United States Department of Agriculture

The Science of Decisionmaking:

Applications for Sustainable Forest and Grassland Management in the National Forest System

Forest Service

General Technical Report WO-88

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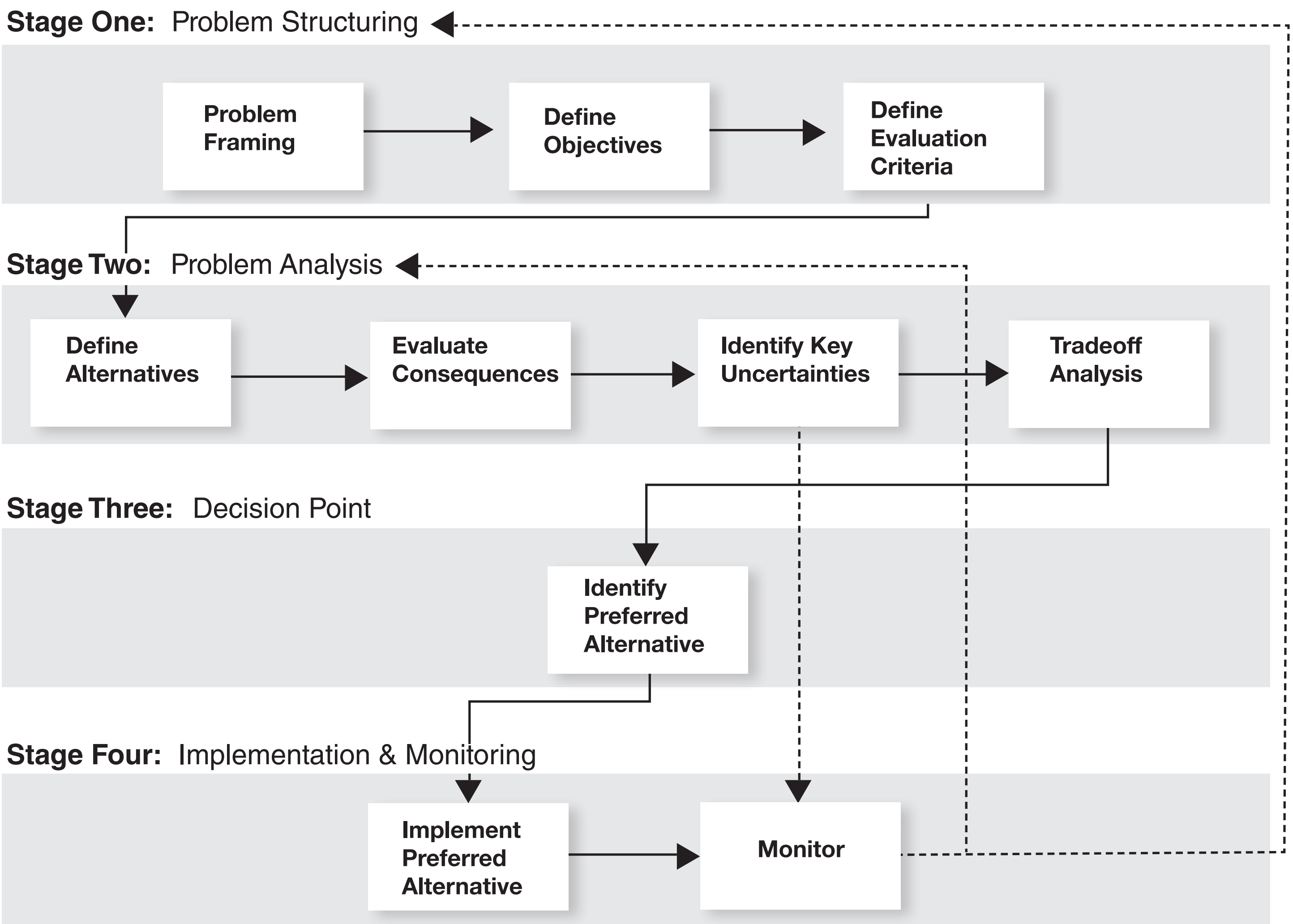
Stages of the structured decisionmaking (SDM) process (Marcot et al. 2012a).



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The Science of Decisionmaking:
Applications for Sustainable Forest and Grassland Management in the National Forest System

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Who Should Read This Report?

1. **Decisionmakers** (including line officers, staff officers, and other managers) and **policymakers** (including agency leadership, station directors, etc.), and
2. **Analysts** (including planning specialists, modelers, interdisciplinary teams, etc.).

Section 1.2 "**A Road Map for Reading This Report**" reviews the contents and intended audience of each chapter.

What Information Does the Report Contain?

Briefly, this report is divided into five main sections, each color coded as follows:

The first section of the report—Chapters 1 and 2—provides an overview of structured decisionmaking in the context of forest and grassland management. This section will be most useful for **decisionmakers**.

The second section—Chapter 3—provides greater detail on the structured decisionmaking framework and related decision support approaches. This section will be most useful for **analysts.**

The third section—Chapters 4 and 5—reviews applications of structured decisionmaking to forest and grassland management, including opportunities, challenges, and case studies. This section will be most useful for **decisionmakers** and **policymakers**.

The fourth section—Chapter 6—summarizes the major conclusions and implications of the report, useful for **all audiences**.

Lastly, appendixes provide additional information to assist **decisionmakers** and **analysts** in tackling tough problems.

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6. Adopting Structured Decisionmaking: Conclusions and Implications

Foreword


At the start of the 21st century, as land management options have narrowed, as issues have become more complex, and as these decisions have become more difficult, many managers are turning to processes that examine and evaluate a problem in a more structured way. Managers and administrators are seeking objective, replicable, and explicit ways to assess choices and the probable outcomes of those choices to make the most optimal choice. The scientific concepts and techniques of risk management and structured decisionmaking have grown dramatically, making it challenging for anyone who does not specialize in this field to keep up with the pace of this advancement.

This General Technical Report (GTR) presents highlights from the existing body of work, illustrations of the relevance to land management decisionmaking, and tips on how to enhance the effectiveness of each aspect within the entire process. As a result of increased natural resource demands and expectations from the public, agencies, and natural resource managers for "sound decisions based in science," the demand for decision science expertise has grown. Hence, we are excited about this synthesis of decision science for land management.

Decision science principles and their component decision-support approaches and tools have become bridges between the "process" of decisionmaking and the "content" of environmental sciences. The U.S. Department of Agriculture (USDA), Forest Service and other organizations have intensified efforts to develop structured decision processes; we believe those processes provide value in codifying and providing access to science and in enhancing problem-solving in complex and uncertain environments more effectively. We are pleased that this report has explored the intersection between "process" and "content" sciences in the design and use of decision support and in the context of National Forest System (NFS) decisionmaking.

When we asked the authors to take stock of our body of decision-support systems and tools, they organized their response under an anatomical framework for generalized decision process that is well established and documented in the decision sciences. Their work has opened a whole new perspective on our investments in decision science and science for decisions. The authors took the charge further by surveying users to better understand how they put these tools to use. The result has been an integrative approach to better understanding how decision-support systems and tools supplement different phases of decision processes, how we can design them to better incorporate science, and how we can better frame and meet land managers' needs for scientific knowledge and expertise.

The approach in this report provides a conceptual meeting place for research and management partnerships. If scientists and tool developers can better understand the nature, limitations, and potentials of human decisionmaking—individual, group, and organizational—they can better interpret present findings and frame new science questions around decision-relevant knowledge gaps. Managers likewise can more realistically judge the applicability of science and science-based tools to the choices they confront and gauge how their own judgment and choice processes influence the interpretation and use of that science.

We hope that this report will encourage future efforts to build decision frameworks and support systems that combine "smarts" about decisions and environmental science. To maintain and improve high-quality attributes of natural resource decisionmaking—consistency, adaptability, transparency, and others—we must become more sophisticated with models of our decisions and the environmental functions we hope to sustain. In the era known as the Anthropocene, in which the environment is pervasively influenced by human decisions and actions at many scales, we must strive to blend knowledge of decision and environmental process toward innovative solutions to challenges.

We offer this report as a window on practice and a stimulus to create new value for science in and of decisions. We hope managers, scientists, researchers, and analysts will use it as a resource and as a centerpiece for bringing these important members of the natural resource decision process closer together.

In summary, Forest Service managers saw a need and asked Forest Service Research and Development to help fill this need. Our many thanks to the authors who have sewn together a very thoughtful and readable piece of work, one integrative stitch at a time. We know their enthusiasm and collaborative spirit will draw others to efforts that follow from this report.

JIMMY L. REAVES
Deputy Chief, Research and Development

DAVID A. CLEAVES
Climate Change Advisor, Office of the Chief

Summary

Sustainable management of national forests and grasslands within the National Forest System (NFS) often requires managers to make tough decisions under considerable uncertainty, complexity, and potential conflict. Resource decisionmakers must weigh a variety of risks, stressors, and challenges to sustainable management, including climate change, wildland fire, invasive species, insects, pests, diseases, demographic shifts, economic conditions, and changing societal values. The craft of natural resource decisionmaking will demand more adaptive qualities in the future and a more flexible toolkit. In light of these current and emerging challenges and the need for science delivery to keep pace with advancements in the disciplines of decision science and risk management, now is a good time to refocus on supporting and enhancing natural resource management decisionmaking. The science of decisionmaking can provide managers with useful concepts and tools to address risks, stressors, and challenges and to achieve desirable outcomes.

Improving natural resource decisionmaking requires a firm understanding of how decisions are currently made and where opportunities for enhancement might exist. To that end, we surveyed U.S. Department of Agriculture (USDA), Forest Service line officers, planners, and specialists to gain an understanding of how decision-support tools and processes are used, under what circumstances they are used, and what improvements may be needed. Although responses varied, line officers principally expressed a desire for a structured decisionmaking framework that is risk informed, transparent, and adaptable; can facilitate evaluation of consequences and tradeoffs; and can be readily explained to stakeholders. More than 90 percent of respondents who had used some form of a decision-support approach stated they were satisfied with the outcome, and their primary reasons for adopting decision-support approaches were to improve the decision process and to mitigate potential social conflict. Their responses suggested that lack of information is the principal impediment to broader adoption of structured decisionmaking and decision-support approaches.

We have therefore focused on reviewing the core principles of decision science and how they can be brought to bear on issues of sustainable forest and grassland management. This report outlines the rationale and pathway for incorporating decision science into the natural resource decisionmaking process. The approach we outline in this report—structured decisionmaking—is a flexible, well-established framework that helps decisionmakers better define the problem context, identify and evaluate management options, and make informed choices under complex and uncertain conditions. In particular, the initial stage of framing the problem is critical for effective problem-solving and decisionmaking. We highlight examples in which principles of decision science were incorporated into forest and grassland management. We also provide an extensive list of appropriate decision-support tools and approaches as they relate to various stages of decisionmaking processes, as well as guidance for identifying those tools and approaches.

Adopting the structured decision framework can streamline decision processes, help ensure the right problem is being solved, lead to high-quality decisions that are defensible and durable under scrutiny, and ultimately lead to improved sustainable forest and grassland management. We highlight key knowledge gaps and identify training needs that could facilitate broader adoption of decision science principles within the NFS. We suggest structured decisionmaking can be more effectively used in forest and grassland management if analysts and planners are equipped to provide guidance to leadership and management on decision support; scientists clearly explain the use of predictive models in decision contexts and participate in decision processes; and decisionmakers and managers foster a collaborative, transparent, and defensible basis for decisions, using structured decision frameworks.

1. Introduction

"Conservation is the foresighted utilization, preservation and/or renewal of forests, waters, lands and minerals, for the greatest good of the greatest number for the longest time."

Gifford Pinchot

1.1 Why Focus on Decisions and Decision Science?

Decisions—made by humans and rooted in science—are the fundamental elements of natural resource management. Often neglected in discussions about natural resource decisionmaking is the science of the human decision process itself. When faced with complex, uncertain decisions, humans can be susceptible to biases, shortcuts, and other limitations that can degrade decision processes—but these pitfalls can be avoided. Much has been learned in the last 30 years in the field of decision science combining contributions from psychology, management science, operations research, economics, statistics, and other fields to provide ways to improve the quality of decisions and problem-solving processes. Decision science provides a sound theoretical basis, and a specific framework and method, for making sound decisions under uncertainty by using formal decision analysis techniques and methods of risk analysis and risk management. Decision analysis is "a formalization of common sense for decision problems which are too complex for informal use of common sense" (Keeney 1982: 806). Decision science is applied increasingly in management of natural resources, including fisheries, wildlife, forestry, rangeland, and fire (Marcot et al. 2012a).

In this report, we present the principles of decision science and a well-established, structured decisionmaking (SDM) framework to help natural resource managers and analysts navigate the decision process (Gregory and Long 2009, Gregory and Keeney 2002, Hammond et al. 1999). SDM is not a new tool or model in and of itself, but rather an integrated system of principles and concepts that link to tools and models and that can improve decision processes and outcomes. We review the wide variety of decision-support tools and approaches useful for each stage in the natural resource decisionmaking process. We perform this review through the lens of insights gained from an extensive survey of U.S. Department of Agriculture (USDA), Forest Service line officers, planners, and specialists describing their experiences and information needs. We also conducted a series of indepth interviews with selected decisionmakers who have considerable experience with these tools and approaches.

The primary objective of this report is to present useful information to help decisionmakers and analysts adhere to decision science principles and select appropriate decision-support approaches. Managing forests and grasslands of the Forest Service's National Forest System (NFS) lands provides a compelling context for the role of SDM under the complex, multiple-use mandates of the National Forest Management Act and its implementing regulations and under mandates of the National Environmental Policy Act (NEPA). We do not set out to comprehensively review and critique past agency decisions in light of the current state of decision science principles. We do hope to make natural resource managers, planners, and scientists more aware of the availability of SDM approaches and tools, how they have been used successfully in the NFS, and how they can be used more effectively for future decisions.

1.2 A Road Map for Reading This Report

This report consists of five chapters, all of which are related but can be read largely independent of each other. The chapters vary in terms of content, scope, and intended audience, as described below. It is our hope that this report will serve as a useful guide that managers and analysts can repeatedly turn to for assistance in tackling tough natural resource management decisions.

The WHY of Structured Decisionmaking: A Guide for Decisionmakers

This chapter addresses the question, "Why should I care about structured decisionmaking frameworks?" and is intended largely for resource managers and decisionmakers. The section provides a broad overview of the structured decision framework and describes the potential benefits from formally incorporating decision science principles into decision processes. We describe how the decision framework aligns with the NFS Land Management Planning Rule promulgated in 2012, as well as NEPA.

The HOW of Structured Decisionmaking: A Guide for Decisionmakers and Decision Analysts

This chapter addresses the question, "How should I implement structured decisionmaking frameworks?" We describe in more detail the various decision stages and their relation to fundamental decision science principles. Although useful for decisionmakers, this chapter is primarily targeted to planners, resource specialists, and other analysts supporting the decision process. We provide concrete examples as they relate to the stages of SDM and describe some major recommended decision-support approaches, including objectives hierarchies, influence diagrams, and multicriteria decision analysis. We also provide broader guidance for identifying appropriate decision-support tools and methods, jointly based on the decision context, the SDM stage, and the nature of uncertainties faced.

Opportunities and Challenges for Adopting Structured Decisionmaking in the NFS

This chapter addresses the question, "How are we currently making decisions, and how can we improve on decision processes?" It is directed toward decisionmakers and policymakers. We present results from a survey we recently conducted to better understand how and under what circumstances decision-support tools and methods are currently being used. We identify opportunities for improvement as well as potential challenges to a broader adoption of SDM within the NFS. We suggest a need to strengthen the agency's commitment to training, communication, and support for structured decision frameworks.

Applications of Decision Science Principles in Forest and Grassland Management

This chapter addresses the question, "How has decision science been applied to date in addressing natural resource management problems?" We highlight selected instances in which principles of SDM have been incorporated into forest and grassland management. These case studies are organized primarily according to the stage of SDM to illustrate how different decision-support tools and approaches can be brought to bear according to the context. We present a more comprehensive application of the SDM framework to a complex natural resource management problem, nonnative fish control, in a much more expansive case study from outside the NFS. Decisionmakers will find this chapter most useful.

Adopting and Implementing Structured Decisionmaking: Conclusions and Implications

We target managers and policymakers with a discussion of the major implications of adopting SDM within agency decision processes. The weight of evidence from the scientific literature we cite describing real-world applications of SDM provides strong support for the value of decisions reached through adoption of structured decision frameworks. These applications come from detailed case studies within the NFS and elsewhere, from survey results regarding NFS personnel use of SDM and decision-support tools, from interviews with individuals who have experience applying SDM, and from the authors' collective experience.

Photo by Larry A. Fisher

2. The WHY of Structured Decisionmaking: A Guide for Decisionmakers

2.1 Decisionmaking Is at the Core of Sustainable Forest and Grassland Management

Natural resource decisionmaking is challenged by considerable complexity, uncertainty, and potential conflict.

Natural resource management is ultimately about making tough decisions in the face of uncertainty, complexity, and potential conflict. Often the outcomes extend beyond the lifetime of the decision process participants, requiring a long-term perspective when making these decisions. Decision environments also may be time-sensitive and require dynamic responses to changing conditions. Decisions sometimes touch values that are deeply felt, yet elusive to measure. They involve complex, interacting processes that make prediction difficult at best. The problem-solving process is subject to the reasoning ability of individuals and groups, human fatigue, competing issues, busy schedules, and the influences of political and organizational power. Not only must natural resource decisions be made, but they must also be communicated to stakeholders, supporters, detractors, employees, experts, the media, legislators, the courts, and others to ensure credibility and trust for sustainable outcomes. Providing for sustainable forests and grasslands and their ecosystem services requires efficient, effective problem solving through structured, transparent human decision processes.

Structured decisionmaking: A template for high-quality decisionmaking

2.2 Science-Based Decisionmaking Includes the Science of Decisionmaking

Natural resource decisionmaking is a broad problem-solving process, not just the choice of an alternative management action (i.e., the "decision point"). Natural resource managers and decisionmakers know that much goes on before and after the point of decision in any problem. Science-based decisionmaking recognizes a need not only to include science in decisionmaking but also to include the science of decisionmaking. Combining the science of sustainability (ecological, social, economic) as decision "content" with the science of decisionmaking as "process" is a fundamental premise of truly science-based decisionmaking.

Process and Content: Science of decisionmaking and science in decisionmaking

Photo by Matthew P. Thompson

Natural Resource Decisions

What is a decision?

A decision and its implementation constitute an "irrevocable allocation of resources…not a mental commitment to follow a course of action but rather the actual pursuit of the course of action" (Howard 1966). A decision can be the choice of a strategic direction, such as a land and resource management plan (LRMP) under the National Forest System Planning Rule, or it can be a project-level decision, such as one that entails specific management practices and resources consistent with an LRMP. Throughout the decision process, a number of "small" decisions will be made—for instance choosing which sources of data, analysis techniques, and decision-support approaches to use. Similarly, many other circumstances exist in which resource managers and specialists face choices regarding research designs, monitoring strategies, etc., that may not be in service of a specific "big" decision. Using structured decisionmaking (SDM) principles might help in thinking through these choices, and such principles could guide thinking toward related decisions in the future; we principally present SDM as a framework to guide "big" decisions.

Who are decisionmakers?

For the purposes of this report, the term decisionmaker can apply broadly to those who make a wide variety of decisions about management of natural resources, including line officers, staff officers, and others, at all administrative levels of the agency. The identity of the decisionmaker will depend on the context—for "big" decisions; this decisionmaker will typically be a line officer. Resource staff and others, although not serving as the decisionmaker per se, nevertheless have important contributions to make at various stages throughout the overall decision process.

How do objectives and desired outcomes differ?

Decisionmakers ultimately choose an alternative based on the choice that best satisfies their established set of objectives. Objectives relate to the decisionmaker's overarching aspirations and desired outcomes. Outcomes, by contrast, are the situations that result after the decision is implemented. Outcomes are influenced by management actions but also by factors outside of management control, such as the actions of other landowners, weather, and other natural variation. A good decision, we hope, will lead to a good outcome, but this outcome is not guaranteed. To quote Howard (1966: page 56)—"We may be disappointed to find that a good decision has produced a bad outcome or dismayed to learn that someone who has made what we consider to be a bad decision has enjoyed a good outcome. Yet, pending the invention of the true clairvoyant, we find no better alternative in the pursuit of good outcomes than to make good decisions."

So then, what are good decisions?

A good decision is a logical decision that is based on available knowledge, uncertainties, and the values and preferences of the decisionmaker. How does one make a good decision? To borrow from the idea expressed above, we find no better alternative in the pursuit of good decisions than to adopt good decisionmaking principles.

Principles of high-quality decisionmaking

Good decisionmaking is defined in large part by the decision process and decision content, which are controllable, and not necessarily by the ultimate outcome, which may not be controllable. Adopting the principles of decision science helps lead to decisions with process and content favorable for a positive outcome and decisions that are robust to scrutiny.

High-quality decisionmaking has the following attributes (Berg et al. 1999):

- Clearly and accurately describes the problem.
- Establishes objectives and measurable criteria with which to evaluate attainment of objectives.
- Effectively uses available information and collects new information wisely.
- Generates a range of alternatives and evaluates the consequences of proposed alternatives in terms of evaluation criteria.
- Examines sensitivities and assumptions and identifies key uncertainties and impediments.
- Integrates, but does not conflate, value-based and science-based information.
- Clearly and logically documents the decision rationale.
- Ensures transparency and accountability.

2.3 The Structured Decisionmaking Framework Is a Template for Understanding, Analyzing, and Implementing Decisions

Structured decisionmaking is a well-established, organized framework by which decisionmakers better understand and frame their decision context, clearly and comprehensively identify and evaluate management options, and make informed choices under conditions of complexity and uncertainty. Structured decisionmaking (SDM) is a generic plan for developing customized approaches to problem solving, and it is a guide for identifying where decision-support tools and approaches might best fit. The components of this generic plan emphasize the importance of knowing one's location in a decision process, and knowing which tools and approaches are available at each stage. SDM also provides a solid platform with which to assess and manage risks, with an explicit focus on identification of uncertainties and outcome probabilities to inform decisionmaking (Haynes and Cleaves 1999).

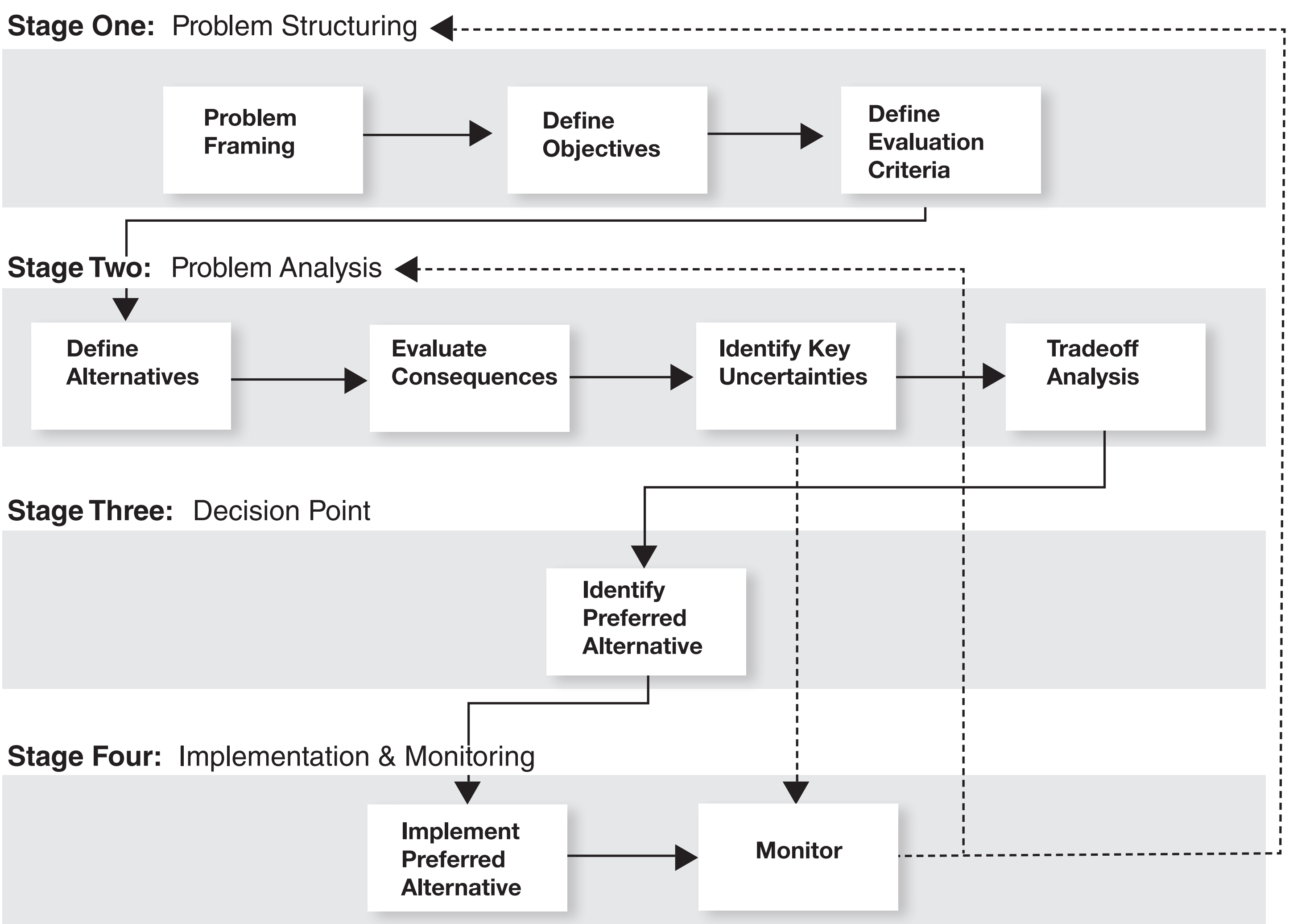
Application of structured decisionmaking can help managers and decisionmakers navigate complex decision processes and directly address potential sources of conflict and uncertainty.

The SDM framework consists of four primary stages: problem structuring, problem analysis, decision point, and implementation and monitoring, and includes several substages and feedback loops (figure 1). This framework helps clearly identify the appropriate roles of science and values in the decision process and provides a template for making and implementing high-quality decisions. Each decision stage can be characterized by a series of questions.

Problem Structuring

- What is the problem or issue to be solved?
- What are the management objectives and desired outcomes to be achieved?
- What are the spatial and temporal scales of analysis?

Figure 1.— Stages of the structured decisionmaking (SDM) process (Marcot et al. 2012a).



Two Hallmarks of SDM: Problem Decomposition and Values-Focused Thinking

A structured approach to making decisions helps resource managers by decomposing tough decisions into logical and manageable elements. These elements—the four stages of structured decisionmaking (SDM)—can then be addressed by the right people with the right tools. A key benefit of the problem decomposition embodied in SDM is the ability to separately analyze the values-based and science-based aspects of the decisions.

Values-focused thinking stresses that values are the driving force behind decisions and that evaluation of alternatives is ultimately tied to the decisionmakers' ability to achieve outcomes consistent with decisionmakers' values (Keeney 1996a, 1996b). That is, science-based information is not the sole basis for making decisions, and scientists' involvement in decision processes does not extend to setting policies or articulating values (Wilhere et al. 2012). Discussion of decision-makers' values and preferences, therefore, precedes other components of the decision process.

Whose values?

In this report, we specifically focus on decisions made by Forest Service employees regarding National Forest System lands. Thus, when we speak of values, we do not mean the personal values and preferences of the individual resource manager or line officer. Rather, a Federal decisionmaker's job is to reflect the values of society at large, as expressed through the mandate of the agency, the legislation that enables it, the regulations that have been promulgated, the court decisions that have clarified the agency's roles and responsibilities, and, as applicable, the stakeholders' viewpoints. It is recognized that balancing multiple objectives and reflecting societal preferences are daunting tasks, especially where non-market resources and ecosystem processes are concerned. (We provide additional guidance for addressing these issues in section 3.4 and in appendix B.)

- Who is(are) the decisionmaker(s)?
- Who should be involved in the decision process, and is conflict likely?
- How can progress toward objectives and desired outcomes be evaluated?

Problem Analysis

- What management options and alternatives are possible and available?
- What are the predicted consequences of each alternative?
- What key uncertainties are presenting an impediment to decisionmaking?
- To what extent are uncertainties controllable?
- What are the tradeoffs across alternatives?
- Is it possible to identify and remove underperforming alternatives from consideration, and to recraft others to provide better performance?

Decision Point

- Are there multiple objectives to balance?
- If so, what is the relative importance of each objective?
- What are managerial attitudes toward risk?
- Which alternative(s) best satisfies overall objectives, manages risk, and approaches desired outcomes?
- Is the selected alternative consistent with the science and with stated objectives?
- Can the selected alternative be feasibly and cost-effectively implemented?

Implementation and Monitoring

- What resources are required to successfully implement the selected alternative?
- What adaptive management principles and procedures are appropriate and feasible?
- What is the primary purpose for monitoring (achievement of objectives, determining system state, reducing future uncertainty)?
- What is the appropriate monitoring protocol and how will it be implemented?
- What happens if implementation does not occur?

"I think the real benefit of SDM is that it's an organized approach to making any kind of a decision, and I think as folks who are familiar with it know, you can use it at just about any level—an individual can use it, a family, an agency, or it can be used by an organized multi-stakeholder group, like the Glen Canyon Dam Adaptive Management Work Group.

"So it has a lot of utility, as a structured, organized way to make as informed a decision as you can. For our purposes, it's served us well—in terms of organizing data, identifying gaps, and identifying uncertainty associated with different aspects of making a decision. It's also served us well in group settings—in bringing stakeholders into processes, in getting their input and their views in how a question or a decision should be structured, and in getting a range of information you can use to evaluate different potential decisions.

"But I'd also say it's been helpful in encouraging participation and buy in from a number of stakeholders. It provides a process through which people can participate in the decisionmaking and have a real sense of benefit from having participated in that process, having a sense of buy-in to the decision because they were directly involved."

Glen Knowles
Chief, Adaptive Management Work Group
Bureau of Reclamation

2.4 Why Use the Structured Decisionmaking Framework?

Adopting the SDM framework and its associated principles is not likely to come without some measure of difficulty or cost. A significant upfront investment might be present in structuring the problem, especially to ensure that the right questions are being asked, the right problem is being solved, and the right players are involved. Clearly identifying the roles of each player (decisionmakers, decision analysts, stakeholders, etc.) is necessary, as is initiating communication among these roles throughout all stages of SDM. Decisionmakers need to commit to collaboration, inclusiveness, clarity, and transparency throughout the entire decision process.

Despite these potential difficulties and costs, the benefits of adopting these decision science principles are likely to prove worthwhile. SDM helps improve decision processes by making them more comprehensive, clear, and consistent with stated values and preferences. These properties of SDM lead to a suite of benefits for sustainable forest and grassland management. These potential benefits include the following attributes.

Greater Defensibility and Durability of Decisions

The use of best available science (for process and content), explicit inclusion of stakeholders, and commitment to transparency could reduce the prospect for appeals, and more importantly, could increase the prospect for successfully withstanding legal challenges.

Clearer Alignment With the Planning Rule and NEPA

The decision framework presented here is well aligned with the NFS Land Management Planning Rule (Planning Rule) and the National Environmental Policy Act (NEPA). The Planning Rule requires that the best available science be used to inform the planning process, and that the use of science in the development of these plans be documented. These mandates are consistent with the approach and concepts of SDM. Similarly, NEPA is the process that the agency uses to analyze and disclose the environmental effects associated with Federal decisions, and the structure of NEPA mirrors all stages of the SDM framework. The purpose and need statement in an environmental impact statement (EIS) serves to frame the problem and to articulate objectives (problem structuring stage). An EIS includes multiple alternatives and their possible consequences (problem analysis stage). Finally, a record of decision documents the decision rationale (decision point stage) and outlines plans for implementation and monitoring (implementation and monitoring stages). SDM methods can provide a rich structure, protocol, and set of tools for decisionmaking reported under NEPA.

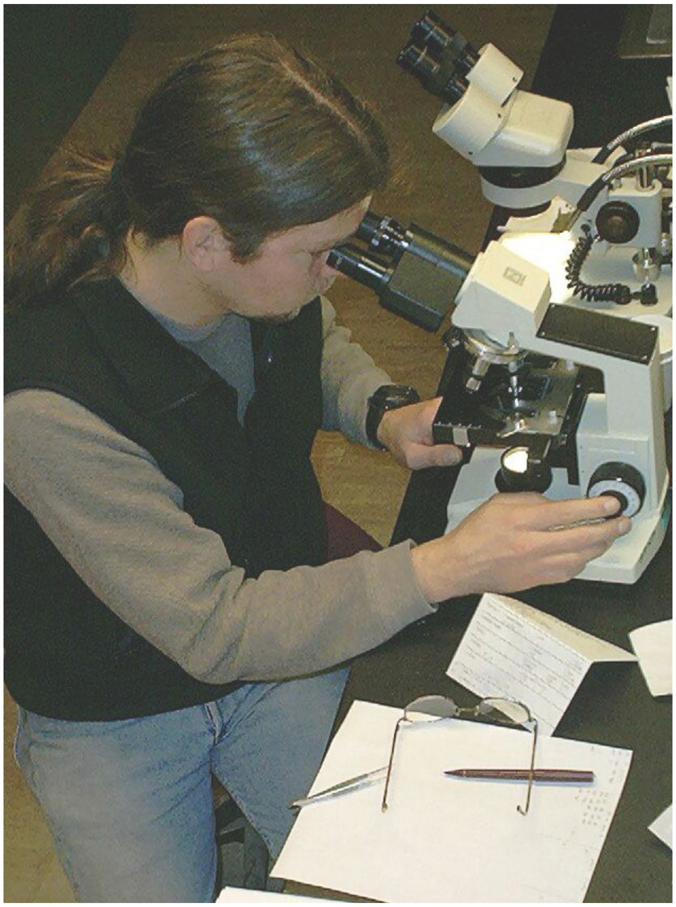


Photo by Bruce G. Marcot

3. The HOW of Structured Decisionmaking: A Guide for Decisionmakers and Decision Analysts

Time and Cost Savings

Adherence to SDM is likely to result in time and cost savings by reducing prospects for "dead ends" due to ill-formed problems or ill-defined evaluation criteria. In addition, SDM will likely enhance synergies with existing decision processes. Thus, SDM may also reduce the time spent addressing legal challenges.

Clearer and More Efficient Decisionmaking

SDM methods can improve clarity in properly defining the right problem to be solved and can help ensure that alternatives and analysis best align with objectives. This approach can engender trust among participants and lead to improved resource management decisions.

Facilitated Adaptive Management

Monitoring and assessment of decision outcomes will facilitate evaluation of success and provide guidance useful to inform future decisions.

"The big issue in public land decisionmaking is 'purpose and need.' So, for example, we have a piece of land out there and we want to do something with it, because we recognize, through our eyes and filters, that—for example—there are bugs out there and we need to do some thinning.

"So we've got a watershed management issue here—what's the purpose and need? Well, to control the bugs, and healthy forests, and restoration, and that sort of thing. And we start developing that on our own. But if we can get everyone together to say in the beginning that we all need to get something done here, and get them to help us develop the purpose and need, it may come out a little bit different. I can almost guarantee you it'll come out a little bit different, if not a lot different, than if we'd have done it on our own.

"And my contention is that it's going to be better, (a) because it has the social license, and (b) because there will probably be six things that hadn't fit into our original view of the problem. It could be, initially, that only our timber people are seeing this, but now our recreation people are seeing it, and homeowners are seeing it, and everybody's seeing it."

Rick Brazell
Forest Supervisor
Clearwater—Nez Perce National Forests

3.1 The Structured Decisionmaking Framework —A Closer Look

Each of the four primary stages in structured decisionmaking (SDM) (figure 1) consists of multiple steps; some are linked with feedback loops to denote opportunities for learning and adaptive management. In the problem structuring stage, the key aspects and drivers of the problem are identified, providing a framework for subsequent steps. Problem structuring includes defining the management objectives and evaluation criteria for achieving the objectives. The problem analysis stage entails predicting and evaluating the consequences of alternatives. The influence of uncertainties and multiple objectives can complicate the evaluation of how well alternatives satisfy overall management objectives. The decision point stage is where the decisionmaker identifies a preferred alternative, integrating science- and value-based information into the selection process and decision rationale. Finally, the implementation and monitoring stage entails putting the preferred alternative into action. Frequently, there are reasons to monitor the outcomes of the decision. Monitoring can help reduce critical uncertainty and provide feedback that can support adaptive management, that is, monitoring can help improve subsequent decisions and actions. We describe each of these stages in detail in the sections that follow.

Photo by Bruce G. Marcot

Each decision stage in the framework entails interaction and collaboration among different groups in the process (i.e., decisionmakers, stakeholders, scientists, and analysts). Decisionmakers have primary responsibility for the problem-structuring and in particular the decision point stages, but need to be involved throughout all stages. Stakeholders' engagement, in general, is present across all stages (Ascough et al. 2008), with primary interaction in the problem-structuring and decision point stages. Scientists and analysts, by contrast, are responsible for objectively evaluating consequences of proposed alternatives. They can also identify the presence and implications of key uncertainties (in the problem analysis stage) and help design monitoring strategies (Kiker et al. 2005).

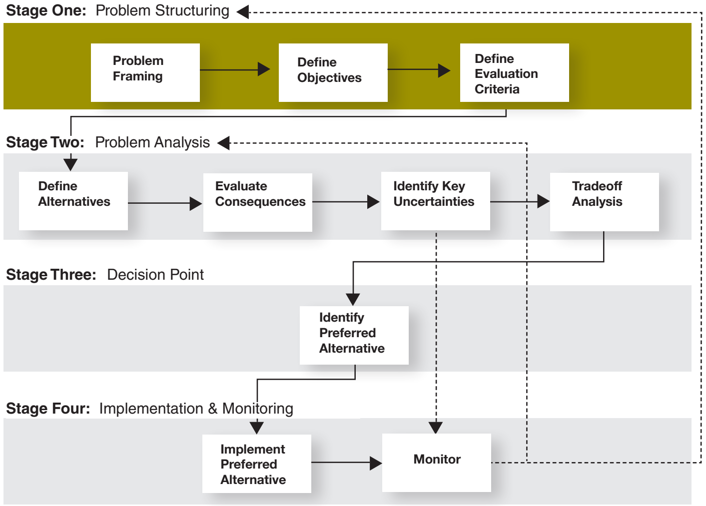
Managing national forests and grasslands provides a compelling context for the role of decision science and risk management. Although adoption of the SDM framework may not solve all conflicts involving social perceptions and political interests, it does help provide a structure for transparency and rigor to decision processes, especially within the context of NEPA and the NFS Land Management Planning Rule (Planning Rule). One of the powerful advantages of SDM is the deliberate process of structuring the decision process, in particular, identifying the problem to be solved, the objectives, the alternatives, the consequences, the tradeoffs, and the analytical logic that leads to a preferred alternative.

> *"If you don't know where you're going, you might not get there."*
>
> *Yogi Berra*

3.2 Stage One: Problem Structuring

A critical first step to making decisions is to answer the question, "Does a decision need to be made?" If yes, this step leads the decisionmaker to the question of "What decision needs to be made?" or alternatively, "What is the problem being solved?" This question will necessarily be informed by management objectives and desired outcomes; i.e., by values-focused thinking. An incomplete or unclear answer to this question will unnecessarily complicate subsequent decision stages. Beyond providing clarity to the decision objectives, problem structuring also helps guide the decision process toward the appropriate tools and information.

SDM Flowchart



Problem structuring also helps determine the appropriate levels of investment in the problem analysis stage and ensures that the right problem is being solved. Three primary components are used to structure a problem statement—framing the problem, defining the objectives, and defining criteria by which alternative solutions can be evaluated. These early steps are specifically based on the management context and the values set by decisionmakers.

3.2.1 Problem Framing

Clearly understanding the context in which a decision is required can provide important information about the nature of the problem and about which decision-support tools may be appropriate. Four broad pieces of information can help guide problem framing:

1. Identify Governance: One component to identifying governance structure is determining who the decisionmaker(s) is (are). In the simplest of cases, one fully authorized decisionmaker is needed to make the decision. Problem complexity will increase when multiple decisionmakers are involved and will depend on whether they are acting together, independently, cooperatively, or competitively. Another component to identifying the governance structure is to establish accountability, which could, in certain circumstances, include staff and external stakeholders.

> "…the most important conversation I had in the whole project, from start to finish, was the 45 minutes to an hour I spent with the ID [interdisciplinary] team leader, just talking about how we wanted that to go, and how we would build a process to start off on, and knowing that we would have to be pretty adaptive as we went through it."
>
> **Gina Owens**
> **Former District Ranger**
> **Green Mountain National Forest**

2. Involve Stakeholders: In agency decision processes, stakeholders do not have the legal authority to make decisions; however, they often exert considerable influence over decision processes and outcomes. Engaging and communicating with the interested public and others can help identify issues, better frame problems that consider managing resources for the greater good, and build ownership and investment for the decision ahead. It is important to note here that the Forest Service is required by the Planning Rule to involve stakeholders in all stages of land management planning.

3. Identify Timing of the Decision: It is important to clarify the timing and frequency of the decision(s) to be made. Some decisions are made only once, such as large land acquisitions or installation of permanent infrastructure. Other decisions may be repeated periodically through time, however, such as annual decisions about the amount and method of timber harvest in a particular forest.

4. Know the Background: Legal, regulatory, policy, ecological, social, and economic drivers all influence how decisions are made. Various statutes and regulations provide legal direction, constraints, and mandates for decisions made on National Forest System land. Collectively these factors circumscribe the decision space of resource managers.

3.2.2 Defining Objectives

Ultimately, a decision is an expression of the values of the decisionmaker(s). Clear and upfront identification of objectives can help ensure that the decision process works toward achieving the decisionmaker's aims. Objectives are the long-range aspirations of the decisionmakers and stakeholders and can include ecological, economic, recreational, cultural, and aesthetic dimensions. In cases with multiple objectives, it will ultimately be necessary for decisionmakers to articulate the relative importance of each objective, and doing so early on can help direct future stages of the decision process. Often, however, this articulation is not possible nor is it necessarily desirable, because how multiple objectives are balanced may depend on the set of real tradeoffs presented by the alternatives (see section 3.4).

Forest and grassland management often involves multiple, possibly competing, objectives. In such cases, an informed decision requires careful attention to defining and structuring objectives. One important element is to differentiate types of objectives.

1.*Fundamental objectives* are the ends that the decisionmaker desires to achieve through the decision. For example, in a large-scale forest plan, the fundamental objectives might be to maximize sustainable timber yield; persistence of threatened, endangered, and sensitive species; and consumptive and nonconsumptive recreational uses of the forest. Note that these fundamental objectives might compete with one another, and the optimal solution might involve balancing the tradeoffs among them. For an example at the project level, a fundamental objective for a fuel treatment could be minimizing the likelihood of wildfire-related mortality to old-growth trees.
2. *Means objectives* are ways of achieving fundamental objectives and, as such, are valued only insofar as they lead to achievement of the desired outcomes. Means objectives could include things such as increasing the number of recreational access points, improving forest access roads, and preserving a portion of the forest as a permanent no-harvest zone. The means objective for the fuel-treatment project example could be reducing stand density and fuel loading through mechanical treatment.

3. *Process objectives* pertain to how the decision will be made, but not what the decision will be. An example of a process objective for a forest plan might involve the level of engagement the public will have in the forest planning process; e.g., through National Environmental Policy Act (NEPA) consultation.

Objectives, which are the long-range aspirations of the decisionmakers and stakeholders, can include ecological, economic, recreational, cultural, and aesthetic dimensions.

"The big issue in public land decisionmaking is 'purpose and need.' So, for example, we have a piece of land out there and we want to do something with it, because we recognize, through our eyes and filters, that—for example—there are bugs out there and we need to do some thinning.

"So we've got a watershed management issue here—what's the purpose and need? Well, to control the bugs, and healthy forests, and restoration, and that sort of thing. And we start developing that on our own. But if we can get everyone together to say in the beginning that we all need to get something done here, and get them to help us develop the purpose and need, it may come out a little bit different. I can almost guarantee you it'll come out a little bit different, if not a lot different, than if we'd have done it on our own.

"And my contention is that it's going to be better, (a) because it has the social license, and (b) because there will probably be six things that hadn't fit into our original view of the problem. It could be, initially, that only our timber people are seeing this, but now our recreation people are seeing it, and homeowners are seeing it, and everybody's seeing it."

Rick Brazell
Forest Supervisor
Clearwater—Nez Perce National Forests

Fundamental and Means Objectives

The distinction between ends and means can be difficult to track in complex decision problems, especially in cases with multiple and possibly conflicting stakeholders' values and viewpoints. Ends and means are not necessarily absolutes but rather depend on the decision context. The process of indicating whether an objective relates more to a "why" or a "how" helps make the transition from an intuitive picture of what is desired to a structured and formal representation of objectives—which is critical for the future stages of the decision process. Using top-down and bottom-up approaches can help clarify fundamental and means objectives and can even help expand, reframe, or redefine a decision context.

Note that the process of identifying fundamental objectives is value driven, whereas the process of identifying causal relationships and connecting means objectives to fundamental objectives is knowledge driven.

"That was the crux of the problem, I think [framing the problem and decision]. It goes back to a class I took in college, called Creative Problem Solving, where we spent most of the semester focusing on how to define the problem. That's where we struggle the most… What problem are we trying to define? And that's why it took so long [on decisions over threatened and endangered species issues]—we couldn't agree. We couldn't come to agreement on what exactly it was we were trying to resolve.

You spend most of your time defining the problem… that's what's going to pay off the most… that's where the focus is, and that's where the improvement needs to come from."

Jim Smalls
National Environmental Policy Act Specialist
Washington, DC

Fundamental and means objectives can often be organized into hierarchies. (An example of an objectives hierarchy is presented in section 5.1.) Structuring objectives in a hierarchy can provide considerable clarity for the decisionmaker, stakeholders, and public, and it might help identify tradeoffs, complementarities, and priorities, where needed. Well-constructed objectives hierarchies portray relationships among objectives, ensure relevance to an inclusive mix of stakeholders, and provide the focus necessary to analyze tradeoffs and assess risks. Fundamental objectives can be stratified according to high-level, general objectives (sometimes referred to as "goals") and low-level, specific objectives and can further incorporate means objectives that describe how to achieve fundamental objective(s). This "top-down" approach is in fact similar to SDM, decomposing a fundamental objective into more manageable elements by asking what the key components of the objective are and how can they be achieved. By contrast, a "bottom-up" approach asks why a given action or activity is important (i.e., to which objective might it contribute), and why that objective is important. That is, moving down in the hierarchy focuses on execution, and moving up the hierarchy focuses on purpose. In some cases multiple linkages and interrelationships may exist between fundamental and means objectives (e.g., a given silvicultural action may help achieve multiple fundamental objectives such as improving forest health and reducing wildfire hazard), in which case, an objective network rather than a hierarchy may be a more appropriate way to structure objectives (Keeney 1996a; see also "means-ends objective network" in appendix B).

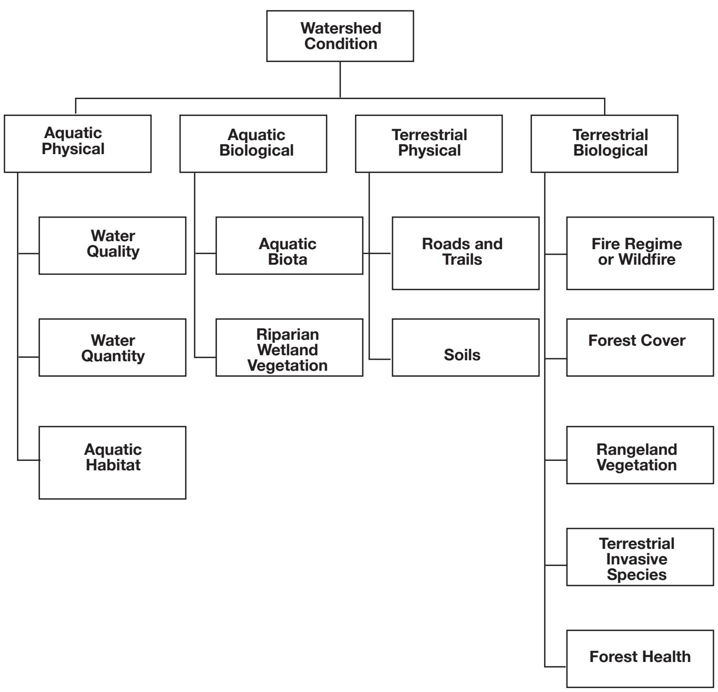
Photo by Bruce G. Marcot

3.2.3 Defining Evaluation Criteria

Evaluation criteria are necessary to measure how well alternatives may achieve objectives. Developing evaluation criteria can be challenging, especially when objectives might seem largely intangible or when quantification methods do not yet exist (for example, to improve landscape resiliency). In many cases, evaluation criteria may be structured in a hierarchy to match an objective hierarchy. For instance, the Forest Service's Watershed Condition Class model is comprised of a hierarchy of multiple evaluation criteria and subcriteria, which are grouped according to four major process categories (figure 2). Defining evaluation criteria consists of the following components:

1. *Measurement scale:* The measurement scale, typically quantitative, is the explicit gauge of how a given alternative performs with respect to fundamental objectives. There are three major types of measurement scales (Keeney 1996b):

Figure 2.— The Watershed Condition Assessment Framework (Potyondy and Geler 2011) as an example of an evaluation criteria hierarchy.



a. *Natural:* These evaluation criteria are direct measures that do not require additional interpretation or assumptions. Timber board-feet production is an example of a natural measurement scale. While natural criteria are preferable, for many natural resource management objectives they may not exist or may be difficult to measure directly.

b. *Proxy:* Proxy evaluation criteria are measures of quantities (often of means objectives) that are indirectly associated with the objective of interest. For example, if the objective was to increase recreational usage, the number of miles of managed trails might be a useful proxy attribute.

c. *Constructed:* For complex objectives, measurement scales can be constructed to gauge performance. These scales cannot be observed or measured on the ground, but rather represent the overall intent of an objective. In some cases constructed criteria can be composites of multiple pieces of information and could consist of multiple natural and proxy measurement scales combined in ways to specifically reflect the objectives. For example, habitat suitability indices are constructed scales that represent the quality of habitat for a particular species.

"...we probably should have taken a more expansive and more deliberate approach to framing the opportunity and the problem. If you don't do things right up front, then you're going to have problems throughout the whole process. In the past few years, that's kind of been my professional conclusion, when it comes to monitoring decisions that get made—for example, reviewing appeals on particular decisions that rangers or supervisors make.

"You can almost always—practically 90 percent of the time—trace just about any error you find in the review back to the beginning of the process. Something wasn't done well in the beginning, or it was misguided conceptually. They didn't think it was important...and it just manifests itself in the question—'Why didn't they think about this in the beginning?' They didn't think about it...or they tried to bandage a bleeding artery.

"You get to the point where you're actually implementing, and you're looking back and saying, 'I think that maybe I should've started somewhere differently'."

Tony Erba
Director, Planning, Appeals, Litigation, and Landscape-Scale Conservation
Eastern Region, Forest Service

Influence Diagram

An influence diagram can be a particularly useful and powerful tool for framing the problem and for developing a conceptual model that can feed into the problem analysis stage. It can be used to collectively understand the major relationships and important causal pathways and (most importantly) to determine how natural variation and management actions may influence or drive outcomes. An influence diagram can help form a bridge between qualitative descriptions and more concrete quantitative specifications, including relationships (e.g., profit is a function of revenue and cost), functions (e.g., profit = revenue – cost), and, where appropriate, actual numbers (e.g., revenue = $20; cost = $10; therefore, profit = $10) (Howard and Matheson 2005). An influence diagram is relatively easy to construct and comprehend, can be used to represent a wide variety of variables and relationships, and can be built off expert judgment rather than relying on availability of data (Marcot 2006). An influence diagram is similar to the means-ends objective networks discussed earlier in this report, but it can include other causal factors with no direct relation to objectives, such as the weather or other uncontrollable factors (see appendix B). An example of an influence diagram is provided in section 5.1.

2. *Desired direction:* This component of evaluation criteria indicates whether higher or lower values on the measurement scale are preferred. For instance, using the example above, timber board-feet production might constitute a natural measure of an evaluation criterion. Higher levels of timber production might be the desired direction.

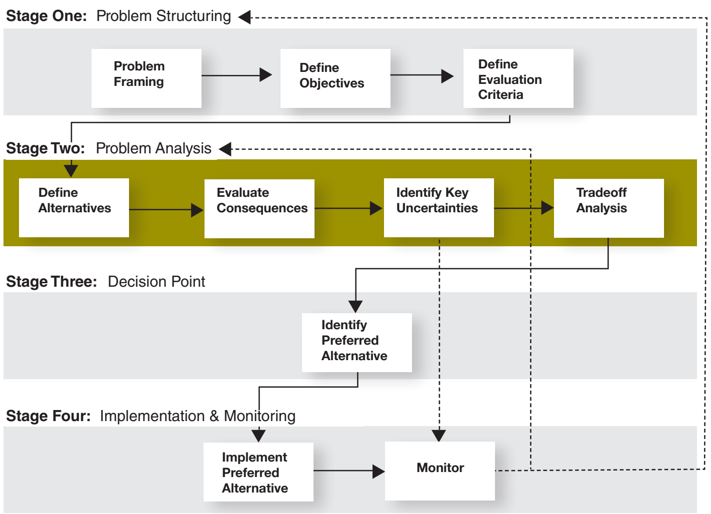
3. *Aspiration:* Aspirations are expressions related to performance of the objective. The aspiration might be to maximize performance of the objective or to achieve some minimum level of satisfactory performance. Threshold aspirations for evaluation criteria are common in natural resource management, such as minimum population levels for recovering a threatened species. In the example above, exceeding a particular level of board-feet production per year might be the desired threshold. Thresholds could be based on avoiding adverse or undesirable conditions. For example, not wanting to exceed a specific concentration of particulates in the air shed caused by controlled burning could constitute a desired maximum threshold.

Table 1 presents some examples of evaluation criteria that could apply for a multiobjective land management project involving timber harvest. Note that aspirations might conflict across criteria. For example, truly maximizing carbon storage might be infeasible or undesirable due to severe impacts on biodiversity, water yield, and fire danger. Figure 3 illustrates fundamental objectives and evaluation criteria developed for a case study applying SDM to respond to hemlock wooly adelgid (Adeleges tsugae) on the Cumberland Plateau of northern Tennessee.

3.3 Stage Two: Problem Analysis

The problem analysis stage entails defining the range of possible alternative actions, evaluating their potential consequences, analyzing potential complementarities and tradeoffs among objectives, and identifying key uncertainties and their implications. Problem analysis also involves identifying and quantifying risks (i.e., the likelihood and severity, or the probability and magnitude, of potential outcomes and their consequences).

SDM Flowchart

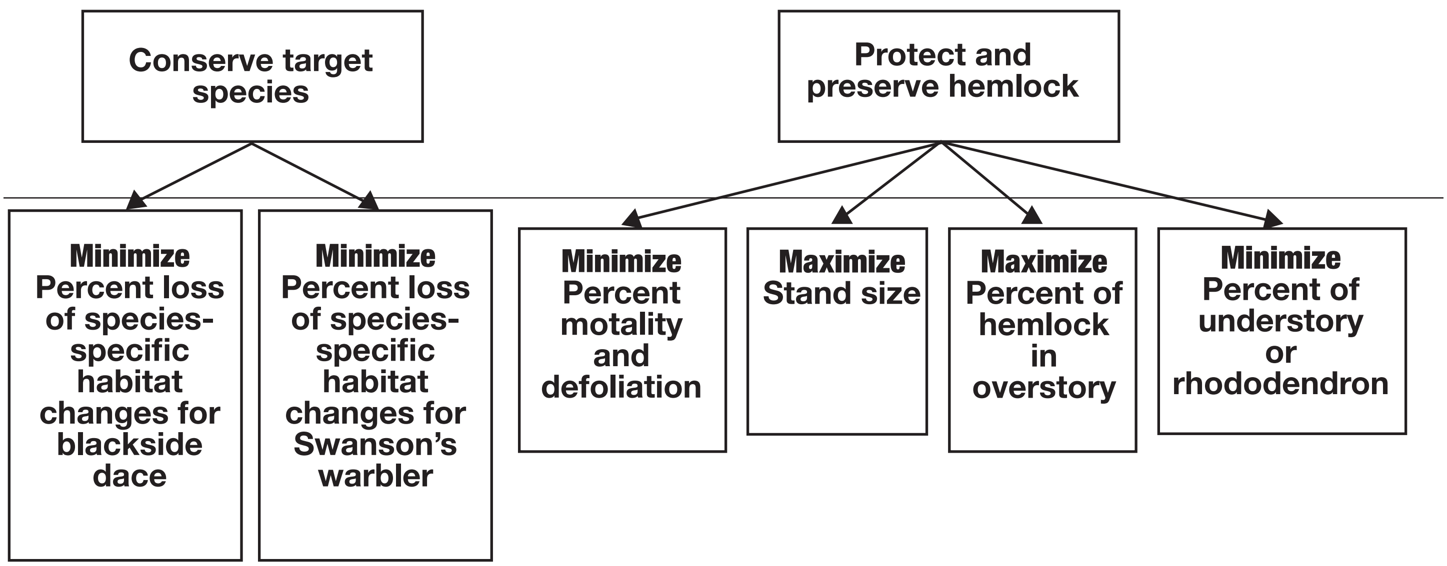


The development of alternative actions has a value component and can involve input from stakeholders. Other components of problem analysis, however, are conducted as a "clinical" set of tasks in which the alternatives are tested against the objectives and the decision evaluation criteria developed in the problem structuring stage. By clinical, we mean that these tasks are conducted unbiased by and separate from the subjective components of desired outcomes and risk attitudes. A wealth of tools is available for analyzing consequences of alternatives and tradeoffs in natural resource management decisionmaking (see section 3.6 and appendix B). Examples of tools include modeling approaches such as simulation, Bayesian networks, fuzzy logic, and optimization analysis, and approaches to analyzing potential and untried management options such as scenario analysis and comparative risk assessment.

Table 1.— Examples of evaluation criteria and their associated measurement scale type, desired direction, and aspiration. In addition, each criterion could have a specific threshold value to achieve (or avoid), such as shown with the soils objective.

Objective Category	Evaluation Criteria	Measurement Scale Type	Desired Direction	Aspiration
Silviculture	Board-feet of timber	Natural	Increase	Maximize
Carbon Storage	Tons of CO_2	Natural	Increase	Maximize
Soils	Percentage of area potentially disturbed from ground-based harvesting	Proxy	Decrease	Threshold; no more than 35%
Recreation	Miles of maintained trails	Proxy	Increase	Maximize
Wildlife	Habitat suitability index	Constructed	Increase	Maximize
Fire and Fuels	Torching index	Constructed	Decrease	Minimize

Figure 3.— Subset of fundamental objectives and evaluation criteria for a case study applying SDM to respond to hemlock wooly adelgid *(Adeleges tsugae*) on the Cumberland Plateau of northern Tennessee. Fundamental objectives included conservation of two target species, blackside dace (*Phoxinus cumberlandensis*) and Swainson's warbler (*Limnothlypis swainsonii*), and protection of hemlocks (*Tsuga canadensis* and *Tsuga caroliniana*). Additional objectives were to minimize treatment and mitigation costs, and to minimize concerns raised by the public. Modified from Blomquist et al. (2010).



"On the Colville, when we did travel management planning, we had all our internal folks and the public, and we said, 'Let's sit down in a room together and figure this out.' We've got to figure out the social issues. We need to know where all the trails are, first of all, because there are trails not on our system that you folks use, and you have to trust us when you tell us where they are that we're not just going to run out and close them.

"So we gathered the data, and of course it takes a lot longer to gather the data because you're gathering it externally and internally. We talked about the need to get from Point A to Point B—there may be five ways to get there, but maybe you only need one or two.

"…you go through the analytical process of collecting data, and discuss the need for getting from here to there. It may be a timber sale, or treating for bugs, or whatever the need is. You talk about the need to do it, you get everybody together on the same page on the need, and then you get ready to make the decision because you've gathered up the information together, and you've got everybody in the room face to face. So you're mixing the collaborative process with the data gathering—all at the same time."

Rick Brazell
Forest Supervisor
Clearwater—Nez Perce National Forests

3.3.1 Defining Alternatives

Alternatives are specifications of potential options for moving from current to desired conditions (i.e., for achieving management objectives). Defining alternatives involves identifying specific decision variables (those items we can control) and acceptable ranges for those variables (e.g., levels of timber harvest or range allotments). Decision variables and their acceptable ranges are informed by the decision evaluation criteria previously articulated by the decisionmaker in the problem structuring stage of SDM. Alternatives can be generated from the decision variables and their acceptable ranges in various ways, such as with modeling (Stage 2003).

In the simplest cases, the decision alternatives are a small set of discrete options, such as the choice to mow, burn, or leave a grassland undisturbed. In some cases, the decision variable(s) might be continuous, so the alternatives (at least in theory) are infinite, such as the specific rate at which to apply an herbicide. Continuous decision variables are often treated as a small set of discrete choices in practice. For example, a decisionmaker might evaluate herbicide application rates of 0, 1, 2, 3, 4, 5, or 6 pounds per acre, although models or formulae could be used to identify more precise rates, given a desired outcome.

Decision Variable

What is a decision variable?

A decision variable is a description of a single element in a decision. Natural resource management contexts typically include multiple decision variables, and, as a result, alternatives are defined as sets of given values and levels of decision variables. Formally defining decision variables leads to improved clarity in problem evaluation, and it facilitates generation of alternatives.

Types of decision variables

Decision variables come in many forms, broadly defined as quantitative or qualitative. These variables will necessarily be tied in some way to evaluation criteria. Quantitative decision variables can be one of the following three:

- Binary (0/1); for instance, a yes or no decision on whether to gate a road.
- Integer (1, 2, 3, etc.); for instance, the number of stands to treat.
- Continuous; for instance, the miles of trail to maintain.

Qualitative decision variables may be characterized categorically (e.g., low, medium, and high) where quantitative depictions are difficult or have not yet been developed. Qualitative values can also indicate general directions of change (e.g., more and less).

In many natural resource management problems, the alternative actions are complex combinations or sequences of multiple decision variables. For instance, in designing a forest management prescription, a manager might build in not only the level of annual timber harvest, but also the method of harvest, the spatial arrangement and timing (scheduling) of harvest, the method of treatment of the residual material, and the rate and method of regeneration. A very large set of combinations is possible. Practically, the analysis often focuses on a smaller set of alternatives that span the range of all the decision variables, but represent contrasting strategies for achieving the objectives. (These alternatives will likely vary in the tradeoffs across objectives. See section 3.3.4.)

Individual decision components (variables) may be eliminated and sets of possible alternatives are often` reduced early in the analysis process by screening out alternatives that exceed set constraints. For example, if staying within set costs is an objective with a threshold aspiration, then the portfolios of management projects might be screened so that those options that are above a given cost are rejected or amended.

3.3.2 Evaluating Consequences

Evaluating consequences is the second step in problem analysis. It involves predicting the likely outcomes of each alternative action in terms of the fundamental objectives. This stage is based on an understanding of the ecological, economic, and social systems affected, and thus relies heavily on the integration of science in decisionmaking. Often models, whether conceptual, field-derived, or expert-based, are helpful in predicting outcomes. Models serve to link the alternative actions to the objectives, using the evaluation criteria as the quantitative scales for prediction.

Consequences can be evaluated qualitatively by using conceptual models such as influence diagrams (Howard and Matheson 2005) that graphically link possible actions through intermediate variables to the outcomes desired by management. Influence diagrams provide a way for the decisionmakers and analysts to clarify their understanding of how the ecological, social, or economic system responds to management actions. Influence diagrams can then be developed into quantitative models (Marcot 2006) for more specific evaluation of consequences.

In natural resource management, perhaps the most common, and often the most reliable, predictive tools for evaluating consequences are quantitative models built on empirical field data. An enormous variety of predictive empirical models is available, each with its own purpose and context, from forest-stand models to Bayesian network models and linked wildlife habitat-population models. Such models are based on empirical data that describe and quantify the linkages between potential management actions and desired outcomes. These models can help reveal the importance and implications of random variability and uncertainty, if appropriately parameterized. Empirical models are limited to situations in which historic conditions are projected to continue into the future, however. If this projection is not the case (e.g., examining climate change effects on forest sustainability and ecosystem services), more mechanistic models may be used. The uncertainties associated with any mechanistic models used, however, must be assessed and understood.

For contexts in which multiple objectives are important, projections of how any potential action will affect each of the objectives are necessary. This approach might require a different predictive model for each objective. Thus, in a multiple-objective tradeoff analysis, the expected consequences of each potential action are compared among all objectives and with respect to their ultimate benefits and costs on multiple scales.

If empirical or mechanistic models are not available or appropriate, decision analysts can use formal methods of expert elicitation (Martin et al. 2012) including expert paneling to develop quantitative predictions (Marcot et al. 2012b). In these methods, expert knowledge is elicited in a rigorous manner to help analyze consequences, particularly when major areas of uncertainty and gaps are in empirical research. As with other consequence evaluation, the purpose of using expert knowledge is to predict consequences (in terms of the evaluation criteria) of alternative actions.

"…as a decision support tool, [SDM] forces you to think about all aspects of the problem. You also engage in identifying all the

resources that are going to be affected by your decision, and what are all the sources of information that are going to be affecting your decision. It causes you initially to focus specifically on what the problem is that you're trying to address, and in doing that, a lot of times the initial question you think you have will change, just based on looking at the whole suite of resources that are going to be affected by your decision.

"And then in thinking about that a little bit, you'll often change your problem statement a bit to be more accurate. Another aspect of this is that you think about how you're going to evaluate alternative decisions you might make, and the way you do that is to define resources and define quantitative metrics (as best you can). Now, of course, for some aspects it's very difficult, if not impossible. But you can qualify at least and get some information, some feedback, in doing that.

"So going through the process of trying to quantify the different things that are going to be affected by your decision: and in this case it included cultural resources, recreation, endangered fish, a trout sport fishery, water deliveries, the production of hydro-power at the dam (so an economic impact), and we also looked at cost for any particular alternative. And just in trying to think about all those aspects of a decision and in trying to define a measurable way of looking at performance of a given alternative or decision, caused us to think more critically about the problem statement at the beginning, and caused us to reframe the problem.

"And it also provided us with a way to assess how well our decision would perform, and in that way SDM guides you to make an informed decision in terms of which is the best decision."

Glen Knowles
Chief, Adaptive Management Work Group
Bureau of Reclamation

Does Uncertainty Matter?

Is uncertainty an impediment to decisionmaking?
Some measure of uncertainty is likely present in every natural resource decision. In many instances, after uncertainties are identified, they can be managed with little disruption to the broader decision process. For instance, when random variability is present, a decision analyst might turn to probabilistic techniques such as simulation or decision trees, without significantly affecting the decisionmaker's ability to choose a preferred alternative. In other cases, however, the uncertainties may be quite substantial, requiring alternative techniques and additional expertise to analyze consequences, or perhaps even invest in additional research or monitoring to improve the quality of available information.

Is the uncertainty controllable?
Some sources of uncertainty are inherently uncontrollable; for instance, weather patterns. In such cases, the question is whether available models and scientific understanding afford a reasonable depiction of the underlying uncertainty. For cases in which uncertainty can be controlled (for instance, through additional monitoring), the question is whether the cost of obtaining improved information is worth the value of that information.

Does uncertainty change the ultimate decision?
The critical question for the decisionmaker is whether the uncertainty makes it difficult to select a preferred alternative. Does the evaluation of the alternatives against the objective depend on information that is highly uncertain? Would reduction of uncertainty lead to different courses of action depending on what was discovered?

3.3.3 Identifying Key Uncertainties

All four stages of SDM may be impeded by uncertainty, leading to difficulty in clearly framing a problem, defining evaluation criteria, evaluating the consequences of alternatives, selecting a preferred alternative, or designing appropriate monitoring protocols. The best approaches for grappling with uncertainty will depend on which stage is most impeded. In identifying uncertainties, it can be useful to distinguish their various types and implications. Table 2 describes four primary types of uncertainty commonly faced in natural resource decisionmaking (Ascough et al. 2008). For instance, uncertainty regarding the definition or evaluation of "landscape resiliency" might be handled very differently than uncertainty regarding the frequency and severity of disturbances that may affect landscape resiliency (see section 3.6). Aiming to reduce uncertainty over time can include decisions related to monitoring and adaptive management (see section 3.5.2)

Identifying key uncertainties is particularly critical with regards to problem analysis, as this stage provides the information to distinguish alternatives and analyze tradeoffs. Uncertainties can pertain to parameter values, overall model structure, definition of terms, and functional relations among variables. Uncertainties can arise from sampling error, limited knowledge of the system, imprecise language, and variable expert judgment (Benke et al. 2007, Brugnach et al. 2010, Janssen et al. 2010, Regan et al. 2002).

Often uncertainty is encoded with probabilities, particularly when attempting to capture variability inherent to natural processes. The use of probabilistic information can be a powerful tool for characterizing processes with random or poorly understood components, and for quantifying the likely consequences of various alternatives. The "expected value," or the probability-weighted average, is a common way to characterize probabilistic information, although it can be of limited use when capturing the range of possible outcomes or values is important. A variety of tools exist to help quantify and analyze probabilistic information (e.g., Monte Carlo simulation, logistic regression, and Bayesian networks). A number of other valid approaches, however, can characterize and manage uncertainty, the applicability of which will depend on the nature of the uncertainty and the stage of the decision process (see appendix B).

Uncertainty can be of prime importance in the decisionmaking stage, particularly when managers deal with linked or sequential decisions. Diverse and conflicting goals and interests, and changing and unpredictable environmental conditions reduce confidence in projecting the consequences of alternatives (Brugnach et al. 2008). Uncertainty analysis can help identify how partial knowledge might affect the projected outcome of each alternative.

The analysis of uncertainty in a decision context is quite different than its analysis in a scientific context. What matters to a decisionmaker is whether the uncertainty would lead to choice of a different course of action. There are cases in which considerable uncertainty exists about the predicted outcomes, yet the best course of action is unaffected. In these cases, the reduction of scientific uncertainty is not important to the decisionmaker's selection of an alternative. Estimating the "expected value of information" is a powerful decision analysis method for evaluating whether uncertainty is relevant in a choice (Runge et al. 2011a, Williams et al. 2011). When the expected value of additional information is high, or when the power to reduce uncertainty is

Table 2.—The four types of uncertainty that may be encountered in a complex natural resource decision (Ascough et al. 2008).

Uncertainty Type	Definitions	Examples
Linguistic Uncertainty	Issues of vagueness, ambiguity, the contextual dependency of words, evolving definitions, and difficulty in explaining results	Definition of "ecosystem resiliency"; distinct notions of the "problem" by different stakeholder groups
Knowledge Uncertainty	Limitations of scientific understanding and observation	Unknown model parameters; limited understanding of ecosystem processes
Variability Uncertainty	Inherent variability that manifests itself in natural and human systems	Climate and weather patterns; political cycles
Decision Uncertainty	Ambiguity or conflict over social objectives and values	Conflicting values of old-growth forest resource use or preservation

high, it may be appropriate to implement monitoring or research to reduce uncertainty before committing to a course of action, or as part of the action itself, thereby establishing a proactive adaptive management strategy. But when the expected value of additional information is low, or when the power to reduce uncertainty is low, there is no advantage in gathering more information, and thus little to no justification for delaying a decision.

3.3.4 Tradeoff Analysis

In some cases, particularly with single-objective decisions that are not greatly affected by uncertainty, the evaluation of the consequences can lead transparently to identification of a preferred alternative. In multiple objective decisions, the consequences could display a complex mix of tradeoffs so that no one alternative is obviously best for meeting all objectives. Before proceeding to the decision point stage, it may be helpful to carefully examine the pattern of these tradeoffs and simplify the set of choices.

A multiobjective land management and fuel-treatment planning project on the Bitterroot National Forest in Montana is an illustrative example of a tradeoff analysis (table 3; Stockmann et al. 2010). The example presents a (reduced) mix of quantitative and qualitative evaluation criteria that relate to fundamental objectives and the desired direction or aspiration for each criterion (table 3). A first step for simplifying the set of choices is to identify criteria for which alternatives do not differ. None of the alternatives are anticipated to have direct effects on wilderness characteristics, and therefore this criterion can be removed from the table (not because adverse effects on wilderness characteristics are not important, but because this objective does not help distinguish the alternatives).

Table 3.— Example tradeoff analysis for a multiobjective land management and fuel-treatment planning project (Stockmann et al. 2010). Management alternatives vary in terms of number and area of treatment units, treatment types, and degree of related restoration work. Various management objectives and details of evaluation criteria are reported for each management alternative. The scores for each alternative are reported in comparison to the no action alternative. The best performing alternative for each objective is shaded in green.

Objective Category	Evaluation Criterion	Desired Direction	Alternative			
			1 (no action)	2	3	4
Fire and Fuels	Area of reduced fireline intensity (hectares)	Max.	0	41	818	375
Watershed	Rate of sediment delivery (% reduction)	Max.	0	19%	15%	19%
Wilderness	Adverse effects on wilderness characteristics	Min.	No effects			
Silviculture	Timber volume harvested (m^3)	Max.	0	23,786	32,176	21,185
Soils	Area of potential detrimental soil disturbance from ground-based harvesting (hectares)	Min.	0	32	45	38

Another step in considering tradeoffs is to identify and remove dominated alternatives, that is, alternatives that do not outperform other alternatives on at least one criterion. Consider alternative 4 with respect to alternative 2—it reduces fireline intensity over a smaller area, has the same sediment delivery reduction, harvests less volume, and has greater potential soil disturbance. Therefore, alternative 4 is "dominated" by alternative 2 and can be removed from consideration. Table 4 presents the reduced set of alternatives and criteria that analyze tradeoffs. Note that the remaining table displays the tradeoffs; a choice of alternative is not obvious, but requires value judgments to determine which objectives are more important to achieve.

Decisionmakers will be faced with alternatives that vary across a range of remaining criteria, which can introduce complexity and uncertainty at the decision point stage. Formal methods for quantifying and visualizing the performance of alternatives (e.g., spider plots; Gareau et al. 2010) can help decisionmakers better identify potential tradeoffs, better distinguish across alternatives, and to better communicate these results of problem analysis. Articulation of the relative importance of objectives with respect to each other is required to determine the preferred alternative and will be addressed in the next section.

Table 4.— Reduced tradeoff analysis for a multiobjective land management and fuel-treatment planning project. Management alternatives vary in terms of number and area of treatment units, treatment types, and degree of related restoration work. Various management objectives and details of evaluation criteria are reported for each management alternative. This table presents a simplified tradeoff analysis from table 3 with nondistinguishing evaluation criterion (direct effects on wilderness) and dominated alternative (#4) removed. The best performing alternative for each objective is shaded in blue.

Objective Category	Evaluation Criterion	Desired Direction	Alternative		
			1 (no action)	2	3
Fire and Fuels	Area of reduced fireline intensity (hectares)	Max.	0	414	818
Watershed	Rate of sediment delivery (% reduction)	Max.	0	19%	15%
Silviculture	Timber volume harvested (m^3)	Max.	0	23,786	32,176
Soils	Area of potential detrimental soil disturbance from ground-based harvesting (hectares)	Min.	0	32	45

"I've long operated under the premise that people support what they help create. And so, giving people a way to join into the development of something, typically results in them being supportive…when somebody from the public comes up and says 'You're clear cutting my backyard, and that's not going to work for me,' we have to be open to not rationalizing why we want to do that, but ask them what they would like to see. What would work for you? And then we can balance out the science and the silviculture with the public perceptions and desires.

"So [on the Nordic vegetation management project] …we began to devise a way to provide the maximum amount of inclusion, not just about what we wanted to do, but in having the people who lived in that area participate in developing what the project looked like. We spent the bulk of our time on the left side of NEPA. We were asking, 'What do you think should happen in this area? How do we return a forest landscape in Vermont, and integrate it into the lifestyle you have here—whether you live on the land, whether you're a second home owner, or whether you only like to come up and ski and look at the pretty fall colors.'

"And so it was interesting to build a public engagement strategy that was not around 'Here's our proposal. What do you think?' But 'Here's a chunk of land ripe for forest restoration, what do you think we ought to do?' And then building open houses and public engagement opportunities where people could see what we had done with what they wanted us to do….

"What we heard over time—the effect of that when we rolled out our proposed action, was that people could really correlate between what they asked for, and what they got. And it was one to one, most of the time. It was pretty cool."

Gina Owens
Former District Ranger
Green Mountain National Forest

3.4 Stage Three: Decision Point

The decision point stage is ultimately one in which a decisionmaker chooses a preferred alternative. This selection could relate to a policy, plan, or management option. In contrast to problem analysis, which focuses on answering the question "what do we know," the decision point stage focuses on answering the questions "what matters most to us?" and "which alternative best achieves our objectives?" When there is a single objective, the decision point stage is fairly straightforward: select the feasible alternative that best performs with respect to the single evaluation criterion. When multiple objectives and a complex set of evaluation criteria exist, however, it can be difficult to find clear solutions that effectively balance tradeoffs across competing objectives.

Fortunately, many tools exist to help decisionmakers navigate through such difficult processes (figure 4). If monetary values can be assigned to all evaluation criteria, the economic impacts of a proposed alternative can be compared against the costs of the alternative with cost-benefit analysis, presuming that the decision is to be based on economic consequences. If benefits exceed costs, an alternative is considered economically efficient. As an example, one appropriate context for cost-benefit analysis might be evaluation of alternative commercial thinning strategies. As another example, suppose a resource economist has generated estimates of the monetary value of various recreational trails. It might be possible in such a case to evaluate alternative trail management strategies with cost-benefit analysis. Methods are available to handle more complicated cost-benefit analyses, such as the comparison of future benefits against current costs (e.g., the cost of precommercial thinning to provide future improved timber quality and volume), or the use of willingness-to-pay surveys to estimate proxies to costs and benefits (e.g., Festa-Bianchet 2012, Waldhardt et al. 2010).

SDM Flowchart

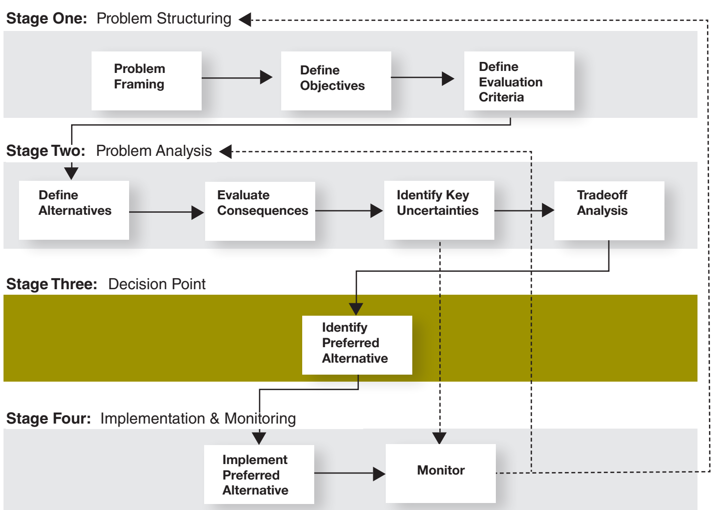
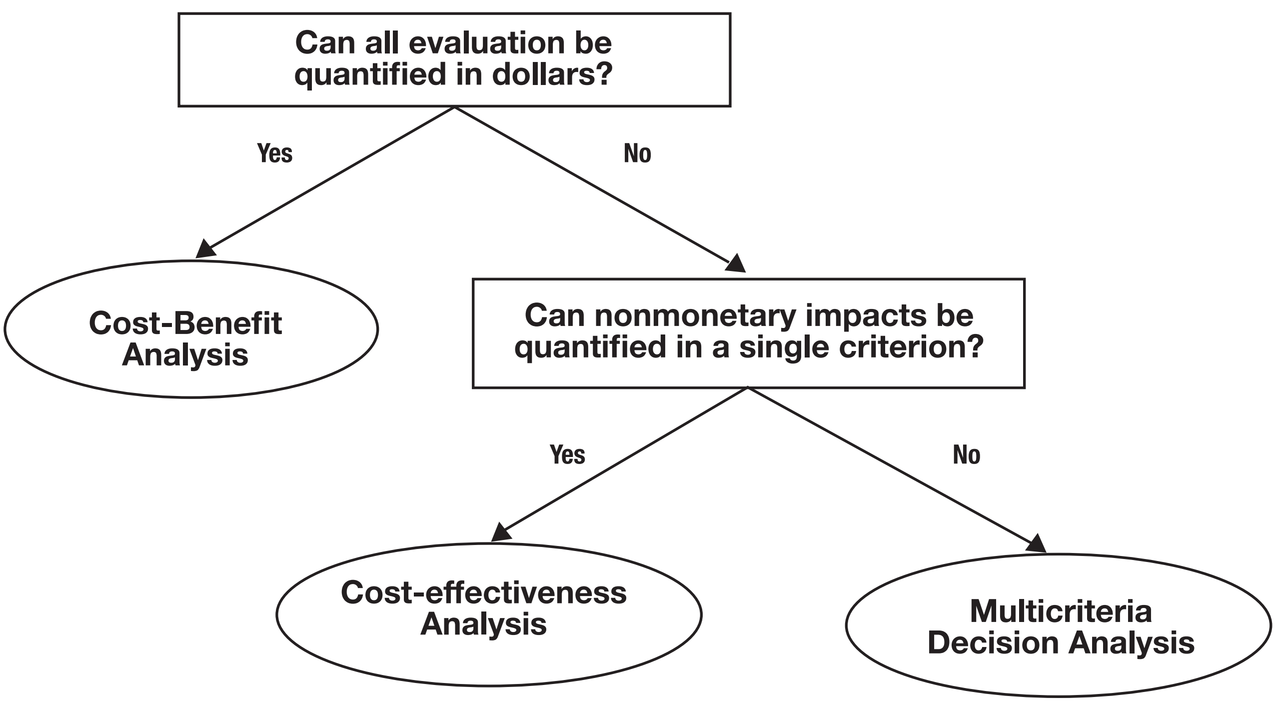


Figure 4.— Flowchart for guiding the decision point. If evaluation criteria can be quantified monetarily, cost-benefit analysis is appropriate. If all non-monetary effects can be quantified in a single criterion, then cost-effectiveness analysis is appropriate. Otherwise, multicriteria decision analysis (MCDA) techniques will likely be necessary to help identify the relative importance of management objectives.



It is often difficult to assign monetary values to all criteria and objectives, even using such approaches as willingness-to-pay, especially when nonmarket resources (e.g., habitat) are considered. One possible approach, based on cost-benefit analysis, is to ask "what are the required benefits associated with known costs such that benefits equal costs?" This type of approach is known as break-even analysis and seeks to determine the minimal value of nonmarket benefits to justify the costs of a management alternative. If a given treatment is selected and implemented, the implication is that the minimum value of the potential resource value change exceeds the cost of the treatment (augmented as appropriate by considering the likelihood of treatment success). Break-even analysis is more limited in situations in which effects to multiple nonmarket resources must be considered and the decisionmaker is uncertain about the extent of possible benefits (see section 3.3.3 regarding uncertainty).

Quantification of effects by a single, nonmonetary evaluation criterion may be possible when cost-benefit analysis is infeasible. Cost-effectiveness is a common alternative to cost-benefit analysis that compares alternatives on the basis of their costs with respect to a nonmonetized performance measure (figure 3). An alternative with a lower ratio of costs to effectiveness is considered more efficient than an alternative with a higher ratio. For instance, an alternative that would restore 10,000 acres of dry ponderosa pine forest at a cost of $5 million (C/E = $500/acre) would be considered more cost effective than an alternative achieving restoration on 20,000 acres at a cost of $11 million (C/E = $550/acre). Limitations to cost-effective analysis include an inability to account for differences in project scale (e.g., 10,000 acres treated versus 20,000 acres treated, although C/E ratios could be weighted by scale), and, more importantly, it is rare that in multiresource, multiobjective problem contexts, all nonmonetary effects can be quantified with a single effectiveness index.

Multicriteria decision analysis (MCDA) approaches can be used when all effects cannot be quantified with a single measure of effectiveness (figure 4). MCDA is a family of tools and approaches that facilitates the systematic evaluation and selection of management alternatives by identifying potential tradeoffs, conflicts, and complementarities across objectives. The most common MCDA approaches in natural resource management rely on what are known as value measurement models. These models seek to quantitatively establish decisionmaker preferences so that the relative importance of objectives can be distinguished. Decisionmakers can transparently and systematically evaluate and rank alternatives when the preference structure is clearly articulated.

The land management and fuel-treatment planning project on the Bitterroot National Forest in Montana (table 4) can be used to illustrate the application of MCDA for the decision point stage. Although a variety of approaches are possible (see appendix B), we demonstrate a relatively simple weighted-sum approach (Ananda and Herath 2009). The first step is to rescale the criteria in table 4 (predicted values for evaluation criteria for each alternative) so that values fall in the range of 0 to 1 (a value of 1 is most desirable) to enable comparisons with a common currency (table 5). Where more is better (i.e., the desired direction is to increase), Equation 1 is used to assign rescaled scores. Where less is better (i.e., the desired direction is to decrease), Equation 2 is used.

$$\frac{\text{(criterion level - minimum level)}}{\text{(maximum level - minimum level)}}$$

(Equation 1)

$$\frac{\text{(maximum level - criterion level)}}{\text{(maximum level - minimum level)}}$$

(Equation 2)

As an example, for areas of reduced fireline intensity, where more is better, Alternative 1 is scored (0 – 0) / (818 – 0) = 0.00, Alternative 2 is scored (414 – 0) / (818 – 0) = 0.51, and Alternative 3 is scored (818 – 0) / (818 – 0) = 1.00. The rescaled criteria (table 5) can be used to help understand the tradeoffs across alternatives in terms of relative achievement of objectives, and to better understand how much importance one would have to place on each objective for a given alternative to be preferred. For instance, Alternative 1 performs the worst on criteria relating to Fire and Fuels, Watersheds, and Silviculture Objective Categories. Thus minimizing soil disturbance would have to be very important to the decisionmaker for Alternative 1 to be preferred.

A set of weights establishing the relative importance of objectives is also required for the weighted sum approach. As with the rescaled criteria, a higher score is considered better. For example, suppose the decisionmaker made the value judgment to place 70-percent weight on the Fire and Fuels objective and 10 percent on each of the remaining objectives. In that case, Alternative 1 is scored (0.70 * 0.00) + (0.10 * 0.00) + (0.10 * 0.00) + (0.10 * 1.00) = 0.10; Alternative 2 is scored 0.56; and Alternative 3 is scored 0.879. Thus, Alternative 3 is the best alternative for collectively achieving the importance-weighted desired outcomes. An advantage to this technique is that the effects of a range of possible weights can be explored to determine how the preferred alternative would change under different weighting schemes (table 6). We strongly suggest that this exploration not be used to justify a predetermined decision, however.

A variety of MCDA techniques are used for different settings. Whichever technique is adopted, it is important to handle the decision point stage in a systematic and documentable manner. One approach is to identify target levels for satisfactory performance for evaluation criteria and use a technique called goal programming to identify the preferred alternative. When weights are difficult to assign directly and satisfaction thresholds are not appropriate, decisionmakers can rely on pair-wise comparisons

Table 5.— Normalized multicriteria decision analysis applied to the multiobjective land management and fuel-treatment planning project from tables 3 and 4. Here the evaluation criteria for management alternatives presented in table 4 are rescaled, which "equalizes" or "normalizes" scoring across variables, for use with the weighted sum approach. The best performing alternative for each objective is shaded in blue.

Objective Category	Evaluation Criterion	Desired Direction	Alternative		
			1 (no action)	2	3
Fire and Fuels	Area of reduced fire-line intensity (hectares)	Max.	0.00	0.51	1.00
Watershed	Rate of sediment delivery (% reduction)	Max.	0.00	1.00	0.79
Silviculture	Timber volume harvested (m^3)	Max.	0.00	0.74	1.00
Soils	Area of potential detrimental soil disturbance from ground-based harvesting (hectares)	Min.	1.00	0.29	0.00

Table 6.— Example of sensitivity analysis paired with multicriteria decision analysis for a multiobjective land management and fuel-treatment planning project. The preferred alternative is identified under various weighting schemes using the weighted sum approach, based on the alternative criteria scores presented in table 5 and with the additional step of applying importance weights to scores.

Example Weighting Scheme	Weights				Preferred Alternative
	Fire and Fuels	Watershed	Silviculture	Soils	
Favor Fire and Fuels	0.70	0.10	0.10	0.10	3
Favor Watershed	0.10	0.70	0.10	0.10	2
Favor Silviculture	0.10	0.10	0.70	0.10	3
Favor Soils	0.10	0.10	0.10	0.70	1
Emphasis on Watershed and Soils	0.15	0.35	0.15	0.35	2

of each objective to establish a ranked priority. In fact in cases with ill-defined values, starting by ranking objectives can provide opportunities to develop and reveal values and can provide a basis for establishing more quantitative weights. In difficult group decision settings, decisionmakers could turn to techniques premised on the principles of voting to identify the degree to which one alternative or objective may be favored more than another (Mendoza and Martins 2006).

In addition to using the techniques presented in figure 4 to help with the decision point stage, it can be helpful to revisit previous stages of the decision process. Doing so can help ensure that the right questions were asked and the correct answers provided. One of these questions is to address the potential costs of doing nothing (often a "no action" alternative in the NEPA context). Appendix A provides some additional guidance for addressing particularly tough decisions. Ultimately, if a decision is made, the principles of good decisionmaking call for clear and logical decision documentation, including a description of how value-based information was considered and how objectives were balanced.

Two Common Multicriteria Decision Analysis Methods for Establishing Weights

One key step in any multicriteria decision analysis is developing weights to apply to each objective. This value judgment reflects the decisionmaker's evaluation of the importance of the various objectives. Two of the most common varieties of methods for eliciting these judgments are described below.

Simple Multiattribute Rating Technique (SMART)

SMART begins by asking decisionmakers to identify the most important objective, based on its importance and the degree to which it differs across the alternatives; this objective is then assigned a score of 100. All other objectives are assigned scores from 0 to 100, relative to the most important one. The weights are found by normalizing the scores so they sum to 100 (or 1 on a 0-1 scale). Weighting can proceed hierarchically for subcriteria. "Swing weighting" can be used to account for the range of variability across objectives; a score of 100 is assigned to the objective for which the swing from worst performance to best performance is most preferable.

Analytic Hierarchy Process (AHP)

AHP relies on a series of pairwise comparisons such as, "How important is objective X relative to objective Y?" Comparisons are scored from 1 for objectives of equal importance to 9 for absolute importance of one objective over another. As with SMART, AHP can proceed hierarchically through criteria and subcriteria. The pair-wise comparisons can be analyzed with statistical techniques to derive importance weights across objectives.

Sources: Ananda and Herath (2009); Diaz-Balteiro and Romero (2008).

3.5 Stage Four: Implementation and Monitoring

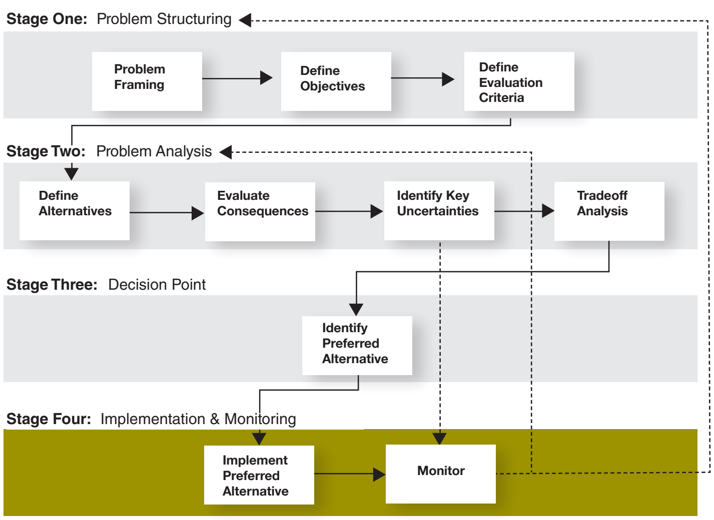
The implementation and monitoring stage follows the completion of the decision point stage. Implementation and monitoring are separate components in the decision process, but for the Forest Service, monitoring is an integral part of land management. Therefore, we discuss implementation and monitoring together.

3.5.1 Implement Preferred Alternative

The implementation stage is the point when the preferred alternative is enacted. Several aspects may be considered for successfully implementing a decision, including the amount of time and cost associated with the implementation, the effect of the implementation, risks and benefits associated with the implementation, and the operational structure needed to implement a complex decision intended to guide management of large land areas with diverse administrative units. Not considering these aspects could result in a decision not being implemented as desired. Indeed, these aspects of implementation should be considered well before the implementation process is undertaken, preferably as part of the evaluation criteria in the problem structuring stage. We address these issues here to stress the importance of considering implementation feasibility and likelihood of success.

The Interior Columbia Basin Ecosystem Management Project (ICBEMP) is an example of how implementation can fail. The ICBEMP intended to produce one set of ecosystem management guidelines in one record of decision for Forest Service and Bureau

SDM Flowchart



of Land Management (BLM) lands in the interior West of the United States, (USDA and U.S. Department of the Interior 2000) for a project area larger than France. The diversity of regional administrative units, the contrasts in policy and management goals between the two agencies, and the complexity needed to interpret and enact the tangle of ecological, economic, and social management guidelines proposed, however, led to the development of two parallel draft environmental impact statements (EISs) for contiguous geographic portions of the interior Columbia River Basin rather than one EIS for the entire area. Additional disagreement among agencies ultimately led to no final EIS and record of decision being created for either portion and, despite the wealth of analysis and scientific data produced (Haynes et al. 2001), the project was abandoned. A key lesson learned here was that the goal and geographic scope of the project were simply too ambitious and complex to satisfy the immense diversity of affected decisionmakers and stakeholders and to provide feasible and cost-effective implementation.

3.5.2 Monitoring Results of Implementing the Decision

Three purposes for monitoring in the context of decisionmaking are (1) to evaluate achievement of the objectives, (2) to determine the state of the system (for State-dependent decisionmaking), and (3) to reduce uncertainty to improve future decisions (Nichols and Williams 2006). First, monitoring for evaluation serves as a way of documenting the outcomes of management. In the case of one-time decisions, monitoring determines whether implementing the decision achieved what was intended. In the case of recurrent decisions, monitoring provides a way to alter management practices if unforeseen outcomes occur or underlying conditions change. Second, for some decisions the preferred action depends on the state of the system, and the system needs to be monitored to determine the appropriate course of action. For example, the basal area needs to be monitored if a treatment prescription calls for thinning whenever the basal area exceeds a specified maximum threshold value. Third, when uncertainty impedes a recurrent decision, monitoring (and perhaps research) provides feedback that reduces uncertainty over time and allows adaptation of future actions. For example, a recurrent decision may pertain to successive thinning entries into a forest stand, timed to provide for at least a minimal economic return but also to provide enough understory space for development of a multilayered canopy structure for wildlife that use mature forests. Uncertainty in this case may pertain to the nature and degree of canopy layering that would provide habitat for the wildlife species of interest. Monitoring would provide information on when the forest stand achieves desired wood volume growth (determining the state of the system), and research and monitoring together would provide information on understory and wildlife response to thinning activities (reducing uncertainty to improve future decisions).

Monitoring design arises from the decision context. The monitoring metrics, the monitoring methods, the geographic scope, and the sampling design (including sampling locations and rate) are all determined based on the information needs of the decisionmaker. The cost of monitoring is an important consideration; to be warranted, cost needs to be offset by the benefit (monetary or otherwise) that accrues from the monitoring information. Collectively these factors help determine the type, extent, and frequency of monitoring required.

3.5.3 Adaptive Management

Monitoring the outcomes of early decisions can be used to improve later decisionmaking. Scientists and decisionmakers can use monitoring to evaluate predictions that were used in the decisionmaking process. Broadly, two potential outcomes of monitoring and assessment are possible. Monitoring can suggest that the current course of action is largely correct and that it is not necessary to change the implemented action. Alternatively, monitoring might provide novel insights that lead to a different preferred alternative, if the original objectives are to be met. Revisiting the management decision may be warranted if it is determined that the present course of action is not producing the desired outcome. Importantly, adaptive management is needed when there are critical uncertainties impeding the decision (e.g., when great uncertainty in predictions results in a high value for additional information).

"…the basic premise of adaptive management is learning by doing, so you're constantly trying to evaluate the decisions you've made, monitor the effects of those decisions, and re-evaluate based on what you've learned. And what SDM really does for you is help you marshal that information.

"So for us, in the Glen Canyon Dam Adaptive Management program… it's a big program; it's a well-organized program that's been in place for about 15 years; we have a mountain of information. We have some pretty good modeling tools in place that we can use. We have a pretty good ecological model; we have a model for the rainbow trout fishery in Lee's Ferry, and we have some really good models on sediment transport and on water temperature in relation to flow and dam releases.

"But SDM makes all that information so much more useful, because it helps you marshal that information in a decision-making process and make your best use of it."

Glen Knowles
Adaptive Management Work Group
Bureau of Reclamation

Adaptive management can be described in terms of two feedback loops (Williams et al. 2007). Monitoring results can be used to revisit the problem analysis stage (so-called "inner-loop learning," figure 1, inner dashed line) or, more fundamentally, the problem structuring stage ("double-loop learning," figure 1, outer dashed line). The knowledge gained through this learning may lead the decisionmaker to include new objectives or, indeed, to identify a need to change the very governance structure of the decision (Pahl-Wostl 2009).

3.6. A Guide To Identifying Appropriate Decision-Support Tools and Approaches

Making decisions in the world of multiresource objectives, such as under the National Forest Management Act and the current Planning Rule, is an enormously complex process. Decisionmaking in this context often entails balancing needs and desires for potentially conflicting land uses, addressing conflicting interests of multiple stakeholders, trading off short-term use for maintaining long-term options for future use, and coordinating among multiple land holders and decisionmakers, within the context of uncertainty. The potential for litigation is constantly present.

Structured decisionmaking is one option for addressing these complexities and challenges by posing a set of questions that can help determine the most appropriate decision-support tools. Thus, the broader decision process itself entails decisions about which tools and approaches to use.

- What is the main decision(s) to be made?
- Will a single decisionmaker or multiple decisionmakers make the decision? If multiple, will they cooperate or compete?
- Who is involved in and affected by the decision and its implementation? Are they government agencies, industries, local communities, NGOs, and other stakeholders?
- How complex is the decision? Is the decision about single or multiple resources, single or multiple objectives, and single or multiple decision variables and evaluation criteria? What are the anticipated important secondary effects of the decision?
- How much contention exists regarding the decision? What potential conflicts may need to be resolved?
- What is the timeframe for the decision? Does the decisionmaking involve a single decision to be made at a specific point in time, concurrent decisions to be made at a single time, or multiple decisions to be made over a span of time?
- To what extent does uncertainty influence the decision? What exactly is most uncertain, how does the uncertainty affect the decision, and how might that uncertainty be addressed in the decision?

We identified six typical combinations of answers to these questions and identified examples of appropriate SDM approaches (table 7). Note the importance of clarity in problem structuring to answer these questions, as well as the connection between decision context and appropriate decision-support approach. Considering if the decision problem fits one of these six types of problems can help determine which general set of SDM approaches might be appropriate for addressing the problem. After the problem type and SDM approach are narrowed, one can then move on to selecting specific decision-support tools and methods. Since the universe of possible decision contexts is broader than these few examples, it is likely that decisionmakers will find themselves in a different situation. The important thing is to clearly answer the above list of questions to enable identification of SDM tools and methods that are appropriate for the specific decision context. Appendix B provides a more comprehensive list of tools and approaches that could support structured decisionmaking.

One key step to sorting through decision-support options is to identify whether uncertainty is a major impediment, and if so, what type of uncertainty (or types of uncertainties) are most prominent. Identifying the type of uncertainty can then lead to families of appropriate decision-support approaches. For instance, substantial variability may be best managed with probabilistic approaches, whereas substantial knowledge gaps may be best managed with expert paneling methods. Decision uncertainty can often be best managed with multicriteria decision analysis techniques that help decisionmakers articulate preferences, visualize tradeoffs, and rank alternatives.

Decision-support systems and approaches DO NOT make decisions—they inform the decisionmaker and support the decisionmaking process.

Photo by Bruce G. Marcot

Table 7.— Six typical resource decision problems and examples of appropriate decision-support approaches that would best help solve them, roughly listed in increasing order of problem complexity.

Type of Resource Decision Problem	Best General Structured Decisionmaking Approach for Solving the Problem	Examples
1. Single resource but with other considerations or implications; single decisionmaker, single objective, single decision variable	If uncertainty is not a major impediment, use management science, optimization, single-objective decision analysis without uncertainty. If uncertainty is a major impediment, use single-objective risk analysis; if uncertainty is uncontrollable, use risk analysis; if controllable, use value information analysis (expected value of information, cost of acquiring additional information).	Restoration of a natural community; anthropogenic fire control
2. Multiple objectives; multiple stakeholders; single decision, single time period	Use multicriteria decision analysis (MCDA) to address tradeoffs among objectives.	Project-level decisions; e.g., wildfire control, fuels management
3. Single objective; multiple decisions over time with substantial uncertainty	Use classic active adaptive management; consider stochastic dynamic programming.	Forest or grassland ecosystem restoration
4. Multiple objectives; multiple stakeholders; multiple decisions recurrent over time; substantial uncertainty (often for secondarily affected resources)	Use MCDA and adaptive management in a multiple-objective approach; break the problem into a series of single-objective problems with the use of ad hoc approaches for considering multiple objectives or treat as a multiple objective problem with optimization solution.	Project or regional, strategic-level decisions, such as setting allowable annual timber harvest levels concordant with other objectives for water quality, wildlife habitat, range use, etc.
5. Multiple resources, objectives, and decision variables; potentially contentious stakeholder involvement; single initial decision, single time period; also sequential decisions later on; moderate to high uncertainty	Use MCDA and adaptive management in a multiple-objective approach; break into a series of single-objective problems and consider use of ad hoc approaches for considering multiple objectives or treat as a multiple objective problem with optimization.	Forest plan direction; strategic plan with monitoring and adaptive management component
6. Multiple objectives; multiple decisionmakers who do not necessarily cooperate	If decisionmakers cooperate, use conflict resolution and negotiation approaches. If decisionmakers do not cooperate, each decisionmaker could use a game theory approach and consider his or her decision independent of the others.	Managing wildfire and fuels that straddle jurisdictional boundaries; fuels and fire management in wildland-urban interface areas with a mix of landownerships

4. Opportunities and Challenges for Adopting Decision Science Principles in the National Forest System

4.1 A Survey of the National Forest System on Use of Structured Decisionmaking

As a foundation for developing this report, we conducted an anonymous, online survey in June 2012 to determine if, how, and under what circumstances structured decisionmaking (SDM) tools and methods are being used and what improvements may be needed. We surveyed 4,819 planners and specialists and 1,738 decisionmakers including line officers in the Forest Service's National Forest System (NFS), who have been recently involved in projects related to the National Environmental Policy Act (NEPA), including planning at the project, forest, and regional levels.

We received 1,562 responses (23.8-percent response rate) of which 14 percent were decisionmakers and line officers, 20 percent were planners and interdisciplinary team leaders, 39 percent were specialists or researchers, and 27 percent were others involved in NEPA activities. Responses were from all nine NFS regions and the Washington Office, and they were roughly in proportion to the total numbers of employees and to numbers in line and staff. The survey revealed that respondents were responsible for a wide range of resource management issues, including recreation, planning and plan revision, wildlife management, water and watershed management, fire and fuels treatment, silviculture, timber scheduling, wilderness management, public affairs, and other issues. Most respondents (58 to 84 percent) noted that they are dealing with a number of high priority issues, including forest ecosystem health, soil and water conservation, biodiversity conservation, legal and institutional issues, socioeconomic effects, and forest ecosystem productivity.

When presented with a list of 10 decision-support processes or methods for risk analysis or risk management, most respondents replied that they have used 6 of them—(1) modeling to generate alternatives, (2) modeling to compare alternatives, (3) comparative risk assessment, (4) scenario planning and analysis, (5) tradeoff analysis of alternatives, and (6) participatory or collaborative group decisionmaking methods. Respondents were familiar with, but have never used, expert paneling and were unfamiliar with optimization, objectives hierarchy assessment, and social choice theory. Importantly, fewer respondents noted that they use any of the 10 processes or methods frequently, and very few noted that they were not relevant to their work.

Most respondents had used 4 of 10 decision-support models and protocols— (1) models based mostly on expert judgment, (2) simulation models, (3) statistical models based on field data, and (4) decision trees. Most respondents were unfamiliar with fuzzy logic models, agent-based modeling, influence diagrams, Bayesian tools, multiattribute utility theory, and multicriteria decision analysis. Fewer respondents used any of the models and protocols frequently, and even fewer noted that they are not relevant to their work.

Photo by Bruce G. Marcot

We asked decisionmakers why they used any of the 10 SDM approaches and allowed them to indicate multiple reasons (figure 5). Most respondents (69 percent) said SDM approaches provided greater clarity or transparency to the decision process, 43 percent said they helped mitigate controversy and conflict, 43 percent said they provided protection against litigation, and 24 percent said they simplified risk management. Only 12 percent of respondents said they did not use any SDM approaches; however, only 17 percent of respondents noted that using the SDM approaches saved time. Clearly, the main reasons for using such SDM approaches pertained to improvement of the decision process and bolstering against informal or formal conflicts, rather than saving time in the decision process. As stated previously in this report, however, increased time in the decision process may still lead to overall time savings due to reduced time spent in appeals and litigation. In addition, of those respondents that had used some SDM approach, a full 91 percent noted that they were very satisfied, satisfied, or somewhat satisfied with the outcome (figure 6). This result is strong testimony of the value and utility of SDM approaches.

When asked about impediments to using SDM approaches (figure 7), most (73 percent) respondents did not know enough about the SDM approaches, with fewer (20 to 30 percent) stating that it is difficult for the public to understand them, that colleagues are not aware of or are resistant to using them, that it does not apply to their work, and that it appears to take too much time (figure 7).

Only 15 percent of the respondents noted that using SDM approaches is not better than what is done now, and only 2 percent noted that using SDM approaches makes the decision process too transparent and vulnerable to appeals and litigation. Thus, most of the reasons given for not using SDM approaches pertained to knowledge gaps, education, and application of those approaches, with very scant concern about additional burdens or making the decision process more open.

Respondents noted a wide array of management problems for which SDM approaches would help. These approaches included the following line items.

- Evaluating consequences and analyzing tradeoffs.
- Monitoring and adapting to results.
- Addressing controversy and conflict with stakeholders.
- Providing greater credibility to the decision process to reduce the likelihood of litigation and appeals.
- Developing evaluation criteria and defining alternatives.
- Identifying and framing problems and articulating objectives.
- Identifying uncertainties.

The least frequent problem noted was choosing and implementing an alternative. This statistic suggests that respondents viewed SDM approaches as potentially more helpful for the early stages of the SDM process than for the decision point and implementation stages.

Figure 5.— Survey results asking respondents why they used listed decision-support procedures or tools, ranked in order of most to least prominent factor.

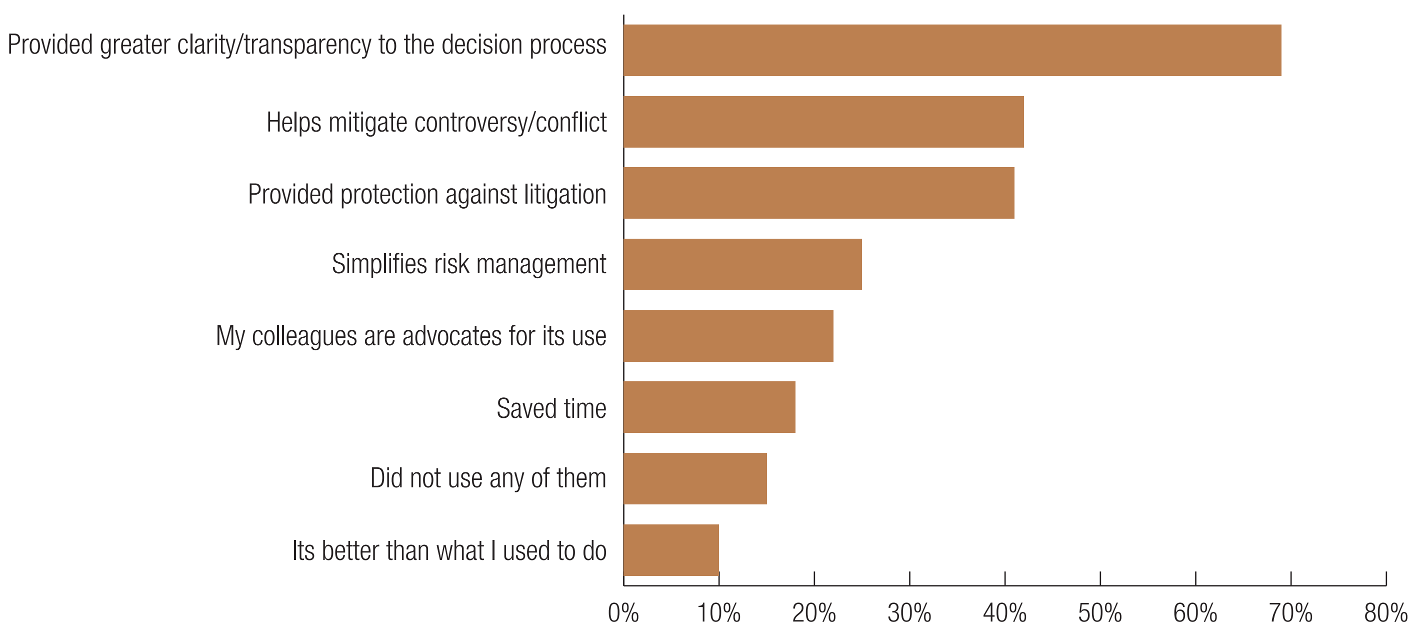


Figure 6.— Survey results asking respondents how satisfied they were with outcomes after having used listed decision-support procedures or tools

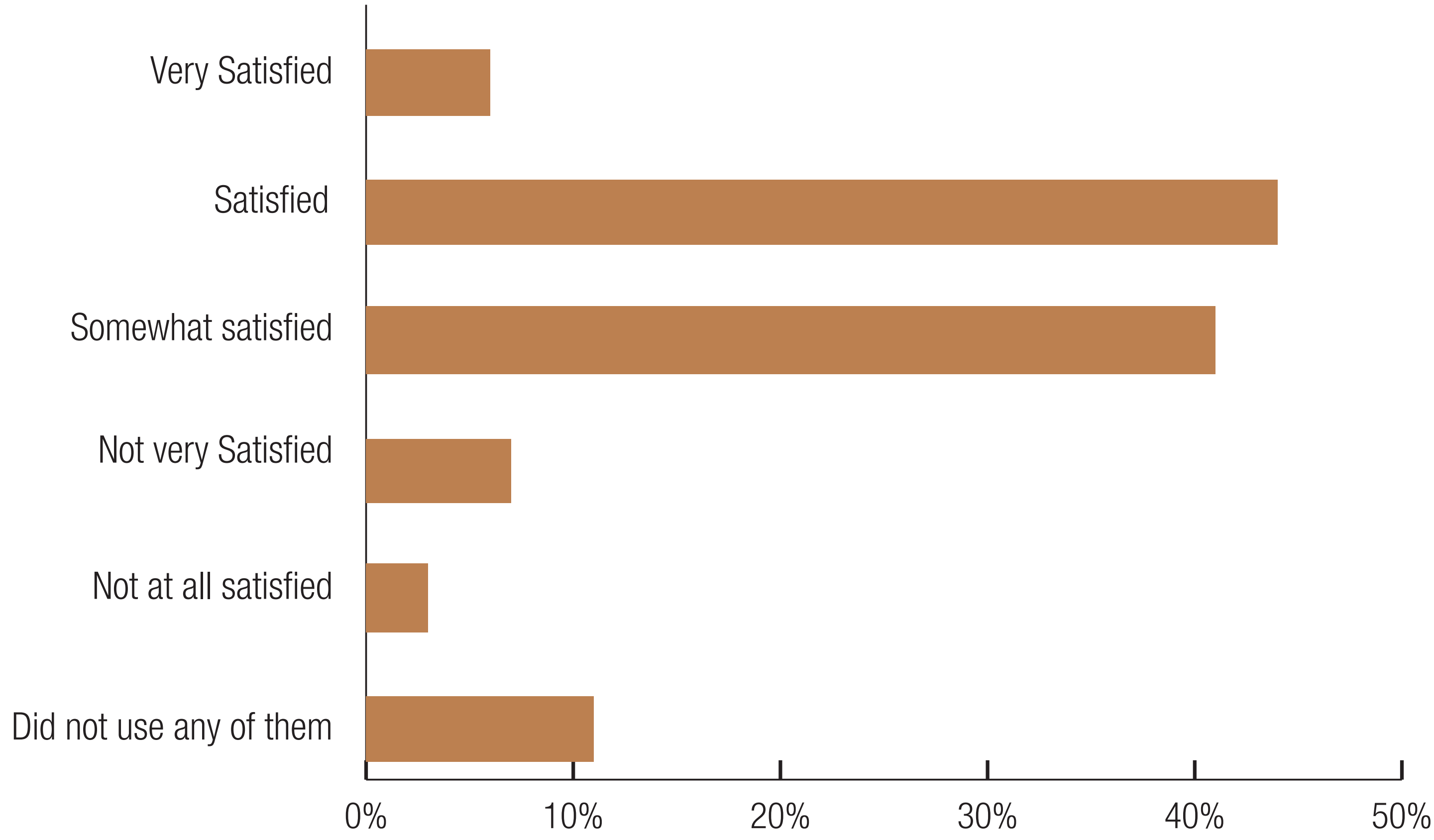
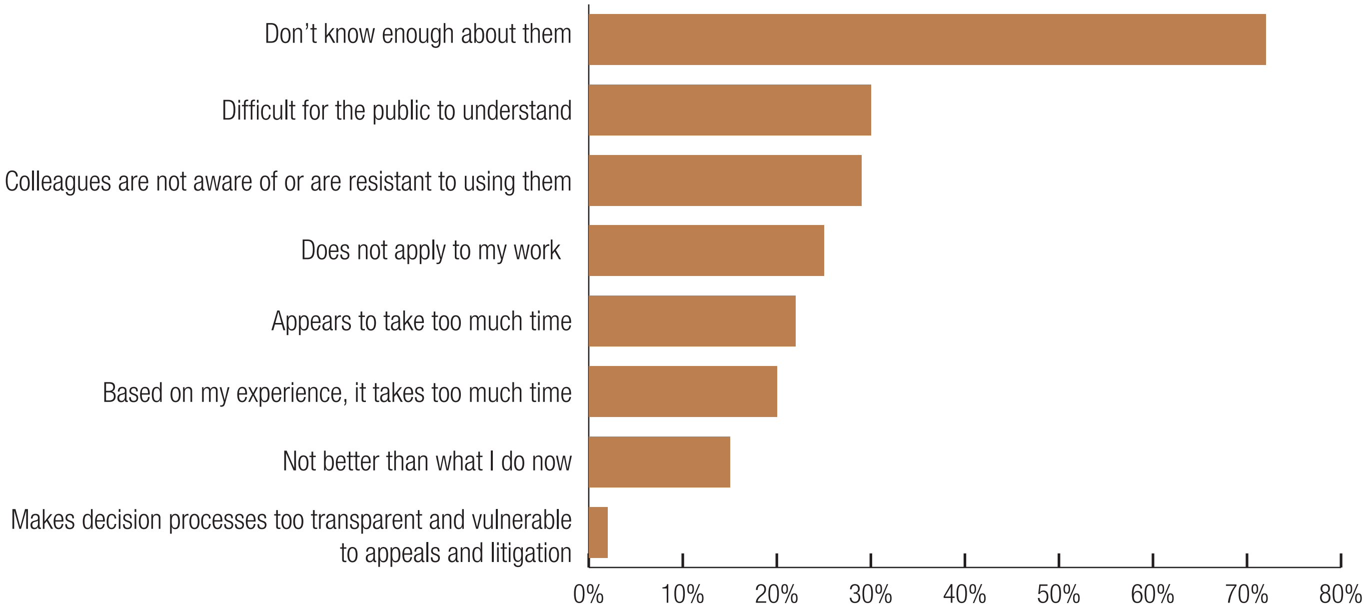


Figure 7.— Survey results asking respondents what impeded them from using listed decision-support procedures or tools, ranked in order of most to least prominent factor.



4.2 Survey Results on Decision-Support Methods and Impediments to Their Use

Our survey also provided insights into knowledge gaps, needs, desires, and concerns over risk analysis and SDM tools and methods. When asked what decision-support processes or methods for risk analysis or risk management they use in addition to the lists provided in the survey, many respondents suggested that decisions are made without recourse to formal procedures. Some sample comments we received in the survey follow:

- [I use] common sense and 40-plus years experience.
- Most decisions are made without formal use of a "method or process" and involve the need to meet targets for accomplishments or respond to some agency or public demand and are based on either common sense or the will of the decisionmaker or person pushing the decision.
- Engaging in conversation, reading materials, and determining a course of action based on that information and what I believe is "right" for the resource.
- In my experience, risk analysis and management is nearly never a formal process for line officers, with the exception of documentation for fires in WFDSS [Wildland Fire Decision-Support System]. It is usually a well-informed assessment made without a formal process after talking with staff.
- [I use] learned experiences and follow what is in the agency handbook.
- In more than a decade as a line officer, I have never heard of a line officer using a decisionmaking model.

Some respondents noted that they use additional, formal procedures, however, such as in the following comments:

- Comparison of alternative effects to soil, water, vegetation, and plans.
- Decision-support tools—frequently (when they are required).
- Really it has been the NEPA process—purpose, need, public input, comparison of alternatives, decision—that I have used. Sometimes I go with my professional opinion (i.e., gut) on some issues that cannot be analyzed in perpetuity, and, of course, I consult my staff and partners on direction and decision.
- Use multicriteria decision-support and ecosystem management decision-support for programmatic planning.
- We do a LOT of budget modeling of forecasts, alternatives, scenarios, and trade-offs—I would say nearly monthly.

The SDM survey results also provided insights into what many respondents noted as high work load and work-related stress that impede interest in and use of SDM approaches. For example, regarding the general kinds of resource management issues they are dealing with, the respondents made the following comments:

- "High level of recreational use on the District—no recreation staff—keeping it going with public pressure and concern is [a] continuous effort."
- "High Priority: Explaining to the public what restoration is and how that is different than how we use to manage the forest."
- "I work on a national grassland. Our major management issues revolve around multiple use and resource conflict management, Forest Service Sensitive and MIS [management indicator species] population and habitat management, and interactions with adjacent landowners within a very fragmented landownership pattern."
- "The topics analyzed depend much less on environmental concerns and much more on risk analysis ... I think most FS [Forest Service] analysis these days is all about litigation and political sell and very little about true environmental concerns!"
- "Watershed health and T&E [threatened and endangered species] protection are critical to my mission work. Helping the forested landscapes heal after years of aggressive harvest and gypo logging methods while still providing commodities and supporting forest health ... A sound approach to forest management allows us to protect our resources while still providing multiple use values."

When queried about what might be impediments to use of SDM approaches, respondents made the following statements.

- "That is not the way we do it."
- "Do not have enough time to learn a new process."
- "I participate mostly at project level planning, seems these tools would be more useful at forest level or above."
- "Another thing about NEPA analysis is that we need to resist appearing to know more than we actually do. NEPA simply requires a comparison of alternatives, not accurate predictions or perfect knowledge. The time factor is one that could be managed more effectively if leadership set clear priorities, but this has not happened in the 11 years I have worked on this forest and I do not expect it to change. Given people's huge work load, time is a real constraint."
- "Currently all of the risk management done here is on the political ability to implement a decision. No consideration is made about environmental risks."
- "I need more open and positive relationships with collaborators and stakeholders to get past differences in ideology, find areas of agreement and develop solutions."

Additional reasons cited as impediments to the use of SDM approaches often included lack of time and funding, lack of supervisory interest or support, that they seem unnecessarily complex, and lack of access to the tools and knowledge to use them. A number of respondents also worried that spending time with computers and models takes away from valuable and irreplaceable field time. Others cited the value of SDM approaches, however, although many more highlighted lack of funding, staffing, and time as major impediments to their use.

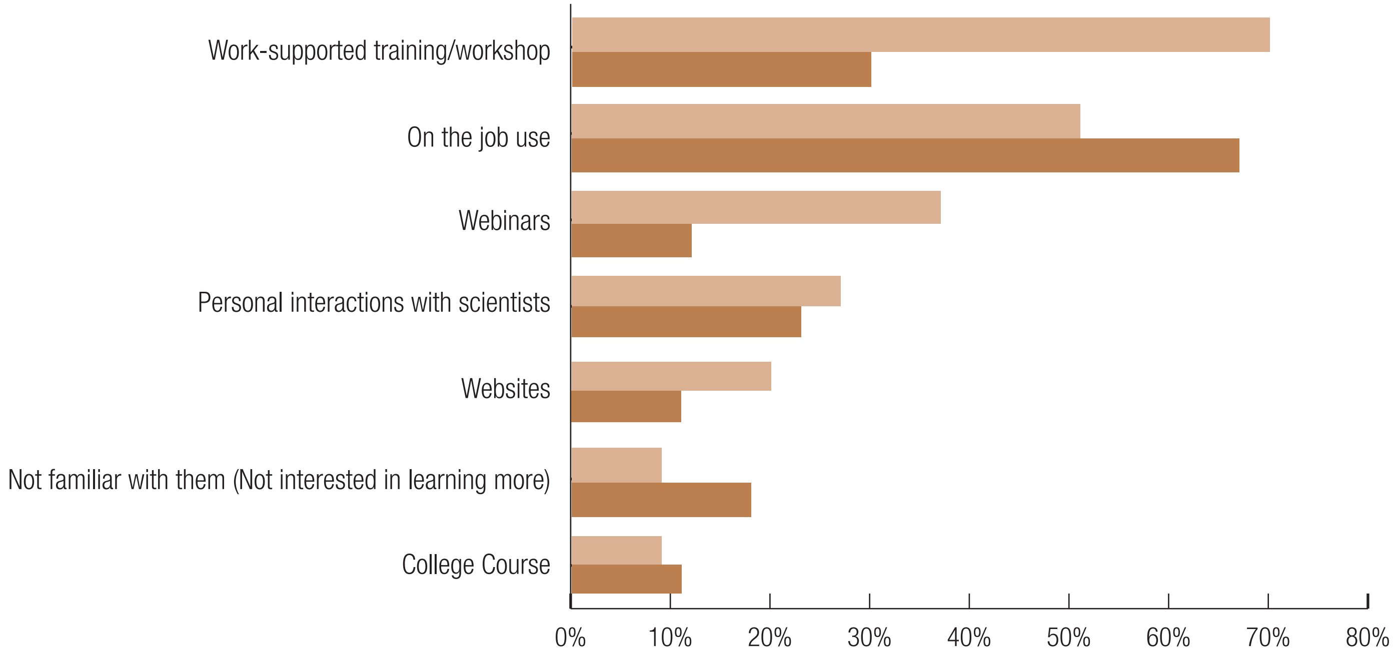
4.3 Survey Results on Needs for Structured Decisionmaking Training

We found NFS personnel have learned about risk management and decision-support procedures and tools from a wide variety of sources: 68 percent from on-the-job experience dealing with appeals, litigation, and NEPA procedures; 40 percent from work-supported training and workshops; 24 percent from personal interactions with scientists; 15 percent from webinars; 13 percent from Web sites; and 11 percent from college courses (figure 8). Some 18 percent of respondents noted that they are not familiar with such procedures and tools. Additional potential sources of learning included: conferences and workshops held by various professional societies, particularly on fire issues; leadership training; colleagues and networking; and incident management teams and fire management leadership.

When asked how they would like to learn more about SDM approaches, most asked for work-supported training and workshops (noted by 70 percent of respondents, figure 8), followed by on-the-job use (52 percent), webinars (37 percent), and Web sites (20 percent). In addition, some would like to learn through personal interactions with scientists (28 percent) and a few by taking college courses (9 percent). Some 10 percent noted that they were not interested in learning more about these topics. Additional suggestions for ways to learn more included how-to guides, guidance from a knowledgeable mentor, consultation with NEPA coordinators, publications, and terse case studies.

Many respondents also expressed concerns suggesting that SDM approaches may be overly complex and inappropriately applied to project-scale decisions; that risk analysis is equated with undue constraints on operations because of mandates on safety; and that models in general are inaccurate, take away from field time, are too complex to explain to the public, and are used to justify premade decisions.

Figure 8.— Survey results asking respondents how they currently learn about decision-support approaches (Current Learning) and how they would prefer to learn about decision-support approaches (Preferred Learning), ranked in order of most to least prominent areas for preferred learning.



4.4. Institutionalizing Structured Decisionmaking: Recommendations for Policymakers

Decision science is solidly grounded in theory and practice. As decision analysts and decisionmakers apply the concepts and tools of SDM, they are rapidly developing sets of best practices for high-quality decisionmaking. With training of analysts and decisionmakers alike, SDM can become an overarching framework and formalized decision structure for decisions made under the NFS Land Management Planning Rule, and a defensible and rigorous means of meeting regulations under NEPA and related directives. The SDM approach can address the complexities of sustainable natural resource management in many venues. Ultimately, application of SDM can help the Forest Service effectively and efficiently achieve sustainable management of forest and grasslands. SDM can be a powerful tool if embedded in the broader context of social decisions that guide management of public natural resources.

The real challenge in any agency or institution is how to bring these useful tools, approaches, and processes into daily implementation. We offer four general recommendations pertaining to more effective use of SDM tools and procedures.

- Analysts and planners can be equipped to provide guidance to management on decision support.
- Scientists and researchers can clearly explain the underlying logic of predictive models so they can be used appropriately in decision contexts, and can clearly articulate to help prioritize studies for adaptive management programs.
- Decisionmakers and managers can foster a transparent and defensible basis of their decisions, big and small, and work efficiently and closely with their support staff and stakeholders to identify important values in decision criteria.
- The agency can develop mechanisms that reward and support communication and interaction between scientists and users of scientific knowledge in the decision process (Pouyat et al. 2010). More specific suggestions for areas of training are provided in table 8.

Table 8.— Some suggested themes and purposes for training in the area of structured decisionmaking.

Theme	Purpose
Types of uncertainties and their characteristics	For building a common lexicon
Use of influence diagrams	For encouraging stakeholder involvement in problem definition
Role of uncertainty analysis, sensitivity analysis, and scenario analysis	For analyzing alternative actions
Structured incorporation of expert knowledge and judgment	For dealing with incomplete data and using available expertise
Application of multicriteria decision analysis and related techniques	For identifying and incorporating diverse preference attitudes across stakeholders, and for transparently documenting decision rationales
Comparative risk assessment	For evaluating and comparing and contrasting consequences of various management alternatives

5. Applications of Decision Science Principles in Forest and Grassland Management

5.1 Case Study 1: Problem Structuring: The National Cohesive Wildland Fire Management Strategy (Cohesive Strategy)

The Cohesive Strategy is an ongoing collaborative process with active involvement of all levels of government and nongovernmental organizations, as well as the public, to seek national, all-lands solutions to wildland fire management issues (http://forestsandrangelands.gov). To ensure a shared vision, participation, and commitment and support for strategy implementation, problem structuring is a critical step for this multistakeholder, complex issue. We briefly review the use of two decision-support approaches that facilitated problem structuring.

Decision-Support Approach #1: Objectives Hierarchy

Regional Strategy Committees are tasked to develop regional goals and objectives in wildland fire management through a collaborative process under the Cohesive Strategy. Regional teams comprised of a variety of stakeholders representing government and nongovernmental organizations, as well as the public, were able to collaboratively create objectives hierarchies by adhering to a structured process of problem framing and objective definition. All hierarchies are tiered to the three overarching goals: (1) Restore and Maintain Landscapes—landscapes across all jurisdictions are resilient to fire-related disturbances in accordance with management objectives; (2) Fire Adapted Communities—human populations and infrastructure can withstand a wildfire without loss of property; and (3) Wildfire Response—All jurisdictions participate in making and implementing safe, effective, and efficient risk-based wildfire management decisions. We present an abbreviated objective hierarchy related to the third goal—Wildfire Response. The hierarchy contains high-level and low-level fundamental objectives, supported by means objectives.

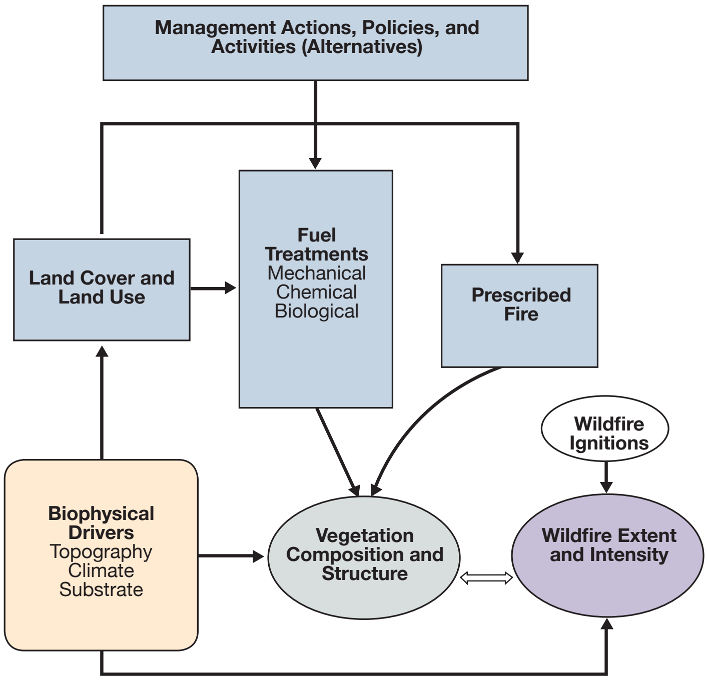
All jurisdictions participate in making and implementing safe, effective, and efficient risk-based wildfire management decisions.

- Protect the health and safety of wildfire responders
  - Improve safety awareness and avoid unnecessary risktaking by all firefighters.
  - Use technology or specialized equipment to minimize firefighter exposure in difficult situations.
  - Minimize firefighters' exposure to smoke or other toxic substances in the short and long term (chronic).
  - Provide adequate personal protective equipment and training across jurisdictions.
  - Ensure effective communication among all responders.
- Maintain fire response effectiveness.
  - Strategically align resources (personnel and equipment) across jurisdictions.
  - Improve cost-share and grant programs to leverage resources.
- Ensure that wildfire suppression response reflects strategic landscape objectives or landowner values.
  - Tactically integrate wildfire use with prescribed fire or mechanical treatments, when appropriate.
  - Ensure that suppression effectiveness is balanced against long-term objectives and landowner or management priorities.

Decision-Support Approach #2: Influence Diagrams

Another critical component in structuring the problem was establishing a shared understanding of the impacts of wildfire, and what management actions and alternatives might be available to ultimately mitigate wildfire risk. Iteratively developing and revising influence diagrams helped provide a shared conceptual model of wildfire, and a common understanding of how specific management actions can affect specific components and processes. Figure 9 illustrates one such influence diagram developed through this process.

Figure 9.— Influence diagram examining how various management activities (land cover and land use change, fuel treatments, and prescribed fire) may influence factors driving wildfire extent and intensity. (Danny Lee, Eastern Forest Environmental Threat Assessment Center).



5.2 Case Study 2: Problem Structuring and Analysis: Hoosier National Forest, 2006 Land Management Plan

Problem framing for the Hoosier National Forest (HNF) plan began in 1999 when the HNF completed an assessment with public input on the need for change in the forest plan and then issued a notice of intent to revise the 1985 forest plan. Based on the need-for-change assessment and public input on the notice of intent, the HNF framed the problem around three issues: maintenance of watershed health; ecosystem sustainability and viability of plant and animal populations; and recreation management. The HNF then identified objective criteria that would be used to compare alternatives. Based on species viability assessments conducted by the HNF with species experts and an ecological assessment of the region (Thompson 2004), the HNF identified 19 focal species that would serve as indicators of the ability of alternatives to maintain viable populations of native and desired nonnative species. Additional criteria reflecting watershed health, ecological sustainability, and recreation opportunities were the spatial and temporal distribution of forest age classes and dominant tree composition.

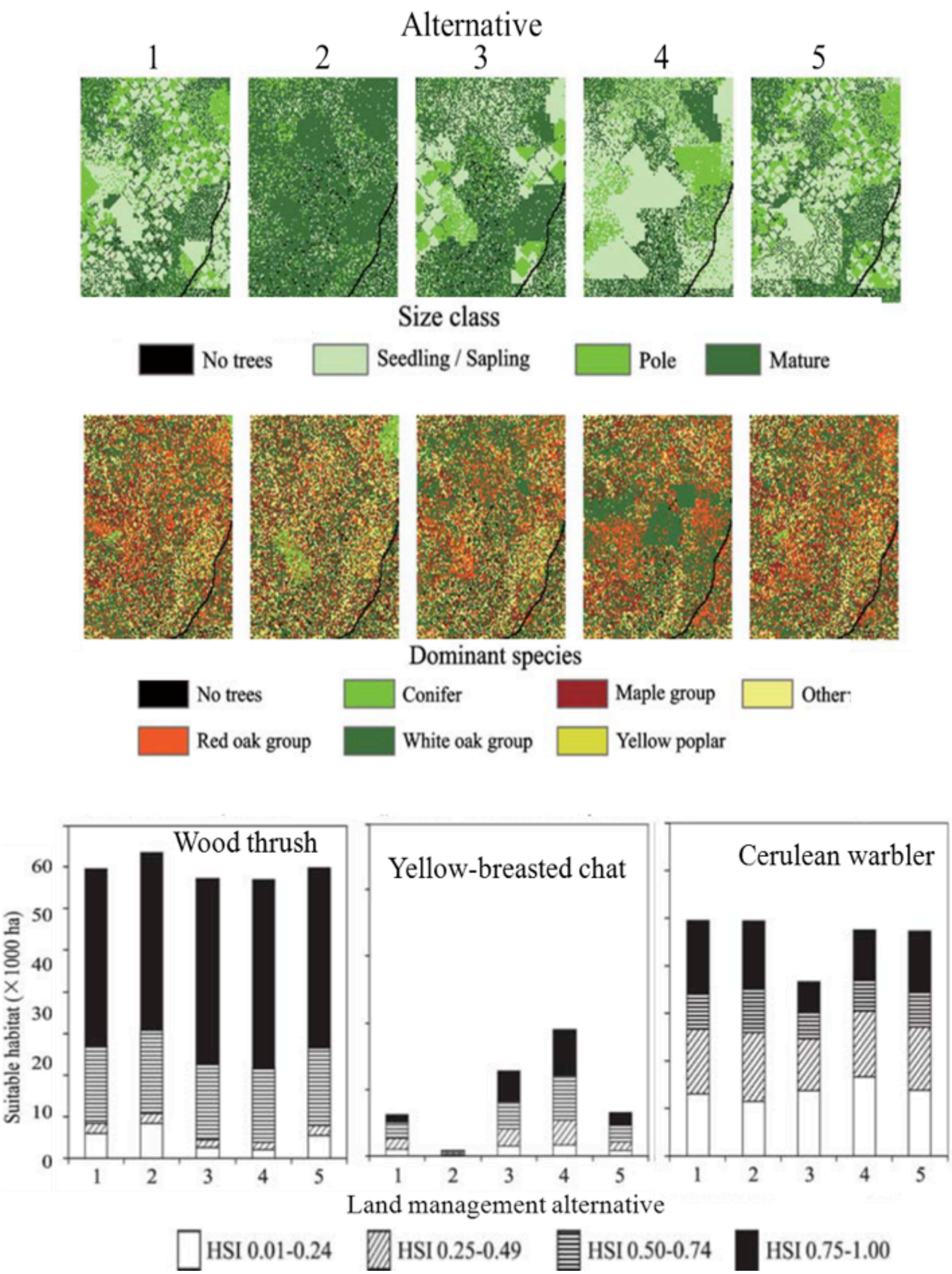
Problem analysis consisted of defining five forest plan alternatives, evaluating the consequence of these alternatives through simulation analysis, and considering tradeoffs among alternatives (Rittenhouse et al. 2010). The five plan alternatives were developed considering the issues raised in the need-for-change assessment and public input. They differed primarily in the amounts and types of forest management and ranged from no timber harvest to different amounts and spatial distribution of even- and uneven-aged forest management and prescribed burning. The forest plan alternatives were simulated with the spatially explicit landscape model LANDIS (He 2009), which modeled management activities, succession, and natural disturbance for each alternative more than 150 years and resulting effects on the spatial and temporal distribution of forest age classes and tree composition (figure 10). Predictions from LANDIS were then assessed with wildlife habitat suitability models to determine the effects of plan alternatives on indicator species (figure 10).

The tradeoffs among forest plan alternatives in wildlife species habitat suitability and forest composition and age class distribution were qualitatively assessed by the planning team and discussed at public meetings using graphical and tabular summaries of model outputs. While formal analytical methods were not used to evaluate tradeoffs and make a decision, the team did weight species differently based on their conservation status when qualitatively assessing tradeoffs. A decision was reached by a consensus recommendation from the planning team to the regional forester, and the regional forester selected the alternative recommended by the planning team (USDA Forest Service 2006). Recognizing that perfect information is impossible and anticipating that new scientific information may become available, the plan proposes an adaptive management approach involving monitoring and a process for amending the plan when needed.

5.3 Case Study 3: Decision Point: Deschutes National Forest, Five Buttes Project

In the National Forest System, the publication of a Record of Decision (ROD) is the culmination of a process incorporating the science supporting the environmental impact statement and the values of agency officers and stakeholders. A good example of this process is the ROD describing the rationale behind a vegetation and fuel-treatment project implemented on the Deschutes National Forest in Oregon, called the Five Buttes Project (USDA Forest Service 2007). The broad goals of the Five Buttes Project were to increase resistance to widescale fire and related disturbance events and to retain large trees, while also providing forest products and supporting local and regional economies. In particular, the project focused on reducing the risk of catastrophic wildfire and associated loss of old-growth forest habitat for the northern spotted owl (Strix occidentalis caurina). The project considered a no-action alternative (A), as well as two alternatives (B and C) that differed in extent and intensity of timber harvesting (commercial and noncommercial) and prescribed burning activities. Implementation of alternative B would result in a larger commercial harvest and associated mill activity, whereas alternative C emphasized modification of fire behavior and retention of spotted owl habitat, treating a larger area but yielding less commercial forest products. Alternative C also included commercial harvest of trees more than 21 inches in diameter and the modification of spotted owl nesting, roosting, and foraging (NRF) habitat, proposals which were the subject of public controversy.

Figure 10.— Predicted patterns in tree size-class and species distribution on a management compartment and predicted area in habitat suitability classes for three bird species on the Hoosier National Forest at year 50, fewer than five land management alternatives. (Rittenhouse et al. 2010)



The project was one of the first to use spatially explicit burn probability modeling techniques for analysis of consequences (Ager et al. 2007). This approach enabled improved estimation of fuel-treatment effects on wildfire behavior, and refined analysis on the basis of comparative wildfire risk assessment. Results indicated that the no-action alternative increased risk of widescale disturbance, while providing no economic benefit. By contrast, results indicated that Alternative C best interrupted wildfire travel routes across the landscape and best provided for overall disturbance risk reduction and long-term maintenance of spotted owl habitat.

The forest supervisor ultimately selected the third alternative (C), stating that it provided the "best combination of commercial and noncommercial activities to reduce risk and improve forest health on the landscape while maximizing the retention of desirable habitat features, including late- and old-structured forest for wildlife species that are dependent upon those habitats" (USDA Forest Service 2007). Notably, the ROD explicitly identified tradeoffs, especially "risk-risk tradeoffs," that is, risks of inaction compared with risks of action. The supervisor stated that thinning within late- and old-structured forest stands was a necessary tradeoff to effectively reduce landscape-scale disturbance risk. The ROD also directly addressed stakeholders' concerns over commercial removal of large trees, acknowledging that ecological objectives ultimately outweighed economic objectives.

Photo by Bruce G. Marcot

5.4 Case Study 4: Implementation and Monitoring: Tongass National Forest, Implementation and Monitoring Plan

The Tongass National Forest completed a review and amendment of its land and resource management plan (LRMP) (USDA 2008a, 2008b) that directed plan implementation to include monitoring and evaluation under an adaptive management strategy. The design and sampling methods are stipulated in the LRMP monitoring protocol guidebook (USDA 2005). Three kinds of monitoring are specified in the LRMP: (1) implementation monitoring, to determine if the plan management standards and guidelines are being fully and correctly implemented; (2) effectiveness monitoring, to determine if the management standards and guidelines actually help achieve the plan objectives; and (3) validation monitoring, to determine if the assumptions and predictions underlying the plan are accurate and valid. Monitoring results are evaluated and, in an adaptive management framework, used to revisit management standards and guidelines, budgets, and work plans, and to determine if new courses of action are needed to respond to changing conditions. Monitoring reports on the Tongass National Forest are completed at 1- and 5-year increments, the former providing time-critical reviews and the latter providing more comprehensive evaluations of plan implementation progress and results.

The 2010 annual monitoring and evaluation report tracks a number of metrics and conditions broadly grouped into three themes: physical and biological environment, human uses and land management, and economic and social environment. For each theme and metric to be tracked, the LRMP monitoring protocol guidebook: provides a clear summary question and more detailed goals and objectives; identifies, by name, the responsible staff, authors, and specialists; and specifies data collection procedures, evaluation criteria, guidelines on desired precision and reliability of monitoring results, and general analysis methods to be used. As an example, one part of biodiversity effectiveness monitoring pertains to the question, "Are the effects on biodiversity consistent with those estimated in the Forest Plan?" The LRMP monitoring protocol guidebook specifies that Geographic Information Systems be used to measure the cumulative harvest of old-growth forest by biogeographical province. As part of the adaptive management process, some of the monitoring questions were changed in the recent LRMP amendment from those in the previous plan to better focus on more appropriate or recent topics of scientific and social interest, and some monitoring protocols are still being developed. Some of the results from the annual monitoring report of 2010 have been used, however, for reevaluating or reaffirming management direction. For example, results of effectiveness monitoring of old-growth forests protected under the LRMP to support viable and well-distributed populations of old-growth-associated species and subspecies suggested that current guidelines are adequate for this objective. In this case, a decision was made to not change the spatial distribution, size, and composition of protected old-growth forest reserves and other

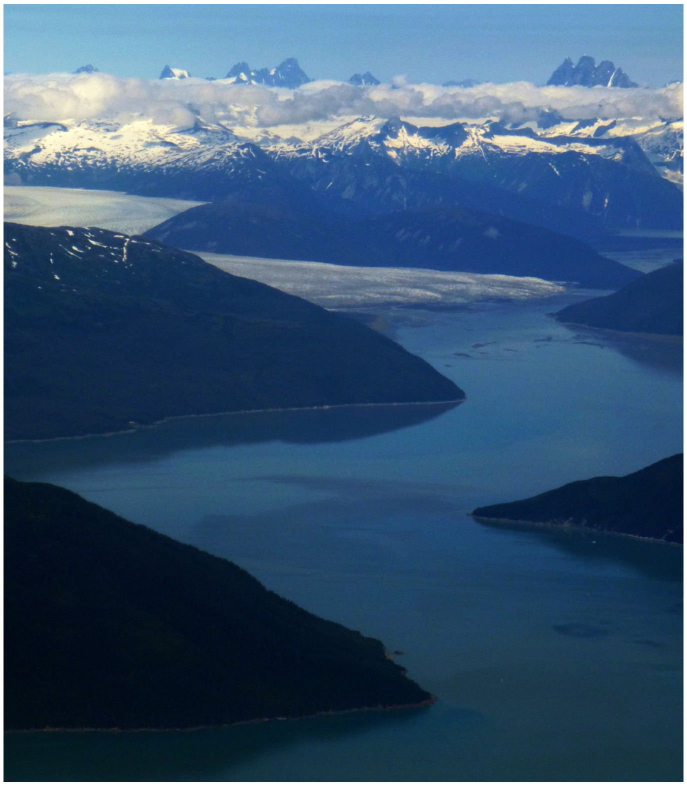


Photo by Bruce G. Marcot

nondevelopment land use designations as currently denoted in the LRMP implementation guidelines. Use of other monitoring results awaits completion of the next comprehensive 5-year monitoring report due in 2013, and during the next LRMP revision which, by mandate of the National Forest Management Act, is to occur every decade.

5.5 Case Study 5: Monitoring and Adaptive Management: The Survey and Manage Program of the Northwest Forest Plan

The Northwest Forest Plan (NWFP) was instituted in 1994 and is a set of guidelines for conservation of old-forest biodiversity on 9.7 million hectares (24 million acres) of Federal public lands of the Pacific Northwest United States, particularly for ensuring the persistence of hundreds of species closely associated with late-successional and old-growth (LSOG) forests. One part of the NWFP is the Survey and Manage (SM) Program, which is a highly structured procedure for a mixed panel of biologists and managers to evaluate recent monitoring data on rare and little-known LSOG-associated species and to assign the species to appropriate conservation categories under the NWFP (USDA Forest Service and BLM 1994, 2001). As the evaluation panels have been held annually, the SM Program thus serves as an adaptive management framework for incorporating new scientific monitoring information and adjusting species conservation goals and activities accordingly.

The suite of species addressed by the SM Program includes bryophytes, fungi, lichens, mollusks, selected vertebrates, and functional groups of arthropods, which may be associated with late successional forests, which are 80 to 200 years old, or old-growth forests, which are more than 200 years old. Under the NWFP, each SM species is put into one of six conservation categories that vary by the type and intensity of surveys required, or into a seventh category in which the species is no longer deemed to require special considerations under the SM Program and is thereby removed from the SM species list (but is still presumed to be conserved under the overall NWFP forest management guidelines) (Molina et al. 2006).

In the SM Program procedures, first, taxa experts compile data on the natural history, occurrence, and ecology of each SM species for which substantial new information is available that might change scientific understanding of species and of their conservation needs. Second, the taxa experts present the new information to the evaluation panel, which consists of four natural resource managers and four natural resource specialists, including biologists. The evaluation panel then deliberates over the information and uses a strict Delphi paneling approach, involving a structured series of steps by which panelists vote, discuss, and revote on their recommended conservation category for each species. The panel's final recommendations are then sent to an interagency decision-making board that provides the final choices on the disposition of each species.

To aid the evaluation panel's deliberations, a decision-support tool was developed by which the SM species evaluation guidelines were codified, in a set of Bayesian network models (Marcot et al. 2006). The models were run using the taxa experts' new information on each species, and provided an initial suggestion of which species conservation category might be consistent with the new information. The models were not prescriptive but aided the evaluation panelists in dealing with the complicated and potentially conflicting conservation guidelines. The models also served to reduce bias and uncertainty in evaluating the new information on each species.

Eventually, the complexity and scope of the SM Program led to its temporary termination after lawsuits were filed in 2001 by timber industry and environmental groups. The SM Program was later reinstated under court order and, as of this writing, is being revised in a more streamlined structure, but is still to serve as a key monitoring and adaptive management component of the NWFP guidelines.

5.6 Case Study 6: The Full Picture: Nonnative Fish Control Below Glen Canyon Dam

The Glen Canyon Dam is located on the Colorado River upstream of Glen Canyon National Recreation Area and Grand Canyon National Park and is managed by the Bureau of Reclamation (Reclamation) for water storage, hydroelectric generation, and other benefits. In a 2008 Biological Opinion under the Endangered Species Act, the U.S. Fish and Wildlife Service found that the dam's operations may affect the humpback chub (Gila cypha)—a federally listed endangered native Colorado River fish—and included nonnative fish control as a conservation measure. Rainbow and brown trout had been introduced into the Colorado River and may pose a threat to humpback chub through predation on juvenile chub, habitat exclusion, and competition for food resources. Trout removal (through electrofishing) had been experimentally implemented in the early to mid-2000s, and Reclamation was considering making this program a part of regular operations. Several North American tribes raised serious concerns and objections about the lethal removal of thousands of fish from their sacred area. Besides the location of the proposed removal, a number of tribes consider all life sacred and object to the killing of nonnative fish. In response, Reclamation deferred undertaking plans for nonnative fish removal and initiated development of an Environmental Assessment (EA) under NEPA to evaluate alternative methods for nonnative fish control in 2010.

A formal structured decisionmaking (SDM) process was convened to help in development of the EA. In the **problem structuring** phase, the Reclamation's Upper Colorado River Regional office was clearly identified as the sole decisionmaker for the EA. Representatives from six Federal agencies, one State agency, and five tribes were invited to participate in the SDM process as stakeholders to provide scientific and policy input to Reclamation for its consideration as part of its decisionmaking process. Assessment teams were assembled to evaluate the nonnative fish control alternatives against the array of objectives. Whereas Reclamation and other stakeholders provided value-based information regarding framing the problem and defining and weighting objectives, the assessment team was to be responsible for science-based information, primarily throughout the problem analysis stage. The decision was viewed as a multiple-objective tradeoff problem under uncertainty; formal methods of multicriteria decision analysis (MCDA) and value-of-information were used to analyze the alternatives (Runge et al. 2011b).

At the heart of the conflict among the stakeholders was a rich set of 22 fundamental objectives, hierarchically structured around 5 main themes: (1) protecting tribal sacred sites and spiritual values, including the sanctity of life and the sacredness of the Canyon; (2) promoting ecological and native species integrity, including humpback chub recovery; (3) preserving and enhancing recreational values and uses, including enhancing the rainbow trout fishery and providing a wilderness experience for visitors to the Colorado River and Glen and Grand Canyons; (4) maintaining and promoting local economies and public services, including hydropower generation and water delivery in the arid Southwest; and (5) operating within the authority, capabilities, and legal responsibility of the Bureau of Reclamation. Stakeholders' input was sought to articulate and define these objectives and to develop evaluation criteria for measuring achievement of the objectives. While conservation of humpback chub and preservation of tribal cultural heritage were the central concerns that motivated the SDM process, it became clear that the full set of fundamental objectives needed to be considered and weighed to more comprehensively analyze alternatives and understand tradeoffs inherent in the problem.

In the **problem analysis** phase, Reclamation and stakeholders' groups used insight about objectives to generate alternatives for consideration in the EA. These alternatives were complex portfolios that considered the degree and frequency of nonnative fish removal, the location of removal, the methods (lethal and live) of removal, and the disposition of the fish removed, as well as other strategies meant to reduce the effect of trout on humpback chub (such as flow management from the dam and trout fishery management). Again, stakeholders' input was used to craft the alternative portfolios—the representatives worked in small, mixed groups to develop alternatives with various themes (e.g., "No Action," "Status quo," "Culturally sensitive removal," "Removal curtain," "Kitchen sink"). In all, 27 alternatives were considered.

"From my perspective, one of the unique values of SDM, if you use it with stakeholders, is that it helps with the transparency of the decisionmaking process and their buy-in."

Glen Knowles
Adaptive Management Work Group
Bureau of Reclamation

Each of the 27 alternatives was evaluated against the 22 objectives. The evaluation took a number of forms, depending on the evaluation criteria associated with the objective. For some of the objectives, such as persistence of humpback chub, predictive models based on empirical data were available. For others, such as the expected catch rate in the trout fishery, some simple models could be constructed based on available data. For still others, expert judgment was used for the evaluation. One of the challenges in the evaluation was critical uncertainty that affected the ranking of the alternatives. For example, the causal relationship and interaction between rainbow trout predation and humpback chub population is disputed and uncertain. To handle this uncertainty, two competing models for that interaction were posited, and an expert panel was asked to weigh the evidence for the two models. Evaluation of the outcomes was made under both models and included in a value-of-information analysis to determine how much that uncertainty affected the choice of a preferred outcome.

Moving towards the **decision point** stage required an additional piece of information—preference weights for the multiple objectives. These weights were elicited individually from the stakeholder agencies and tribes using MCDA, and an integrated assessment of the alternatives against all the objectives was computed for each stakeholder group. Reclamation was not asking the stakeholder agencies for a consensus recommendation; instead, individual stakeholders' viewpoints were being sought, as a way for Reclamation to understand the differing perspectives. As it happened, the analysis resulted in identifying nearly the same preferred alternative for all agencies: a trout removal strategy that was focused about 60 miles upstream from the most sacred part of the Canyon (in the Paria-Badger Reach, PBR), which avoided, if possible, lethal removal and sought substantial beneficial use for the trout removed. This strategy was not one that any agency had promoted at the beginning, but neither was it one that was deeply objectionable.

Reclamation published a draft EA in January 2011, identified the PBR strategy as the preferred alternative, and included a detailed decision analysis as an appendix (Runge et al. 2011b). The SDM process was readily integrated with the NEPA process; indeed, the SDM report provided much of the raw material for the EA. Subsequent public comment, government-to-government consultation with the tribes, and additional scientific evaluation and analysis led to important modifications to the preferred alternative, including the inclusion of monitoring and adaptive management to address several key uncertainties. This modified PBR strategy was identified as the preferred alternative in the final EA and Finding of No Significant Impact, released in May 2012.

Now Reclamation is in a position to move forward with **implementation and monitoring**, having incorporated best available science for process and content. The SDM process provided a framework and tools for stakeholders' engagement, clear articulation of objectives, development of creative alternatives, formal evaluation of alternatives, deliberation over tradeoffs, and evaluation of uncertainty. In addition, it provided a detailed administrative record of how Reclamation approached, analyzed, and arrived at the decision, and it integrated well with the agency's NEPA compliance efforts.

Photo by Amy S. Martin

6. Adopting Structured Decisionmaking: Conclusions and Implications

"…the existence of decision analysis concepts as a language for communication may be its most important advantage."

Ronald A. Howard

6.1 A Change of Paradigm

Adoption of structured decisionmaking (SDM) may change the way resource managers think about decisionmaking, because it entails making values and preferences explicit while making decisions informed by science. Therefore, the decision context drives the science needs, not the reverse. SDM separates the clinical problem analysis process from the value-based decision process. This structure provides for a full consideration of science in all phases of the decision process. SDM requires commitment from decisionmakers and analysts to communicate and stay involved from the start. In the setting of natural resource management agencies, SDM calls for objective participation by conservation scientists, and transparent exposition and early articulation of decision criteria by decisionmakers. The independence of Research and Development and the National Forest System in the Forest Service provides a firm foundation for the objective delivery and application of science in the context of SDM, and more broadly in the sustainable management of national forests and grasslands.

The decision context drives the science needs, not the other way around.

6.2 Contemplating the Role of Uncertainty

For complex environmental and natural resource management problems, a need exists for explicit identification and analysis of uncertainties, clear articulation and separation of subjective and objective components, and a systematic framework for approaching decision analysis that includes explaining how uncertainties are used in developing evaluation and decision criteria. Different uncertainties and challenges present themselves at different stages of the decisionmaking process, and a wide variety of tools exist to address particular manifestations and aspects of decisionmaking under uncertainty (appendix B). Using SDM as an overarching framework can help to identify, critique, and discuss sources and implications of uncertainty, to support decisionmaking in the context of natural resource management.

6.3 The Challenge and the Promise Ahead

SDM is a template for considering data, knowledge, values, and uncertainty transparently in the decision process. Indeed, uncertainty—appropriately explained and displayed—is a form of useful information. Analysts and planners can present uncertainty in a useful light by evaluating its implications in tradeoffs among alternative actions, and by estimating the incremental value of additional knowledge. The decisionmaker's risk attitude will determine the implications of such uncertainties in practice (Cussen 2010).

Never has a better time existed to focus on enhancing decisionmaking. The coming years will demand closer attention to achieving and demonstrating tighter alignment with stated goals, despite increasing financial constraints and increasing social conflicts over natural resources. Decision processes will increasingly weigh environmental costs and benefits against those of economic development, social equity, and contribution to financial solvency.

SDM will not solve every problem, but it can improve transparency and clarity in decisionmaking processes. This review of SDM principles and concepts suggests that SDM can be helpful in a number of ways. Notable ways include deciphering, decomposing, and understanding complex problems that create the need for decisions; maintaining the sequences and internal consistency of the various stages of decisionmaking; articulating and quantifying values that guide the design and selection of alternatives; guiding the input from scientific, experiential, and traditional forms of knowledge; and organizing and documenting the logic of choice and tradeoff.

6.4 Summary

The craft of natural resource decisionmaking will be more demanding in the future, and it will require a more flexible toolkit to support decisions that address complex problems. Choosing decision processes and support tools in the face of new challenges may require multiple returns to the basics of decision support that have been discussed in this synthesis. Large-scale drivers of change—climate, demographics, global economic patterns, and changing social values—will increasingly provide surprises and uncertainties that will further shape decision spaces and prompt rethinking decisions already made. Resource managers will have to learn from the past without being shackled by it and use evolving tools to deliver the agency's mission. Adoption of decision science principles can help resource managers address these challenges more effectively and, ideally, will lead to improved decisions and effective actions supporting sustainable management of forests and grasslands.

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Appendix A: Guidance for Tough Choices

What Are the Practical Ways To Deal With Complex Decisions?

Below are some practical approaches and tactics (not necessarily mutually exclusive) that could help if you find yourself stuck at a crossroads when facing a tough decision.

1. How Did I Get Here?

First, you might ask—"how did I get here?" It may help to go back through the previous stages of the structured decisionmaking (SDM) process, recounted below, and ensure that the work performed up to the decision point stage is sufficiently clear and comprehensive and provides enough information to make a fully informed decision.

Problem Structuring Stage

Objectives and evaluation criteria

- Be sure that all key terms in your objectives and decision criteria are fully defined.
  - In simple English—articulating terms brings far greater clarity and may suggest further, guiding ideas, as words often have multiple meanings and connotations (linguistic uncertainty).
  - If appropriate, with threshold or acceptable values and clear units of measure (evaluation metrics).
- Simplify, combine, or exclude some of your objectives and decision criteria.
  - If some are redundant or highly correlated with others.
  - If some are illogical or clearly contradictory with others.

Problem Analysis Stage

Creating alternatives and evaluating their consequences

- Break the problem down into smaller, simpler problems that already have solutions or methods for solutions.
  - Separate out sequences of decisions and their effects into individual units.
  - Separate out type of effects or geographic areas affected.
- Simplify the range of potential alternatives.
  - Exclude outright alternatives that are infeasible or illegal.
  - Combine the remaining alternatives into a smaller set that are feasible and practicable, and that all meet the overall, initial decision objectives.
  - Identify those alternatives that are truly infeasible, illegal, or intractable, and the elements of decisions that would lead to them, in which case these elements may be ones to avoid in the final solution; call this the "painting the negative space first" approach.
- Work backwards from desired outcomes.
  - Clearly state your decision criteria.
  - For each outcome, write down several possible means by which it could be met.
  - Combine all these means into a single table with columns for decision criteria and rows for possible means; compare the performance of each alternative to this table and identify those alternatives that best meet the most decision criteria; and consider amending some alternatives if new solutions can be identified.

Tradeoff analysis—or, characterizing and distinguishing alternatives

- Title each decision alternative with a catchy name that best characterizes its main attributes.
  - Use this catchy name to help identify how alternatives differ in key ways, rather than how they are similar.
  - Restate each alternative and its potential consequences as a story, avoiding the use of math, probabilities, and numbers.
- Group the alternatives into a few, well-named categories.
  - Ensure that the first choice, if it exists, is among the general categories.
  - The next choice is among the (fewer) alternatives within that category(s).

2. Use Methods to Balance Alternative and Objectives

Second, you might turn to decision-support approaches that directly relate to the decision point stage itself and that provide guidance for balancing alternatives and objectives.

Decision Point Stage

Comparing performance of alternatives and examining sensitivities

- Consider your objectives and decision criteria one at a time.
  - Add them on incrementally and list which alternatives still meet the set.
  - Help narrow down the set of alternatives for fuller analysis by using this evaluation.
- Consider the effects of each of your decision criteria.
  - Think about how alternatives might rank differently if you were to drop each of the decision criteria individually (sensitivity testing of the criteria).
  - Consider alternative ways the most influential decision criteria could be met, perhaps outside the specific set of decision alternatives presented.

Think "outside the box"—beyond the specific decision context

- Consider the outcome of some similar problem already solved.
  - Use metaphor and analogy to reconsider the problem at hand. (This evaluation is a good heuristic to help discover a solution.)
  - Look at the uncertainties—think of a problem that has similar unknowns.
    - Focus on those key unknowns that are most uncertain and that might most influence the outcome (your decision) if known.
  - Consult with fellow decisionmakers on similar problems they may have addressed.
  - Find another situation in which the objectives have successfully been met, even if the problem statement per se was different, and see how they got there.
  - If you cannot find another similar problem, find one that has similar key unknowns and look at how the unknowns were handled in that solution.
  - Based on any of the above actions, find out if the problem, objectives, and perhaps even the decision criteria can be restated for greater tractability, clarity, and feasibility.
  - Exploit your success! (Polya 1973)
    - Determine if you can apply a successful approach, and solution, to another problem.

Turning to more formalized approaches (e.g., multicriteria decision analysis)

- Use an objective hierarchy approach.
  - Prioritize those objectives you initially laid out.
  - Rank each alternative according to how well the alternatives meet each objective.
    - Note that "How well" can be denoted by a probability or on a 1-to-10 scale.
  - Sum all the rankings, weighting them by the priority level of the objectives.
    - May establish priorities with ordinal scale (e.g., 1st, 2nd), or
    - May establish priorities with subjective weights.
  - Filter out the alternatives that fall below an acceptable threshold.
    - Or simply order the alternatives according to their rankings.
    - And then consider the top-ranked alternatives as best possible choices.
  - And consider that perhaps one decision criterion may pertain to the degree of reversibility of a decision.

Still Can't Make a Decision?

Ask yourself if not making a decision is more detrimental to the suite of objectives than is making a decision under uncertainty. Do not forget the key role of monitoring and adaptive management, although these actions do not substitute for a poorly made or ill-informed decision.

Appendix B: Tools and Approaches Useful in Stages of Structured Decisionmaking, With Examples of Applications.

Many tools or approaches can serve more than one stage. Types of uncertainty (see table 2) addressed by each tool or approach: LU = linguistic uncertainty, KU = knowledge uncertainty, VU = variability uncertainty, DU = decision or preference uncertainty.

Name of Tool or Approach	Use and Type of Uncertainty Addressed	Examples of Application
Problem Structuring Stage		
Cognitive mapping and modeling	Organizes and synthesizes system components and dynamics. LU, KU	Mendoza and Prabhu 2005 (participatory modeling and sustainable forest management), Wolfslehner and Vacik 2011 (forest management sustainability evaluation)
Influence diagrams	Represents key system parameters, decision points, and outcomes in a qualitative graph. Can be further developed into other quantitative model types (e.g., state and transition models, Bayesian network). LU, KU	Bashari et al. 2009 (rangeland management)
Decision tree	Diagrams choices, outcomes (utilities), and probabilities to evaluate expected values of alternatives; evaluates knowledge and preference (risk attitude) uncertainties; useful for all SDM stages. KU, VU, DU	Coops et al. 2011 (tree growth modeling), Failing et al. 2004 (adaptive management), Wan et al. 2009 (vegetation modeling)
Objectives hierarchy analysis	Helps resolve conflicting objectives, social values, and preferences. VU, DU	Maguire et al. 2004 (invasive species management)
Means-end objective network	Helps to identify causal relationships between actions and outcomes, and to connect means objectives to fundamental objectives. KU	Keeney 1996b (hydroelectric management)
Problem Analysis Stage		
Simulation modeling	A broad set of tools useful for modeling system dynamics and response to management; e.g., timber growth and yield, wildfire, hydrology, climate change, weather. VU, DU	Krawchuk and Cumming 2011 (forest fire under climate change), Vuilleumier et al. 2011 (invasive species control), Rittenhouse et al. 2010 (forest management, succession, and wildlife habitat)
Bayesian networks	Models the conditional dependence between variables accounting for prior knowledge. KU, VU	Aalders 2008 (land-use decisions), Dlamini 2010 (fire risk analysis), Aguilera et al. 2010 (species distribution), Galan et al. 2009 (reforestation)
Data mining	Analyzes relationships between numerous data fields in an existing database, gaining new knowledge. KU	Dlamini 2011 (vegetation mapping)
Fuzzy logic, fuzzy set theory models	Allows computation of vague and uncertain data using a membership function for data inputs. LU, KU, VU	Glenz et al. 2008 (flooding impact on woody species growth), Reeves et al. 2006 (evaluating watershed condition and aquatic habitat), Andreucci et al. 2000 (environmental responses of plant associations)
Rough set theory	Unknown values for data are represented by their approximated lower and upper bounds. KU, VU	Xie et al. 2011 (land cover data retrieval), Tan 2005 (life-cycle environmental burdens of products or processes)

Analytic hierarchy process (AHP)	Hybrid approach allowing for imprecise and vague definitions embedded within a hierarchy. Allows for joint consideration of objective and subjective information with expert judgment. KU, VU	Coulter et al. 2006 (forest roads), Hessburg et al. 2007 (wildfire danger, fuels treatments), Vadrevu et al. 2009 (fire risk evaluation)
Analytic Network Process (ANP)	Better for expert judgment use and capturing feedbacks and interdependencies, relative to AHP. KU, VU	Bottero et al. 2011 (wastewater treatment assessment), Wolfslehner et al. 2005, Wolfslehner and Vacik 2007 (sustainable forest management)
Rule and network induction	Results in rules or networks based on the relationship between a given set of attributes; networks can then be further developed as probability transition models or Bayesian networks. LU, KU, VU	Berger 2004 (crop suitability)
Neural networks	Allows modeling of nonlinear and unknown relationships. KU, VU	Ejrnaes et al. 2002 (habitat quality), Scrinzi et al. 2007 (forest distribution data), Lippitt et al. 2008 (species distribution model), Özçelik et al. 2010 (tree bole volume)
Reliability analysis	Assessment of the potential failures (probabilities and timing) of a system and their effects. VU	Chowdhury et al. 2009 (drinking water contaminants)
Scenario analysis	Considers multiple outcomes providing a range of alternatives and their likelihoods. KU	Bohnet et al. 2011 (sustainable landscape development), Dougill 2008 (grassland response to climate change)
Comparative risk assessment	Extends traditional risk assessment to include decision space available to managers and stakeholders to allow them to explore tradeoffs between alternative courses of action. VU, KU	Ager et al. 2007 (fuel-treatment strategies), Calkin et al. 2011 (wildland fire management)
Decision Point Stage		
Valuation and cost-benefit analysis	A family of stated and revealed preference models for establishing the value of nonmarketable goods and services. VU, DU	Champ et al. 2010 (hedonic pricing model and homebuyer wildfire risk perceptions), Holmes et al. 2004 (contingent valuation and riparian restoration), Rolfe et al. 2000 (choice modeling and tropical rainforest preservation)
Exact optimization methods	A variety of mathematical techniques that can identify a set of nondominated alternatives or a single best answer. Includes linear programming, nonlinear programming, integer programming, others. VU, DU	Thompson et al. 2010 (forest road erosion control), Toth et al. 2009 (spatial harvest scheduling with habitat objectives), Snyder et al. 2004 (reserve site selection)
Heuristic optimization methods	Iteratively update solution(s) through process of information exchange, self adaptation, and competition; entails perturbing decision vector, accepting and retain new solution(s) according to various criteria. Includes evolutionary algorithms, genetic algorithms, simulated annealing, tabu search, others. VU, DU	Icaga 2005 (water quality monitoring), Kennedy et al. 2008 (fuel-treatment planning), Ducheyne et al. 2004 (even-flow forest management), Madej et al. 2006 (sediment reduction and road removal)
Multiattribute utility theory (MAUT)	Defines a cardinal utility function according to all criteria, typically by defining performance of each. VU, DU	Merkhofer et al. 1997 (siting hazardous waste management facility), Moffett et al. 2005 (conservation planning)
Analytic hierarchy process (AHP)	Pairwise comparisons of attributes and criteria based on linguistic scale then converted to ratio-scale weights, which can be aggregated up through an objective hierarchy. LU, VU, DU	Darin et al. 2010 (invasive plant management), Wolfslehner et al. 2005 (sustainable forest management)

Simple multiattribute ranking technique (SMART)	Assigns criteria weights on 0–100 scale, by scaling weights for all attributes relative to the most important attribute, assigned 100. DU	Kajanus et al. 2004 (tourism management and sustainable development), Reynolds 2001 (salmon habitat restoration)
Stochastic multicriteria acceptability analysis (SMAA)	Family of methods designed to facilitate decisionmaking for contexts in which both criteria and preferences may be subject to uncertainty; based on exploring the weight space to describe the preferences that would make each alternative the most preferred one, or that would give a certain rank for a specific alternative. DU, VU	Kangas et al. 2003 (forest management plan development), Kangas et al. 2005 (natural resource management by Finnish Forest and Park Service)
Implementation and Monitoring Stage		
Multimodel analysis	Multiple models for evaluating various representations of expert knowledge, scales, and variable interactions. KU, VU	Rehme et al. 2011 (general application)
Multiagent systems	Models multiple interacting "agents" (programs, humans, or human teams), representing diverse interests, in role-playing scenarios. VU	Lynam et al. 2002 (rangeland management)

References—Appendix B

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