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# Recent advances in applying decision science to managing national forests

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ABSTRACT

Management of federal public forests to meet sustainability goals and multiple use regulations is an immense challenge. To succeed, we suggest use of formal decision science procedures and tools in the context of structured decision making (SDM). SDM entails four stages: problem structuring (framing the problem and defining objectives and evaluation criteria), problem analysis (defining alternatives, evaluating likely consequences, identifying key uncertainties, and analyzing tradeoffs), decision point (identifying the preferred alternative), and implementation and monitoring the preferred alternative with adaptive management feedbacks. We list a wide array of models, techniques, and tools available for each stage, and provide three case studies of their selected use in National Forest land management and project plans. Successful use of SDM involves participation by decision-makers, analysts, scientists, and stakeholders. We suggest specific areas for training and instituting SDM to foster transparency, rigor, clarity, and inclusiveness in formal decision processes regarding management of national forests.

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## 1. Introduction

Natural resource management is ultimately about human decision making. Natural resource management decisions are often influenced by varying levels of complexity, uncertainty, and conflict that may extend well beyond the life of the decision process participants. The scope and complexity of issues that need to be addressed is part of the reason that decision-making in natural resource management is difficult. In the United States, public land managers and planners consider several overarching issues regarding sustainability, including loss of native forests and grasslands, degradation of ecosystem services derived from them, effects of climate change, and managing in the face of ecosystem disturbances from fire, insects, disease, development pressures, and changing demographic and settlement patterns (USDA Forest Service, 2010). Approaches and tools that facilitate good decision-making can help managers and planners provide for sound, science-based natural resource management decisions.

Decision science is a broad field with roots in economics, but it has since drawn expertise from many fields and has been applied in many contexts. 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, p. 806). In this paper, "decision-maker" refers to line officers, staff officers, and others, at all administrative levels of an agency or organization, and private landowners. 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).

Decision science is applied increasingly in management of natural resources (Haynes and Cleaves, 1999), including fisheries (Runge et al., 2011a), wildlife (Johnson et al., 1997), forestry (Ogden and Innes, 2009), rangeland (Bashari et al., 2009), and fire (Calkin et al., 2011). This paper presents a structured approach to use of decision science – referred to here as structured decision making (SDM) – in forest and natural resource management on federal public lands of the United States, in particular those administered by the US Forest Service. SDM includes rigorous procedures for defining and structuring problems, analyzing problems and

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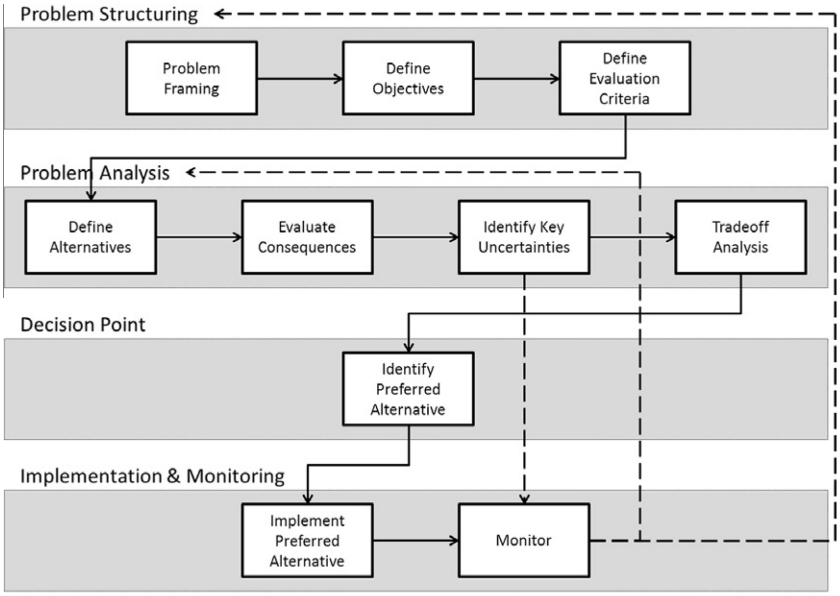

**Fig. 1.** Stages of the structured decision making process (after Hammond et al., 1999).

devising alternative solutions, making a decision on which course of action to follow (“decision point”), and implementing the decision and monitoring results (Fig. 1).

Managing forests and grasslands of US Forest Service’s National Forest System (NFS) lands, in particular, 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). NEPA is essentially a disclosure process supporting decisions, and provides a structured framework much like parts of SDM for evaluation of environmental impacts, although SDM provides a richer and more general structure for all steps in the management and decision process, including dealing explicitly with uncertainties in all steps of the decision process. However, SDM will not solve all conflicts of social perceptions and political interests.

Land management options have narrowed in the 21st century and, 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 their probable outcomes by which to make the best management decisions, but keeping up with advances in the field of decision science is difficult at best. The purpose of this paper is to describe the stages of SDM and, with use of three case studies, present how it is being used in NFS resource management. Our goal is to make natural resource managers, planners, and scientists more aware of the availability of SDM approaches and tools, how they have been successfully used in NFS, and how they can be used more effectively. We describe the basis and methods of SDM, present three case studies of its use in NFS, and provide conclusions and lessons for its future use.

## 2. SDM as a decision support framework

SDM is a framework that supports sound decision-making. As adapted from Hammond et al. (1999), each stage of SDM – problem structuring, problem analysis, decision point, and implementation and monitoring – consists of sub-stages, some of which are linked with feedback loops to denote learning from monitoring and adaptive management (Fig. 1). Each stage further entails interaction and collaboration among decision makers, stakeholders, scientists, and analysts. Decision makers have primary responsibility for the problem-structuring and in particular the decision-point stages, but need to be involved throughout all stages. Stakeholder engagement is generally 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 and identifying key uncertainties (problem analysis), for helping to frame and possibly conduct monitoring (Kiker et al., 2005), and advising and guiding the decision maker in identifying the form and implications of their risk attitude.

Next, we briefly review the main stages and components of the SDM process as a context for three case studies of applying SDM to NFS management.

### 2.1. Stage one: Problem structuring

The first stage of SDM is a clear statement of the problem to be solved; this entails framing the problem, defining the objectives, and defining criteria by which alternative solutions can be evaluated. Problem structuring – the primary responsibility for which rests with the decision maker – guides the process toward the appropriate tools and information, determines appropriate levels of investment, and ensures that the right problem is being solved. Problem framing and defining objectives result from the policy, legal, and social contexts of the decision, and reflect values of decision makers and stakeholders. Although analysts can advise on defining evaluation criteria, this too is mainly the purview of the decision maker. Many tools and procedures are available to help with problem structuring (Supplementary Appendix).

### 2.1.1. Problem framing

A decision problem can be described with three broad sets of questions regarding governance, timing, and background. In the simplest of decision problems, the governance is clear—there is a single decision maker with full authority to make the decision. But in complex natural resource management decisions, it is frequently difficult to clearly identify the governance structure. There may be multiple decision makers, either acting independently or in concert. There may also be many stakeholders who do not hold decision-making authority, but are keenly interested in, and may have considerable influence over, the outcome.

Communication with and involvement of the public at large may be required to best frame the problem, when decisions involve resources managed for the common good, such as the Forest Service's national forest lands. Further, the Forest Service is often required to involve the public through the procedures specified by NEPA. Clarity of the governance structure early in the process of framing the decision problem is valuable, as it leads naturally to the next steps of analysis. For some large-scale problems, the governance structure and process can be difficult to identify and methods of adaptive governance may be needed (Brunner et al., 2006).

The second aspect of problem framing involves clarifying the timing and frequency of the decisions. Some decisions are made only once (such as large land acquisitions, or installation of permanent infrastructure). But other decisions can be replicated in space, time, or both. The nature of the timing and recurrence of a decision will guide the choice of different decision support tools and the best way to frame the decision problem initially.

Problem framing also involves understanding the background context of the decision including policy, legal, ecological, social, and economic drivers. Various statutes and regulations provide legal direction and constraints for decisions made on NFS land, and thus are part of problem framing. The NFS 2012 land management planning rule (hereafter, "NFS planning rule;" USDA Forest Service, 2012) provides a framework, consistent with the SDM approach, for integrated resource management that guides decision-making on national forests and grasslands, in that it describes a structured decision-making and adaptive management process emphasizing stakeholder engagement and requiring use and documentation of the best available science to inform the planning process. Management of national forests and grasslands also must meet many other legal requirements outlined in the National Forest Management Act, as well as the Multiple-Use Sustained-Yield Act, the Endangered Species Act, the Wilderness Act, the Migratory Bird Treaty Act, and others.

### 2.1.2. Defining objectives

Objectives are the long-range aspirations of the decision makers and stakeholders, and can include ecological, economic, recreational, spiritual, cultural, and aesthetic dimensions. Because forest and grassland management often involves multiple, possibly competing, objectives, an informed decision requires careful elicitation, articulation, classification, and structuring of these objectives. Increasingly, formal facilitation methods are used as a part of SDM to help decision makers, stakeholders, and the public to clearly articulate their objectives. Social scientists and experts in human dimensions play key roles in helping participants in these processes better understand each other's values (USDA, 2010).

Keeney (2007) described four types of objectives. *Fundamental objectives* are the ends that the decision maker desires to achieve through the decision. *Means objectives* are ways of achieving the fundamental objectives and are valued not for themselves but for how they lead to the fundamental objectives. *Process objectives* pertain to how the decision will be made, but not what the decision will be. Finally, *strategic objectives* are desired directions that are influenced by the entire set of decisions made by an organization over time. Examples of objectives are noted in the case studies, below.

Fundamental and means objectives often can be organized into hierarchies. There may be multiple ecological objectives and multiple economic objectives, all of them fundamental (with at least some potentially conflicting), for a forest or grassland management plan. For example, a range management decision might involve objectives for restoration of natural vegetation conditions, rangeland production for livestock, and browsing resources for native ungulates. Structuring these fundamental objectives in a hierarchy can help clarify tradeoffs and priorities among multiple objectives.

### 2.1.3. Defining evaluation criteria

Evaluation criteria are measurement scales for the fundamental objectives, i.e., quantitative expressions of the objectives that can be used to measure performance of the alternatives. Developing evaluation criteria is often challenging, requires clarity in the definition of the objectives, and demands a creative search for ways to measure what otherwise are only intangible aspirations. As often used in NFS planning, evaluation criteria are of three types: natural attributes, proxy attributes, and constructed attributes (Keeney, 1996). Natural attributes are direct and transparent measurement scales for the objectives in question; they don't require interpretation or assumptions, and they often have established methods for measurement, such as board-feet as a measure of the performance of an objective to achieve a desired timber yield. But when natural attributes do not exist, or are difficult to measure, as for many natural resource management objectives in NFS planning, proxy attributes are used. Proxy attributes are measures of quantities (often for means objectives) that are indirectly associated with the objective of interest. For example, if the objective was to provide recreational opportunity for hiking, the number of kilometers of managed trails might be a useful proxy attribute. Finally, constructed attributes can be created to express performance on a complex objective. Constructed attributes cannot be observed or measured directly on the ground, as they are created to represent in composite fashion the intent of an objective. For example, habitat suitability indices are constructed scales that represent the quality of habitat for a particular species.

Evaluation criteria consist of (1) a measurement scale, as described above, (2) a desired direction (i.e., whether higher or lower values are preferred), and (3) sometimes an aspiration (i.e., how the decision maker's satisfaction is related to performance on the objective). The aspiration might be to maximize performance on the objective, to achieve some minimum level of satisfactory performance (e.g., an "objective threshold," Martin et al., 2009), or to maximize some non-linear function of the objective (e.g., a "utility curve," Keeney, 1996). Identifying the aspiration is the onus of the decision maker, often in concert with stakeholders (Zorilla et al., 2010) and in consultation with analysts, and is an important prerequisite for being effective in the decision-point stage (see Section 2.3). Threshold aspirations for evaluation criteria are common in natural resource management, such as minimum population levels for recovering a threatened species, or maximum acceptable percentage loss of timber volume (Long et al., 2010). Constraints can serve to generate and screen out alternatives, and are often imposed by institutional policies, environmental regulations, or fiscal or logistical limitations (e.g., Chang et al., 2009; Converse et al., 2011).

## 2.2. Stage two: Problem analysis

The problem analysis stage of SDM entails defining alternative actions (the range of decision options), estimating their potential consequences, analyzing tradeoffs, and identifying key uncertainties. Defining alternative actions has a value component and can effectively involve input from stakeholders, but the rest of the problem analysis stage should be conducted as a "clinical" set of tasks where the alternatives are tested against the objectives listed in the problem structuring stage. This is a process of comparison, as unbiased as possible by desired outcomes and risk attitudes. A wealth of tools is available for analysis of the consequences of alternatives and tradeoffs in natural resource management decision making (Supplementary Appendix). Examples of tools include many modeling approaches such as use of simulations, Bayesian networks, fuzzy logic, optimization analysis, and approaches to analyzing potential, untried management options, such as scenario analysis and comparative risk assessment.

### 2.2.1. Defining alternatives

Defining alternatives involves first identifying specific decision variables (those items we can control) and acceptable ranges for those variables (e.g., levels of timber harvest or range allotments), then generating alternatives from combinations of those variables that could achieve the objectives as measured by the evaluation criteria developed in the previous stage of problem structuring. Alternatives can be generated in various ways, such as with modeling (Stage, 2003). For example, Chung and Lee (2009) identified potential alternatives to a complex water management problem by varying inputs to a hydrologic simulation model.

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 the method of harvest, the spatial arrangement and timing of harvest, the method of treatment of the residual material, the rate and method of replanting, and effects on wildlife habitat, water quality, forage, and other resources. 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 combine them in ways that can be feasibly evaluated and that represent a wide contrast of strategies for achieving the objectives. In some NFS planning efforts, a tool known as "strategy-generation tables" has proven valuable (Howard, 1988), where the alternatives are depicted as combinations of like elements known as portfolios. For example, given a list of possible management projects A, B, and C, the alternative portfolios are all possible combinations of those projects.

Some aspects of defining alternatives entail value-based judgments. The choice of the evaluation criteria, and the range of values to include, reflect implicit values of the decision makers. For example, in managing an emergent disease in a wildlife or livestock population, a manager may not include prophylactic culling as an alternative for evaluation because of deeply-held values against culling, thereby eliminating up front any such possible alternatives. In another example, if staying within budget is the objective with a threshold aspiration, the portfolios of management projects might be screened so that those options that are above a total budget are rejected.

### 2.2.2. Evaluating consequences

Evaluating consequences entails predicting the outcomes of each alternative action, based on an understanding of the ecological and social systems affected, in terms of the objectives. Decisions on sustainable management of natural resources are by definition about taking action with future consequences. Often, models of some sort, whether conceptual, quantitative, or expert-based, are used for this purpose. Models 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). Such graphical models link the possible actions through intermediate variables to the outcomes that are important to management, providing a way for the decision makers and analysts to clarify their understanding of how the system might respond to management actions. Such influence diagrams are often developed into quantitative models (Marcot, 2006), but sometimes they are adequate themselves for decision analysis.

In NFS management, common predictive tools for evaluating consequences are quantitative models built on empirical data. There is an enormous variety of predictive models, each with its own purpose and context, from forest-stand models to Bayesian networks to linked habitat-population models. Increasingly, predictive habitat models are being linked to climate models to forecast future conditions under system change. In all cases, however, these models use empirical evidence to quantify the linkage between potential management actions and desired outcomes. These models can include specific treatment of stochasticity and uncertainty (see case studies for examples). In this way, a consequence-analysis approach explicitly predicts the possible outcomes of each potential action, the probabilities of those possible outcomes, and the expected value of outcomes under each alternative action (e.g., Aven, 2003). Expected values are calculated by weighting outcomes by their probabilities. Some tools and approaches useful for evaluating consequences include decision trees, probability networks, population and landscape simulation, and comparative risk analysis (Supplementary Appendix). Also, as a general approach, scenario analysis can help to frame the evaluation of consequences (e.g., Mahmoud et al., 2009).

With multiple-objective decisions, the decision maker requires predictions regarding how any potential action will affect all objectives; this might require a different predictive model for each objective. Thus, in a multiple-objective tradeoff analysis, the expected values of each potential action are compared as to their ultimate benefits and costs on multiple scales. For example, Blomquist et al. (2010) used structured decision-making to assess tradeoffs of cost and effectiveness of alternative approaches for managing an invasive insect (*Adeleges tsugae*) that was threatening native hemlocks (*Tsuga canadensis*) in the eastern US. In another example, Thompson et al. (2010) demonstrated potential conflicts and complementarities associated with decommissioning forest roads, recycling recovered road surfacing materials, and reducing aquatic habitat degradation potential.

In many cases, there are few empirical data to support predictive model building. Increasingly, decision analysts are relying on formal methods of expert elicitation (Martin et al., 2012) including expert paneling (Marcot et al., 2012) to develop quantitative predictions. In these methods, the privileged knowledge of experts is mined, with careful attention paid to minimizing linguistic confusion, to articulating uncertainty, and to reducing the effects of overconfidence.

### 2.2.3. Identifying key uncertainties

Identifying key uncertainties helps to determine how much confidence one should put in model predictions of effects of alternatives actions. Uncertainties can pertain to parameter values, overall model structure, definition of terms, and functional relations among variables, and can arise from sampling error, limited knowledge of the system, imprecise language, and variable expert judgment (Benke et al., 2007; Brugnach et al., 2010; Regan et al., 2002; Janssen et al., 2010). Because uncertainty fundamentally reduces confidence in predictability, it can be of prime importance in the decision-making stage where managers typically deal with linked decisions, diverse and conflicting goals and interests, changing environmental conditions, and the lack of predictability (Brugnach et al., 2008). Uncertainty analysis results in identifying how variability or partial knowledge of each of these key areas might affect the outcome (i.e., expected value) of each alternative. Kann and Weyant (2002) suggested useful approaches for assessing uncertainty by articulating and examining model assumptions and appropriateness of different model types.

The analysis of uncertainty in a decision context, however, is quite different than its analysis in a scientific context. The uncertainty that matters to a decision maker is uncertainty that affects what course of action is best taken. There are cases where there is considerable uncertainty about the predicted outcomes, but the best course of action is unaffected. In these cases, the reduction of scientific uncertainty is not important to the decision maker's choice in the decision at hand. Calculating the ''expected value of information'' is a powerful decision analysis method for evaluating whether uncertainty is relevant in a choice (Runge et al., 2011b; Williams et al., 2011). Where the expected value of information is 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 where the expected value of information is low, or where 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.

#### 2.2.4. Analyzing tradeoffs

Evaluation of the consequences will sometimes clearly lead to a preferred alternative, particularly with single-objective decisions that are not greatly troubled by uncertainty. But in most cases in NFS planning and management, the consequences display a complex mix of tradeoffs so that no one alternative is clearly best considering all the desired objectives. Before proceeding to the decision-point step, it is useful to carefully examine the pattern of tradeoffs and to simplify the set of choices. Tradeoff analysis can be used to identify and remove dominated alternatives that do not outperform other alternatives on at least one criterion. The complexity of the decision can be further reduced by identifying evaluation criteria across which alternatives do not differ and removing those criteria from consideration (e.g., if all alternatives cost roughly the same, cost can be removed as an evaluation criterion). Still, NFS decision-makers are often faced with a range of alternatives that vary across a range of remaining criteria and that entail high complexity and uncertainty. Formal methods for quantifying and visualizing the performance of alternatives (e.g., spider plots; Benke et al., 2007; Gareau et al., 2010) can help decision-makers better identify potential tradeoffs and complementarities, better distinguish across alternatives, and better communicate results of problem analysis particularly for complex, multi-criteria assessments.

### 2.3. Stage three: Decision point

The decision point is ultimately where an alternative policy, plan, or management option is selected. A decision can be choice of a strategic direction, such as a land and resource management plan (LRMP) under the NFS planning rule, or project-level decisions, such as those under an LMRP that entail specific management practices and resources. The SDM framework is equally applicable at both LRMP and project-level decision-making, in particular where problem framing involves understanding the nature of the resources that need to be allocated and who is responsible for making that decision.

In contrast to problem analysis, which is focused largely on the generation, synthesis, and critique of the knowledge base, the decision point stage is focused on the articulation and application of preferences. Critical evaluation of the knowledge base and preference structure of the decision maker enhances the comparison and ranking of alternatives on the basis of achieving objectives (Amgoud and Prade, 2009). Good choices thus are the result of considering not only available science but also well-articulated values and preferences of the decision-makers and considerations raised by stakeholders and others involved in the decision process (Gregory and Long, 2009).

Cost-benefit analysis (CBA) is commonly used in NFS decision-making with multiple objectives. CBA depicts potential impacts and tradeoffs of alternatives in a common currency that may use non-market valuation methods (e.g., Champ et al., 2010; Fisher et al., 2008). In practice, CBA is often challenged by difficulties in accurately quantifying social preferences and assigning monetary or other proxy values (Brown et al., 2008; Venn and Calkin, 2011).

Multi-criteria decision analysis (MCDA) approaches, by contrast, are useful where a common currency is not readily found. For example, Schwenk et al. (2012) used MCDA to compare effects of forest management alternatives on objectives for carbon storage, timber production, and biodiversity conservation, where these objectives had disparate units of measure. MCDA presents a fundamentally different approach than CBA by exploring multiple dimensions of a problem, explicitly identifying tradeoffs, conflicts, and complementarities across objectives, and considering a range of knowledge bases and preferences across stakeholders (Gregory and Keeney, 2002; Kiker et al., 2005). MCDA encompasses a family of tools and approaches that facilitate the systematic evaluation and selection of management alternatives (Mendoza and Martins, 2006). MCDA is useful for articulating the nature and implications of preferences and values of decision-makers, and the types and influence of uncertainties and perceived risk. Other approaches can help determine decision-makers' risk attitudes and implications on decisions (Hanewinkel et al., 2010; Kangas and Kangas, 2005; Williams et al., 1996).

Further complexity occurs when the preferences themselves are uncertain. Imperfect information involved in decision-making (i.e., decision or preference uncertainty) makes selection of the ''best'' alternative a difficult exercise. Kurtilla et al. (2009), for instance, identified decision uncertainty as the dominant form of uncertainty in the development of forest management plans involving multiple criteria. This uncertainty can manifest itself in terms of unknown individual preference structures, or difficulties finding an appropriate balance across conflicting stakeholder preference structures. Managing this uncertainty requires identifying the best approach for eliciting preferences, and critically analyzing expressions of preference (Ananda and Herath, 2009; Kangas and Kangas, 2005). Ultimately, with a preference structure clearly articulated, decision-makers can transparently and systematically evaluate and rank alternatives.

### 2.4. Stage four: Implementation and monitoring

Implementation and monitoring follows the completion of the decision point stage. In NFS and other federal agencies, in land and natural resource management monitoring is integrated with implementation of the preferred alternative and final decision.

#### 2.4.1. Implementing the preferred alternative

A decision is enacted in the implementation phase of SDM. Successful implementation of a decision in NFS management entails considering the amount of time and cost associated with the implementation, the level and degree of impact of the implementation, the risk and benefit associated with the implementation, and the structure needed to implement a complex decision intended to guide management of large land areas with diverse administrative units and diverse objectives. Not considering these aspects can result in a failure; indeed, they should be considered well before the implementation process is undertaken, preferably as part of the evaluation criteria themselves. An example was institution of the Interior Columbia Basin Ecosystem Management Project (ICBEMP), intended to produce one set of ecosystem management guidelines in one record of decision (ROD) for Forest Service and Bureau of Land Management lands in the interior West, US (USDA and USDI, 2000) in a project area larger than France. However, 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, led to the project instead developing two draft environmental impact statements (EISs) for contiguous geographic portions of the interior Columbia River Basin. Further disagreement among agency administrative bodies ultimately led to no final ROD being created for either portion, and, despite the wealth of analysis and scientific data produced (Haynes et al., 2001), the project was abandoned. The goal and geographic scope of the project was simply too complex and too ambitious to satisfy the immense diversity of affected decision makers and stakeholders and to provide feasible and cost-effective implementation.

Under the NFS planning rule and within the NEPA process, no land management decision can be implemented until either the finding of no significant impact (FONSI) or a ROD associated with a final environmental impact statement has been entered. The actions should then be carried out as substantially directed by either the FONSI or ROD. These actions may include mitigation, coping, or adaptation activities.

### 2.4.2. Monitoring results

Three purposes for monitoring in NFS planning and management are evaluating achievement of the objectives, determining the state of the system (for state-dependent decision making), and reducing 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, this is simply a good-faith proof that the manager achieved what was intended, but in the case of recurrent decisions, monitoring provides a way to correct course if unforeseen outcomes occur. As natural resource management becomes increasingly scrutinized, evaluation monitoring demonstrates accountability to the public. Second, some decisions are state-dependent where the preferred action depends on the state of the system. Thus the system needs to be monitored to determine the appropriate course of action. For example, if a forest prescription calls for thinning whenever the basal area exceeds 85 square feet per acre, then the basal area needs to be monitored to determine when that threshold has been reached. Third, when uncertainty is prominent, monitoring provides the feedback that reduces uncertainty over time and allows adaptation of future actions.

Monitoring design will be most effective when it arises from the decision context. The metrics to monitor, the methods for monitoring, and the sampling design (including sampling rate) should be determined based on the information needs of the decision maker. Examples include development of protocols for monitoring potential effects of climate change on wildlife and ecosystem response on NFS lands (Davison et al., 2012; Peterson et al., 2011). Cost of monitoring also is an important consideration; to be warranted, cost needs to be offset by the benefit that accrues from the monitoring information.

The quantities to measure, the scale at which to monitor, and the sampling intensity should all arise from the decision context, with a clear understanding of how the information gathered will be valuable to the decision maker. A forest monitoring system often needs to be geographically extensive. The McNary Forest Research Act of 1928 (P.L. 70-466) established a series of forest remeasurement (once every 5 years) plots that now number in the hundreds of thousands across the US. The continued remeasurements form a baseline to help guide changes in national forest management policy, as directed by the Healthy Forests Restoration Act of 2003 (P.L. 108-148). Long-term remeasurement of forest age, size, and species composition will help gauge the effectiveness of decisions. The cost of time and money, and the benefits of monitoring (such as those emphasized in the NFS planning rule) must all be considered to best assess the type, extent and frequency of monitoring required.

### 2.4.3. Adaptive management

Adaptive management is the application of monitoring and assessment results to prior stages in the SDM process that is then used to learn for the purpose of improving future decisions (Fig. 1). Broadly, there are two potential outcomes of monitoring and assessment. First, monitoring can suggest that the predictive models were largely correct, and there is no need 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, or even to a different set of objectives. More specifically, monitoring results can be used to revisit the problem analysis stage (Fig. 1, inner dashed line) or, more fundamentally, the problem structuring stage (Fig. 1, outer dashed line). Learning that accrues may lead the decision-maker to include new objectives, or indeed, to identify a need to change the very governance structure of the decision (Pahl-Wostl, 2009). Importantly, adaptive management is needed when critical uncertainties would impede the decision and when the uncertainties in the predictions have a high value of information.

## 3. Case studies

We present three case studies to illustrate the application of SDM to NFS land and resource management and which exemplify various stages in the SDM process and use of particular SDM tools.

### 3.1. Problem structuring and problem analysis: Hoosier National Forest, 2006 Land Management Plan

NFS directives established governance for the Hoosier National Forest (HNF) LRMP by naming the regional forester as the decision maker and requiring input from stakeholders to be considered throughout the process. Problem framing 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. From the assessment, the HNF established three fundamental objectives: maintenance of watershed health, ecosystem sustainability and viability of plants and animal populations, and recreation management. The HNF then identified evaluation criteria to compare alternatives. Based on species viability analyses 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 proxy attribute indictors of the degree to which each alternative would maintain viable populations of the fuller set of native and desired nonnative species. Additional evaluation 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 first defining the decision space in terms of five planning alternatives that considered the issues raised in public scoping. The five alternatives differed primarily in the amounts and types of forest management and ranged from no timber harvest to various amounts and spatial distributions of even- and uneven-aged forest management and prescribed burning activities. Consequences of the alternatives were predicted by simulation modeling using the spatially-explicit landscape model LANDIS (He, 2009) and wildlife habitat suitability models to determine the effects of plan alternatives on the indicator species (Rittenhouse et al., 2010). The tradeoffs, among the alternatives, of 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. Whereas formal analytical methods were not used to evaluate tradeoffs and make a decision, the planning team did weight species differently, when qualitatively assessing tradeoffs, based on the species' conservation status, with greater weights given to less secure species. The Regional Forester reached a decision based on a consensus recommendation from the planning team (USDA, 2006). Recognizing that perfect information is impossible and anticipating new scientific information, the plan proposes an adaptive management approach involving monitoring and a process for amending the plan when needed based on evaluation of monitoring results.

### 3.2. Decision point: Deschutes National Forest, Five Buttes Project

In the NFS, under NEPA regulation the publication of a ROD is the culmination of a process incorporating both the science supporting a final EIS, and the values of agency officers and stakeholders. A good example of this process is the ROD describing the final decision and the rationale behind a vegetation and fuels treatment project implemented on the Deschutes National Forest in Oregon, called the Five Buttes Project (USDA Forest Service, 2007). The fundamental objectives of the Five Buttes Project were to increase resistance to wide-scale fire and other disturbance events and to retain large trees, while also providing forest products and supporting local and regional economies. Means objectives included reducing stand density and fuel loadings and modifying fuel arrangements to affect desired reductions in wildfire hazard and risk. Process objectives were driven largely by NEPA considerations, including public involvement and consultation with tribes and other government agencies, but also by other guiding laws, regulations, and policies such as the National Forest Management Act and the Endangered Species Act. Lastly, strategic objectives related to trending towards desired conditions consistent with the Deschutes Forest Plan and the Northwest Forest Plan.

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 non-commercial) and prescribed burning activities to reduce fuel loads and future fire incidence. Implementation of alternative B would result in a larger commercial harvest and greater associated timber mill activity, whereas alternative C emphasized modification of fire behavior and retention of habitat for Northern Spotted Owls (*Strix occidentalis caurina*), treating a larger area but yielding less commercial forest products. Alternative C also provided for commercial harvest of trees over 21" in diameter and the modification of spotted owl nesting, roosting, and foraging (NRF) habitat, which were the subject of public controversy.

The project was one of the first to use spatially-explicit burn probability modeling techniques for analysis of consequences (Ager et al., 2007). This is an example of use of a quantitative, stochastic model to evaluate consequences and to estimate uncertainties of outcomes. This enabled improved estimation of fuel treatment impacts on wildfire behavior, and refined analysis on the basis of comparative wildfire risk assessment. Results indicated that the no-action alternative increased risk of wide-scale disturbance from future fires, 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 non-commercial 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 to 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 stakeholder concerns over commercial removal of large trees, acknowledging that ecological objectives ultimately outweighed economic objectives.

### 3.3. Implementation and monitoring: Tongass National Forest, Implementation and Monitoring Plan

The Tongass National Forest's (TNF) recent amendment of their LRMP (USDA, 2008a, 2008b) 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: implementation monitoring, to determine if the plan management standards and guidelines are being fully and correctly implemented; effectiveness monitoring, to determine if the management standards and guidelines actually help achieve the plan objectives; and 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 TNF 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 most recent annual monitoring and evaluation report, of 2010, 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 GIS is to 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 focus on more appropriate or recent topics of scientific and social interest, and some monitoring protocols are still being developed. Still, some of the results from the recent annual monitoring report of 2010 have been used 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 non-development 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 NFMA, is to occur every decade.

## 4. Discussion and conclusions

### 4.1. A change of paradigm

For some decision makers and scientists, SDM is a change in paradigm because it makes explicit a previously implicit values-focused approach, and does not assume that science alone provides answers to complex, multi-objective problems, but rather that a decision needs to integrate science with policy. One consequence of the SDM framework is that the decision context drives the science needs, not the other way around. Another consequence is that the policy and scientific analysts need to understand their respective roles, but also need to collaborate closely. SDM recognizes that science is best conducted and scientific knowledge best created in a context that allows unbiased discovery and inference, but that this knowledge can be brought into a value-rich decision process for conversion into management actions. SDM techniques help separate judgments about science from judgments about the values of alternative actions in an attempt to more fully consider science in all phases of the decision process. SDM requires commitment throughout all stages, so that the decision maker is informed and involved from the start, and so that analysts and decision makers have access to each other. In the setting of natural resource management agencies, particularly the US Forest Service, the SDM approach also calls for objective participation by scientists, and transparent exposition and early articulation of decision criteria by decision makers.

### 4.2. The role of uncertainty

Decision-makers face uncertainty in several key ways: (1) in the very lexicon of their craft, with unclear or variable definitions of such terms as "sustainable" and "resilient;" (2) in the natural variability of the managed systems, that makes prediction difficult and limits the scope and precision of control; (3) in the limited scientific understanding of complex ecological systems; and (4) in the unknown or conflicting preferences of stakeholders (Regan et al., 2002; Kurtilla et al., 2009). For complex environmental and natural resource management problems, there is a need for transparency, explicit identification and analysis of all of these types 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 decision-making process, and a wide variety of tools exist to address particular manifestations and aspects of decision-making under uncertainty (Supplementary Appendix). Using SDM as an overarching framework can help to identify, critique, and discuss sources of uncertainty and support decision making in the context of natural resource management.

### 4.3. Closing the gap

Decision science is solidly based in both theory and practice. As decision analysts and decision makers apply the concepts and tools of SDM, they are rapidly developing sets of best practices and archetypal attributes for high-quality decision making. With training of both analysts and decision makers alike, SDM can become the new operating framework under the NFS planning rule and a defensible and rigorous means of meeting regulations under NEPA and related directives.

Although our presentation of SDM focuses on NFS management, SDM can be applied to other natural resource and nature conservation institutions and ecosystems. The SDM approach can serve the basic principles and address the complexities of sustainable natural resource management in many venues. High quality decision-making clearly and logically documents the decision rationale, reflects both outcome and process objectives, examines sensitivities to assumptions and conditions, and ensures transparency and accountability (Berg et al., 1999). That is, good decision-making is defined by both the entire decision process from problem structuring through implementation and monitoring.

The real challenge in any agency or institution is how to bring these tools, approaches, and processes into daily implementation. We offer three general recommendations pertaining to providing training and education in SDM tools and procedures. First, analysts and planners can be well equipped to provide guidance to management on decision support. Second, scientists and researchers can clearly explain the underlying logic of predictive models to be used more appropriately in decision contexts, and clearly articulate key unknowns and their implications to help prioritize studies for adaptive management programs. Third, decision makers 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. More specific suggestions for areas of training are provided in Table 1.

**Table 1**
Suggested themes and purposes for training in the area of structured decision making.

| 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 multi-criteria 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/contrasting consequences of various management alternatives |

### 4.4. The challenge and the promise ahead

SDM is inherently a template for applying objective analysis and subjective values at appropriate stages in the decision process, and for identifying and appropriately using the degree of confidence in potential outcomes of alternatives. Indeed, uncertainty – when appropriately explained and displayed – is information too, and not a justification for indecision. Analysts and planners can present uncertainty in a more useful light by evaluating its implications in tradeoffs among alternative actions, and by estimating the incremental value (and cost) of additional knowledge. When used appropriately, uncertainty is not used as a rationale to invert the burden of proof and the precautionary principle, such as erroneously assuming no adverse effects of a decision if the outcome is unclear and unless "proof" is presented otherwise. Of course, the inverse is also of concern, in that uncertainty should not be viewed as a rationale to necessarily assume adverse effects of a decision if the outcome is unclear. The decision maker's risk attitude will determine the implications of uncertainties in practice, such as how some have adduced the precautionary principle (Cussen, 2010).

Many existing protocols for decision analysis and exposition, such as those found in the NFS planning rule and in NEPA regulations, are quite amenable to the rigor of SDM procedures. For example, many multi-criteria decision analysis approaches (Supplementary Appendix) are similarly premised in existing regulations on clear articulation of objectives and measurable attributes, and systematic approaches to scoring, ranking, and evaluation of alternatives. In many respects, the NEPA process can provide a structure by which to display the results of all stages of the SDM framework: the purpose and need statement in an EIS serves to frame the problem and to articulate objectives (i.e., the problem structuring stage of SDM); an EIS considers multiple alternatives and their possible consequences (i.e., the problem analysis); and a ROD documents the decision rationale (i.e., the decision point) and outlines plans for implementation and monitoring.

There has never been a more relevant era for the application of decision science to land and natural resource management. The coming years will demand closer attention to achieving and demonstrating tighter alignment with stated goals despite increasing financial constraints. Decision processes will increasingly weigh environmental improvement costs and benefits against those of economic development, social equity, and contribution to financial solvency.

SDM is not a panacea but it can improve transparency and clarity. Our review of SDM concepts and applications leads us to believe that this body of practice can be helpful in decomposing and understanding complex problems that create the need for decisions, maintaining the sequences and internal consistency of the various phases of decision making, 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. The approach is applicable not just for NFS lands, including national forests and grasslands, but for guiding management of all types of natural resources, ecosystems, and land bases.

Finally, we concur with Pouyat et al. (2010) in encouraging scientists to participate more in the SDM process and to have agencies institute formal mechanisms to encourage, reward, and support communication and interaction between scientists and users of scientific knowledge in the decision process. SDM can be a powerful tool if embedded in a broader context of social decisions that guide management of public natural resources.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2012.08.024.

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