Boise (ID): National Interagency Fire Center. [cited 2009 October 27]. Available from: http://www.fpa.nifc.gov/Library/Docs/Science/FPA_SimulationPrototype_0705.pdf

Finney MA, Grenfell IC, McHugh CW. 2009. Modeling containment of large wildfires using generalized linear mixed model analysis. *For Sci* 55: 249–255.

Fried JS, Fried BD. 1996. Simulating wildfire containment with realistic tactics. *For Sci* 42: 267–281.

Gebert KM, Calkin DE, Yoder J. 2007. Estimating suppression expenditures for individual large wildland fires. *West J Appl For* 22: 188–196.

Hammer RB, Radeloff VC, Fried JS, Stewart SI. 2007. Wildland-urban interface housing growth during the 1990s in California, Oregon, and Washington. *Int J Wildland Fire* 16: 255–265.

Hann WJ, Bunnell DL. 2001. Fire and land management planning and implementation across multiple scales. *Int J Wildland Fire* 10: 389–403.

Hann W, Shlisky A, Havlina D, Schon K, Barrett S, DeMeo T, Pohl K, Menakis J, Hamilton D, Jones J, Levesque M, Frame C. 2004. Interagency fire regime condition class guidebook. Version 1.3.0. www.frcc.gov

Hardy CC, Schmidt KM, Menakis JP, Samson RN. 2001. Spatial data for national fire planning and fuel management. *Int J Wildland Fire* 10: 353–372.

Hardy CC. 2005. Wildland fire hazard and risk: Problems, definitions, and context. *For Ecol Manag* 211: 73–82.

Heninger B, Biddinger G, Joy C, Kling C, Reagan D, Schmidt T. 2007. Organizing and integrating the valuation process. In: Stahl RG, Kapustka L, Munns WR Jr, Bruins RJF, editors. Valuation of ecological resources: integration of ecological risk assessment and socio-economics to support environmental decisions. New York (NY): CRC, p 130–163.

Kauffman JB. 2004. Death rides the forest: Perceptions of fire, land use, and ecological restoration of western forests. *Conserv Biol* 18: 878–882.

Klein JT, Newell WH. 1997. Advancing interdisciplinary studies. In: Graff JG, Ratcliff JL, editors. Handbook of the undergraduate curriculum: A comprehensive guide to purposes, structures, practices, and change. San Francisco (CA): Jossey-Bass, p 393–415.

Larichev OL, Olson DI. 2001. Multiple criteria analysis in strategic siting problem. Boston (MA): Kluwer, 226 p.

Linkov I, Satterstrom FK, Kiker GA, Bridges TS, Benjamin SL, Belluck DA. 2006. From optimization to adaptation: Shifting paradigms in environmental management and their application to remedial decisions. *Integr Environ Assess Manag* 2: 92–98.

Lynn K, Gerlitz W. 2005. Mapping the relationship between wildfire and poverty: A collaborative project between the National Network of Forest Practitioners, Resource Innovations at the University of Oregon, and the United States

Department of Agriculture Forest Service State and Private Forestry, Cooperative Programs and Research and Development. Draft. [cited 2008 November 14]. Available from: http://cwch.uoregon.edu/publicationspress/firepovertydraft_11-21-05.pdf

McDaniels TL. 2000. Creating and using objectives for ecological risk assessment and management. *Environ Sci Policy* 3: 299–304.

McDaniels T, Gregory R, Fields D. 1999. Democratizing risk management: Successful public involvement in local water management decisions. *Risk Anal* 19: 497–510.

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: A framework for assessment. Washington (DC): Island, 245 p.

[NASF] National Association of State Foresters. 2003. Field guidance: Identifying and prioritizing communities at risk. [cited 2007 March 14]. Available from: http://www.fireplan.gov/reports/NASFfieldguidancecommunities.pdf

[NASF] National Association of State Foresters. 2007. Communities at Risk Report FY2007. [cited 2008 November 14]. Available from: http://www.stateforesters.org/node/38

[NIFC] National Interagency Fire Center. 2006. Standard attribute categories. Internal Fire Planning Analysis System Project Paper. Boise (ID): NIFC, 2 p.

Nikitina S. 2002. Navigating the disciplinary fault lines. *Issues Integr Stud* 20: 27–44.

Noss RF, Franklin JF, Baker WL, Schoennagel T, Moyle PB. 2006. Managing fire-prone forests in the western United States. *Front Ecol Environ* 4: 481–487.

[NRC] National Research Council. 1983. Risk assessment in the federal government: Managing the process. Washington (DC): National Academy, 192 p.

[NRC] US National Research Council. 2005. Superfund and mining megasites: Lessons from the Coeur D'Alene River Basin. Washington (DC): National Academy, 484 p.

[OMB] Office of Management and Budget. 2003. Circular A-4, regulatory analysis. Washington (DC): OMB, The White House.

[PCCRARM] Presidential/Congressional Commission on Risk Assessment and Risk Management. 1997. Framework for environmental health risk management. Washington (DC): PCCRARM.

Public Lands Council. 2007. PLC advocates for updated Forest Service budget. [cited 2007 May 25]. Available from: http://67.100.156.138/plc2/default.asp?pID=4057

Radeloff VC, Hammer RB, Stewart SI, Fried JS, Holcomb SS, McKeefry JF. 2005. The wildland urban interface in the United States. *Ecol Appl* 15: 799–805.

Repko AF. 2008. Interdisciplinary research: Process and theory. Thousand Oaks (CA): Sage.

Rideout DB, Botti SJ. 2002. Performance-based interagency fire program analysis system: Blueprint for fire planning. *J For* 100: 36–41.

Rideout DB, Ziesler PS, Kling R, Loomis JB, Botti SJ. 2008. Estimating rates of substitution for protecting values at risk for initial attack planning and budgeting. *For Policy Econ* 10: 205–219.

Rollins MG. 2009. LANDFIRE: A nationally consistent vegetation, wildland fire, and fuel assessment. *Int J Wildland Fire* 18: 235–249.

Schmidt KM, Menakis JP, Hardy CC, Hann WJ, Bunnell DL. 2002. Development of coarse-scale spatial data for wildland fire and fuel management. Fort Collins (CO): US Department of Agriculture, Forest Service, Rocky Mountain Research Station. General Technical Report RMRS-GTR-87.

Schoennagel T, Veblen TT, Romme WH. 2004. The interaction of fire, fuels, and climate across rocky mountain forests. *Bioscience* 54: 661–676.

[SAF] Society of American Foresters. 2004. Preparing a community wildfire protection plan: A handbook for wildland–urban interface communities. [cited 2007 March 6]. Available from: http://www.safnet.org/policyandpress/cwpphandbook.pdf

Stahl RG, Bachman RA, Barton AL, Clark JR, deFur PL, Ells SJ, Pittinger CA, Slimak MW, Wentsel RW, editors. 2001. Risk management: Ecological risk-based decision-making. Pensacola (FL): SETAC Press, 202 p.

Stahl RG Jr, Kapustka L, Munns WR Jr, Bruins RJF, editors. 2007. Valuation of ecological resources: Integration of ecological risk assessment and socio-economics to support environmental decisions. New York (NY): CRC, 231 p.

Turner MG, Romme WH, Tinker DB. 2003. Surprises and lessons from the 1988 Yellowstone fires. *Front Ecol Environ* 1: 351–358.

Turnley JG, Kaplowitz MD, Loucks OL, McGee BL, Dietz T. 2007. Sociocultural valuation of ecological resources. In: Stahl RG, Kapustka L, Munns WR Jr, Bruins RJF, editors. Valuation of ecological resources: integration of ecological risk assessment and socio-economics to support environmental decisions. New York (NY): CRC, p 9–44.

[UNEP] United Nations Environmental Programme. 1996. Environmental risk assessment for sustainable cities. Osaka, Japan: UNEP, International Environmental Technology Centre. Technical Publication Series [3].

[USACE] US Army Corps of Engineers. 2000. Planning guidance notebook. Washington (DC): USACE. ER, 1105-2-100.

[USDA and DOI] US Department of Agriculture and US Department of the Interior. 2000. Managing the Impact of Wildfires on Communities and the Environment: A Report to the President In Response to the Wildfires of 2000. [cited 2009 January 9]. Available from: http://www. forestsandrangelands.gov/reports/documents/2001/8-20-en.pdf

[USDA and DOI] US Department of Agriculture and US Department of the Interior. 2002. Developing an interagency, landscape-scale fire planning analysis and budget tool. Report to the National Fire Plan Coordinators: USDA Forest Service and US Department of the Interior.

[USEPA] US Environmental Protection Agency. 1998. Guidelines for ecological risk assessment. Washington (DC): USEPA, Risk Assessment Forum. EPA/630/R-95/002F.

[USEPA] US Environmental Protection Agency. 1999. The benefits and costs of the Clean Air Act 1990 to 2010. Washington (DC): USEPA, Office of Air and Radiation and Office of Policy, Economics and Innovation. EPA-410-R-99-001.

[USEPA] US Environmental Protection Agency. 2000. Guidelines for preparing economic analyses. Washington (DC): USEPA, National Center for Environmental Economics. EPA/240/R-00/003.

[USEPA] US Environmental Protection Agency. 2001. Planning for ecological risk assessment: Developing management objectives, external review draft. Washington (DC): USEPA, Risk Assessment Forum. EPA/630/R-01/001A.

[USEPA-SAB] USEPA Science Advisory Board. 2000. Toward integrated environmental decision-making. Washington (DC): USEPA, Science Advisory Board. EPA-SAB-EC-00-011.

[USEPA-SAB] USEPA Science Advisory Board. 2009. Valuing the protection of ecological systems and services. Washington (DC): USEPA, Science Advisory Board. EPA-SAB-09-012.

[USFS] US Forest Service. 2002. National forest system land and resource management planning; proposed rules. *Fed Reg* 67: 72769–72816.

Veblen TT, Kitzberger T, Donnegan J. 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. *Ecol Appl* 10: 1178–1195.

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW. 2006. Warming and earlier spring increase western US forest wildfire activity. *Science* 313: 940–943.