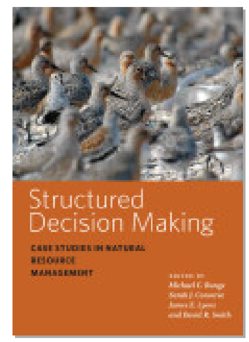
Structured Decision Making

Runge, Michael C., Converse, Sarah J., Lyons, James E., Smith, David R.



Published by Johns Hopkins University Press

Runge, Michael C., et al.
Structured Decision Making: Case Studies in Natural Resource Management.
Johns Hopkins University Press, 2020.
Project MUSE. doi:10.1353/book.74951.

PART II ADDRESSING TRADE-OFFS

This page intentionally left blank

5 Introduction to Multi-criteria Decision Analysis

Sarah J. Converse

Multiple-objective problems are ubiquitous in natural resource management. Often, solving these problems requires dealing with trade-offs between multiple potentially competing objectives. In this chapter, I provide an overview of approaches to solving multiple-objective problems. I begin by contrasting 2 general classes of solution methods within multiple-objective decision making: multi-objective programming approaches and multi-criteria decision analysis. Multi-objective programming focuses on technical solutions to identifying preferred alternatives from large sets of implicitly defined candidate alternatives. Multi-criteria decision analysis is typically used to evaluate smaller numbers of explicitly defined alternatives, with a unifying theme of evaluating trade-offs between objectives in decision-making processes. I introduce 3 primary classes of methods within multi-criteria decision analysis: methods based on multi-attribute value or utility, the analytic hierarchy process, and outranking methods. I also briefly consider deliberative, discussion-based approaches to dealing with trade-offs and then introduce 3 multiple-objective case studies from the United States, Australia, and Canada.

Introduction

Arguably, nearly all decision problems are multiple-objective problems. Indeed, multiple-objective decision problems are so central to decision making that some experts define structured decision making explicitly as a process designed to address multiple-objective problems (Gregory et al. 2012). Dealing with trade-offs between different values is the key challenge in multiple-objective problems, and certainly this is the case in many natural resource management applications. Decision makers need to understand and utilize the methods available to make these trade-offs—economic development versus environmental protection, recreation access versus wilderness values, persistence of species *X* versus persistence of species *Y*, and more—to make transparent decisions that are most likely to meet their objectives.

When decisions are highly visible and complex, when the values at stake are difficult to quantify, and when stakeholder viewpoints about the proper course of action are entrenched, it is hard for decision makers to deal with trade-offs transparently and deliberatively. Natural resource management problems exemplify this challenge (e.g., Retief et al. 2013). Against this backdrop, how can we design multiple-objective decision-making processes that will move us forward?

Several points deserve mention prior to a discussion about dealing with trade-offs. First, the critical factors determining the success of a multiple-objective decision process are most often the organization and facilitation of the process, rather than the technical method chosen for dealing with trade-offs (Saarikoski et al. 2016). Organization and facilitation encompass considerations about who should be engaged, how the decision can best be framed, how work on the process will be undertaken, and how the process and results will be communicated. A capable decision analyst who can guide the process is valuable, and in high-stakes and high-visibility multiple-objective decisions, an experienced decision analyst is indispensable.

Second, decision-making processes that focus on dealing with difficult trade-offs must be collaborative to receive wide acceptance (Gregory et al. 2012; Williams et al. 2007). Identifying acceptable solutions to these problems is contingent on understanding the values of stakeholders and the trade-offs they are willing to make. Carefully considering who the stakeholders are and how to engage them in a process is likely to pay benefits when it comes to implementation of the resulting decision (Gregory et al. 2012).

Third, there will often need to be substantial time investment in the articulation of objectives. Clarity about objectives is central to good decision making (Keeney 1992). Furthermore, formalizing objectives permits stakeholders to see that their concerns are included in the analysis of a problem. Explicitly identifying objectives takes vague assurances about commitment to engaging stakeholders and gives them content and meaning. However, identifying objectives can be a key challenge for a variety of reasons. Some values relevant to natural resource management are inherently difficult to express. The values people place on wild places, clean water, clean air, and healthy populations of native species don't necessarily lend themselves to easy articulation or quantification. Also, frequently what are originally identified by stakeholders or decision makers as important objectives are in fact means to achieve some higher-level (fundamental) objective, and analysis based on means rather than fundamental objectives can lead to poor decisions (Keeney 2002). For instance, increasing survival rate in a threatened species may appear to be an objective, but it is more likely a means to a higher-level objective, such as long-term persistence of the species. Developing objective hierarchies to clearly understand the various objectives and their relationship to each other can be a powerful approach to clarifying multiple-objective problems (Gregory et al. 2012; Keeney and Raiffa 1976).

Fourth, for multiple-objective problems, time spent generating alternatives can be particularly important. Time invested in developing creative new alternatives might allow decision makers and stakeholders to identify "win-win" alternatives, under which everyone is happier compared to the status quo (Gregory et al. 2012). In this way, some of the more unpalatable trade-offs can be avoided. Ultimately, the best alternative that can be chosen is only as good as the best alternative that is considered.

Once we've set up the problem, identifying a thoughtful and sensible approach to dealing with trade-offs will be key to solving multiple-objective problems. The case studies in this part emphasize different approaches to dealing with trade-offs, including quantitative approaches and deliberative approaches that focus on structuring discussions around trade-offs. I provide here an introduction to quantitative approaches based in multi-criteria decision analysis, briefly discuss deliberative approaches to negotiating trade-offs, and then introduce 3 case studies from the United States, Australia, and Canada.

Multi-criteria Decision Analysis

Multi-criteria decision analysis (MCDA) arose as an alternative to single-criterion approaches in decision analysis. Single-criterion approaches stem from the assumption that a single relevant criterion can be developed *a priori* to evaluate any of the alternative courses of action under consideration (Roy 2005). MCDA rests on the recognition that there are often multiple relevant criteria and that they exist on different scales, such that no single criterion can be easily developed to evaluate alternatives. The field of MCDA is enormous, and it is not possible to provide a comprehensive review of even major classes of methods in this short review. Instead, I introduce some major classes of MCDA methods and focus on those that are used most in the case studies in this part (and elsewhere in this book): methods based in multi-attribute value theory.

To develop an overview of MCDA (table 5.1), it is useful to consider first the wider field of multi-objective decision making, which includes both multi-objective programming (MOP) and MCDA. In MOP problems, there is typically not a defined set of alternatives (Ehrgott 2005). Instead, alternatives are numerous and only identified implicitly. MOP problems are characterized by having 1 or more decision variables that are continuous or take a large set of discrete values. Solution approaches tend to be computationally intensive. A relevant application is the selection of land parcels for protection (Ball et al. 2009; Golovin et al. 2011; Williams 1998; see also Converse et al., chapter 11, this volume). For a set of available land parcels, we want to select a subset that, for example, maximizes the number of species protected while minimizing acquisition cost. The set of alternatives increases as an exponential function $(2x - 1)$ of the number (x) of possible parcels. There are a large variety of approaches to solving MOP problems, only a few of which I mention here; Ehrgott (2005) provides a comprehensive overview. One is the ε-constraint method, wherein all but 1 of the objectives are converted to constraints and the optimal solution is the one that maximizes attainment of the remaining objective while meeting all established constraints. Another is the weighted-sum approach, wherein the decision maker specifies weights indicating the relative importance of the different objectives, and through use of these weights a single metric is developed on which to evaluate the alternatives (Coello Coello 1999). Both the ε-constraint method and the weighted-sum method have clear analogs in MCDA. Finally, another approach worth

Table 5.1. Major classes of approaches used in multi-objective decision making and introduced in this chapter, along with key characteristics

Approaches	Characteristics
Pareto-based approaches	Relevant to multi-objective programming or multi-criteria decision analysis problems; focus is on identifying a (possibly complete) set of alternatives that are nondominated, i.e., a gain in performance on 1 objective cannot be obtained without a loss on some other objective
Multi-objective programming	Decision variables are continuous or composed of a large set of discrete values; distinct alternatives are not specifically identified
ε-constraint method	All but 1 of the objectives are converted to constraints, while performance on the remaining objective is maximized
Weighted-sum method	Relevant weights are assigned to objectives and used to develop a single criterion
Goal programming	Objectives are expressed in terms of desired levels of performance
Multi-criteria decision analysis	Alternatives are discrete and specifically identified
Outranking methods	Outranking relationships are determined given indifference, weak preference, and strong preference on each of a set of criteria for pairs of alternatives (e.g., ELECTRE, PROMETHEE)
Multi-attribute value theory	Predicted performance on objectives is ideally quantitative, and weights are placed on objectives; uncertainty is relatively unimportant or can be addressed through sensitivity analysis (e.g., SMARTS)
Multi-attribute utility theory	Predicted performance on objectives is quantitative but presented in terms of utility, a transformation of value to account for risk tolerance in the face of uncertainty
Analytic hierarchy process	Pairwise comparisons of criteria are based on their influence on the decision, and these are combined with pairwise comparisons of alternatives on each criterion to develop alternative scores

Note: See main text for sources.

mentioning because of its relative familiarity is goal programming (Tamiz et al. 1998), wherein a desirable level of performance is specified for each objective. The optimal alternative is the one that minimizes deviance from the desirable level across the objectives. In any case, solving an MOP problem requires dealing, either implicitly or explicitly, with the relative importance of the objectives to the decision maker. In this sense MOP problems are like MCDA problems: to solve any multiple-objective problem, we face trade-offs.

In MOP problems, there is often substantial attention paid to whether selected alternatives are Pareto efficient, and identification of Pareto-efficient alternatives can be challenging. Pareto efficiency is a state wherein improvement in performance on 1 objective cannot be achieved without a loss on some other objective (Williams and Kendall 2017). The Pareto frontier is the set of Pareto-efficient alternatives in a decision problem. Pareto efficiency is also relevant to MCDA problems.

In MCDA, solution methods begin with the assumption that we have a well-defined set of discrete alternatives (unlike MOP problems) and multiple objectives relevant to the selection of a course of action. A sensible initial step involves simplification of the problem to as great a degree as possible before directly wrestling with trade-offs. There are several ways to do this. One is through identification of the set of Pareto-efficient alternatives. Sometimes this can be done via simple inspection and tends to be much simpler than in MOP problems. Another way to simplify is through identification and elimination of irrelevant objectives. An irrelevant objective is one that is important to the decision maker on the surface yet does not help to distinguish among alternatives. For example, a decision maker may identify the cost of an alternative as an important consideration, but if all identified alternatives cost the same, cost becomes irrelevant in making the decision. Finally, the even swaps method can be used to simplify MCDA problems (Gregory et al. 2012; Hammond et al. 2000). When 2 objectives can be expressed in the same currency with relative ease, we can cancel out the differences between alternatives on 1 objective, thereby creating an irrelevant objective, and reflect those differences in the other objective (Hammond et al. 2000). We then delete the irrelevant objective from the analysis.

Once the problem has been simplified to the greatest degree possible, the analysis should have exposed the key trade-offs with which decision makers will ultimately need to grapple. The goal should be to identify a method for evaluating trade-offs that is explicit, transparent, and can be communicated to stakeholders (Gregory et al. 2012).

One simple approach for evaluating trade-offs is the MCDA equivalent of the ε-constraint method: convert all objectives to constraints save 1 and choose the alternative that maximizes that objective while satisfying all constraints. The method requires identifying what minimum level of performance is satisfactory on the objectives that will be converted to constraints, while also deciding which objective should be retained for maximization. However, it does not require explicitly considering how much of a loss on 1 objective is made up for by a gain on another. While the simplicity of this approach is attractive, information is lost by converting objectives into constraints, and the resulting solution may be less satisfactory than one arising from a process in which trade-offs are evaluated explicitly. For formal evaluation of trade-offs, we consider 3 classes of MCDA approaches: methods based on multi-attribute value theory / multi-attribute utility theory, the analytic hierarchy process, and outranking methods. The last 2 of these are covered in relatively sparse detail.

Multi-attribute value theory (MAVT) and multi-attribute utility theory (MAUT) build quantitative functions to represent decision-maker preferences for alternatives. The value or utility function can be used to score and evaluate the alternatives, given performance predictions on the individual criteria. Construction of this value or utility function is recognized as a key challenge. The distinction between

MAVT and MAUT is that MAUT is concerned with utility rather than value. Utility is a transformation of value designed to account for attitudes toward risk in cases of decision making under uncertainty (Keeney and Raiffa 1976). A utility function can be treated as a value function for the purpose of scoring alternatives (see Runge and Converse, chapter 13, this volume and the case studies in part 4 for more on utility).

The basic case in MAVT/MAUT is an additive value function, V, for alternative j, constructed as

$$V_j = \sum_{i=1}^{n} w_i x_{i,j} \tag{1}$$

where $x_{i,j}$ are performance predictions on each of a set of $i = 1 \ldots n$ criteria (attributes), evaluated for each of the alternatives $j = 1 \ldots K$. These criteria are used to distinguish between alternatives, that is, they represent the decision maker's objectives (Keeney and Raiffa 1976). The w_i represent weights associated with each attribute and capture the relative importance of the attributes to the decision maker. The w are chosen such that $\sum_{i=1}^{n} w_i = 1$. If we have, for example, $w = (0.2, 0.8)$ for 2 attributes $i = 1, 2$, which typically are measured on different scales, the decision maker is indifferent to trading off a loss of 4 units of attribute 1 for a gain of 1 unit of attribute 2. For a criterion $i = I$, if we place each of the $x_{i=I,j}$ on a standardized scale (e.g., where 0 represents the poorest performance on that attribute and 1 represents the best performance; see also Martin and Mazzotta 2018a) and repeat that process for each of the $i = 1 \ldots n$ criteria, we can calculate the value of any alternative, given a set of weights, using eq. 1. This is the process behind, for example, the simple multi-attribute rating technique with swings (SMARTS; Edwards 1977; Edwards and Barron 1994). SMARTS assumes that value scales linearly across the range of performance values for any $x_{i=I,j}$, and it makes use of *swing weighting* for determining objective weights (von Winterfeldt and Edwards 1986). Swing weighting arises from the idea that the weight of an objective should be a function of not just its general importance to the decision maker but also the degree to which the alternatives vary on that objective. A decision maker might claim that cost is important, but if the alternatives range in cost between, say, \$20,000 and \$20,500, the cost may not carry a lot of weight in the decision. SMARTS is demonstrated in this part by both Smith and McRae (chapter 6) and Walshe and Slade (chapter 7). Other methods for eliciting weights include those based on ordinal scales of importance—that is, ranks—of objectives (e.g., rank order centroid weights; Edwards and Barron 1994) as well as additional methods based—as swing weights are—on cardinal scales, including direct elicitation of weights. Srivastava et al. (1995) describe and evaluate 7 weighting methods based on experimental data and tentatively conclude that rank order centroid weights, derived from an interim step in the swing-weighting procedure, offer a favorable combination of predictive performance and ease of elicitation. The process of specifying weights can provide insights and guide the creation of additional creative alternatives, in that the best alternatives will help to achieve the most important and therefore highest-weighted objectives.

Closely related to, but distinct from, MAVT methods is the analytic hierarchy process (AHP; Saaty 1980; Saaty and Vargas 2012). In AHP, the decision maker performs pairwise comparisons of objectives on ratio scales (e.g., 9 = reference objective is 9 times as important as the comparator, 1 = reference objective is exactly as important as the comparator, 1/9 = reference objective is 1/9 as important as the comparator). This step is followed by pairwise comparisons of alternatives in terms of their performance on each objective. Pairwise comparisons of objectives can be used to calculate objective weights from the eigenvectors of the matrix of pairwise comparisons, and in combination with the output of comparisons of alternatives they can be used to develop quantitative scores for alternatives.

Outranking methods do not assume that a decision maker has a value or utility function that is known, nor do they assume that judgments about preferences are certain. Instead, the focus is on producing outranking relationships, or degrees of preference, for the alternatives under consideration. Outranking methods are an outgrowth of voting theory and particularly suit processes in which at least some of the relevant criteria are qualitative in nature (Kangas et al. 2001). Key concepts include indifference and preference thresholds. A difference in performance between 2 alternatives on a given criterion (objective) that is less than an indifference threshold indicates that the decision maker is indifferent between the alternatives on that criterion. A difference in performance that is greater than a preference threshold indicates that the decision maker has strong, or strict, preference for the alternative with the more favorable value on that criterion. Between the indifference and preference thresholds, a decision maker will have weak, or fuzzy, preference for the alternative with the more favorable value. Within this general framework, the various outranking methods differ in the approach used to ascertain and quantify indifference, weak preference, and strong preference and on how overall outranking relationships are assessed given the set of criteria under consideration. Major classes of outranking methods include the ELECTRE family (Figueira et al. 2005; Roy 1991) and the PROMETHEE family (Brans and Mareschal 2005). Kangas et al. (2001) describe the use of outranking approaches in forest management strategy selection, and Martin and Mazzotta (2018b) describe an application to wetland restoration.

Deliberative Approaches to Negotiating Trade-Offs

Not all problems need to be solved through quantitative analysis of trade-offs. In some cases, just by going through the preceding steps—clearly defining the decision, articulating objectives, identifying alternatives, making predictions, and simplifying the problem to eliminate dominated alternatives—a decision maker will find that a clear winner emerges. Perhaps, through emphasizing creative, and often iterative, generation of alternatives, an alternative will be identified with which all stakeholders are happier compared to the status quo. If a clear winner does not emerge, the decision maker and stakeholders should still be much better prepared to understand and discuss trade-offs because the process of framing and simplifying the problem should make the key trade-offs explicit. At this point, some groups may be prepared to undertake approaches to trade-off analysis that focus on structured discussions rather than quantitative techniques. This may involve direct negotiations around a reduced set of alternatives. If only 2 or 3 objectives are important to the decision, a plot of the alternatives on the Pareto frontier can be useful in facilitating this discussion. Such deliberative approaches may also be used in conjunction with quantitative approaches. For example, Gregory et al. (2012) advocate use of multiple methods in conjunction, including (1) comparative discussions of pairs of alternatives to identify practically dominated alternatives that can be eliminated without controversy, (2) direct ranking of alternatives, and (3) quantitative analyses. Inconsistency in the outcomes from direct ranking of alternatives and quantitative analyses can expose weaknesses in the framing, such as missing objectives. Discussion itself can provide insights to decision makers that might be missed if there were too strong an emphasis on the results of quantitative analyses. Ultimately, the goal should be a decision that is most likely to satisfy the decision maker and stakeholders, and several pathways may lead to that goal.

Case Studies

In chapter 6, David Smith and Sarah McRae describe a process undertaken to support the development of a conservation strategy for an endangered mussel endemic to North Carolina, in the southeastern United States. Management objectives included maximizing probability of persistence and the genetic diversity of the mussel, maximizing public support, and minimizing management costs. Thus, the problem exemplifies a fundamental challenge in species conservation problems: How do we trade off conservation against monetary costs? Alternatively, how do we efficiently allocate our precious monetary resources? The persistence objective contained further complexity: Managers wanted to conserve the species in each of 2 watersheds where it is endemic. Therefore, this problem illustrates another common aspect of species conservation problems: where conservation happens matters. Frequently managers want to conserve things in many places, but some spatial allocations of resources may perform worse than others in terms of overall species conservation. We then must consider how to trade off local benefits for global benefits. The analysts used SMART to deal with trade-offs. The decision analysis contributed to a management plan for the species that can be used to determine how to allocate relatively scarce monetary resources when they become available. The plan emphasized actions in the watershed with a relatively intact population and deemphasized actions in the watershed with greater threats. Many conservation spending decisions tend to be made without careful attention to their impacts on fundamental objectives, resulting in an inefficient use of scarce resources. This case study emphasizes the value of a structured approach so that efficient decisions can be identified.

In chapter 7, Terry Walshe and Stephanie Slade describe a process for deciding among alternatives for fisheries closures to protect finfish on the Great Barrier Reef off the coast of Queensland, Australia. The problem was made challenging by the strongly differing values of stakeholders and the tight timeline that was set for completing the process. In addition to protection of finfish populations, objectives included maximizing access by fishers in commercial, recreational, and charter sectors and realizing ecosystem benefits, among others. The analysts used a novel approach to make the problem tractable for the time allowed. They began with eliciting *global weights* on a wide suite of objectives. Global weights are based on a global scale of values derived from the decision maker's experience or imagination, while *local weights*, such as swing weights, are based on a local scale derived from the specific alternatives available (Monat 2009). That is, the bounds of a global scale are determined by the decision maker's experience or imagination about the extreme values that a given criterion might take, while the bounds of a local scale are based on the best- and worst-performing alternatives on that criterion in the alternative set. The weakness of global weights is that they don't account for the range of performance on the objectives. Walshe and Slade used global weights to reduce the problem to a manageable scope. They then used a SMART analysis with context-specific (local) weights to evaluate alternatives. The analysis was completed individually for a range of stakeholders with strongly varying views. The analysts demonstrated how to identify alternatives that are robust to uncertainty, using sensitivity analysis and a minimax optimization approach. They also identified alternatives that represented reasonable compromises for a variety of stakeholders, as opposed to alternatives that were polarizing. The information gained directly informed a decision by the minister responsible for fisheries. Walshe and Slade emphasize the value of a technically simple approach, like SMART, in the context of a contentious decision and limited time.

In chapter 8, Dan Ohlson and colleagues describe a process for determining allowable water withdrawals from the Lower Athabasca River for oil sands mining in Alberta, Canada. Water withdrawals have potential effects on a multitude of values. The decision analysts, in this case, used a negotiation-oriented approach to trade-offs between values represented by different interest groups (oil sands mining industry, First Nations, and nonprofit environmental organizations). Through a modeling platform that allowed for creation and evaluation of water withdrawal alternatives in real time, stakeholders collaborated to build alternatives that struck an acceptable balance between different stakeholders' values. In other words, trade-offs were not evaluated formally, but instead, the process was designed to facilitate collaboration and negotiation to identify mutually acceptable trade-offs. The results of the process were consensus recommendations on water withdrawals under most flow conditions and articulation of exactly where disagreements lay under extreme low-flow (drought) conditions. That information directly informed government regulators' decisions. While the analysts initially undertook the problem with a plan to use quantitative trade-off methods, their realization was that, given that values trade-offs were quite apparent, a quantitative trade-off approach (i.e., weighting objectives) risked increasing polarization. An informal approach preserved their collaborative environment and led to a search for creative and widely palatable alternatives.

Open Questions and Sticky Issues in Multi-objective Decision Making

Perhaps more than any other, a key challenge in multiple-objective decision problems is our ability to fully capture important values. The set of criteria identified in a multiple-objective process should be exhaustive, cohesive, and nonredundant (Roy 2005). Unfortunately, attaining an exhaustive set of objectives is not simple. Stakeholders and decision makers often find it challenging to identify all their objectives. In a series of experiments, Bond et al. (2008) found that decision makers, when making a decision that was of substantial personal consequence, missed nearly half of the objectives that they later identified as important. Furthermore, they identified the objectives that they initially missed as being as important as the objectives they did identify. This is startling: People are only able to identify about half of the things that are (or ought to be) influencing their decisions! Failing to recognize all important objectives can seriously undermine a decision-making process; unrecognized objectives cannot be used to help generate new alternatives, and they cannot be accounted for in making trade-offs. Bond et al. (2010) and Keeney (2013) provide suggestions for improving the generation of objectives; the most effective methods they identified experimentally included categorizing objectives and challenging participants to do better by warning them that important objectives are (or might be) missing.

One class of objectives is particularly challenging to work with: There may be a tendency to ignore or downplay values that do not easily lend themselves to quantification or even monetization, such as indigenous or other cultural values (Chan et al. 2012; Turner et al. 2008). The values that people place on ecosystems, for example, often include cultural components, including spiritual, aesthetic, artistic, and educational values derived from experiences in nature (Runge et al. 2011; Satterfield et al. 2013). While cultural values cannot easily be quantified, they are often our most personal and closely held values. Furthermore, certain cultural values are sacred to those who hold them, and trade-offs between sacred and secular values may be considered taboo, such that stakeholders asked to consider these trade-offs find the question not just impossible to answer but offensive to consider (Daw et al. 2015; Fiske and Tetlock 1997; Tetlock 2003; Tetlock et al. 2000), although evidence indicates that the degree to which certain types of trade-offs are considered taboo may be context-specific (Baron and Leshner 2000). The difficulty in measuring cultural values and the existence of taboo trade-offs suggest that substantial care must be taken in considering and characterizing cultural values in decision-making processes. Satz et al. (2013) identified challenges associated with inclusion of cultural values in environmental decision making, including interconnected benefits, which make it difficult to develop independent measures of cultural and noncultural benefits; fundamental noncomparability with noncultural values; and others.

MCDA approaches have been identified as an alternative to conventional cost-benefit approaches that rely on monetization of values in environmental decision making (e.g., de Groot et al. 2010; Langemeyer et al. 2016). An important benefit of MCDA in this context is its ability to account for nonmonetary values. Saarikoski et al. (2016) contrast economic valuation and MCDA approaches in environmental decision making and conclude that MCDA offers benefits in terms of its ability to capture nonmonetary values. However, MCDA does not alleviate the challenge of eliciting and quantifying such values; it simply provides a framework for analysis if this elicitation can be achieved. Gould et al. (2014) describe an interview-based approach to assist with elicitation and description of cultural values provided by ecosystems and note that, while not providing quantitative measures, their protocol could guide the design of surveys to obtain quantitative metrics. There are 3 basic types of quantitative measurable attributes (units in which performance on an objective is measured; Gregory et al. 2012): natural measures, proxy measures, and constructed measures. Natural measures reflect achievement on an objective in natural units (e.g., dollars to measure cost); proxy measures are correlated with, but do not directly measure, performance on an objective (e.g., number of fish caught to measure fisher satisfaction); constructed measures are based on scales constructed for the decision at hand, typically to measure things that are otherwise difficult to measure (e.g., scale of 1–7 to measure recreational opportunity). Presumably, cultural values will often be quantified through use of constructed scales. In one of the few MCDA efforts in natural resource management to delve deeply into elicitation and quantification of cultural values, Runge et al. (2011) conducted a process in which spiritual values of Native American tribes were included explicitly in a decision process, using constructed measures. Further approaches for, and examples of, formalizing cultural values are needed.

There is no silver bullet to address the challenges of identifying and appropriately describing objectives in multi-objective decision problems. Perhaps the best practice is developing in decision makers and stakeholders a willingness to see the process of decision analysis as iterative. Once it is recognized that an objective is missing or characterized inappropriately—and this may not happen until a nominally optimal alternative is identified—it is important to go back and consider how this needs to be integrated into the process. Each successive attempt at solving the decision problem is a prototype (Garrard et al. 2017), and the need for further prototyping should be evaluated based on the decision maker's needs and preferences.

LITERATURE CITED

Ball IR, Possingham HP, Watts M. 2009. Marxan and relatives: software for spatial conservation prioritisation. Pages 185–195 in Moilanen A, Wilson KA, Possingham HP, eds. *Spatial Conservation Prioritisation: Quantitative Methods and Computational Tools.* Oxford, UK: Oxford University Press.

Baron J, Leshner S. 2000. How serious are expressions of protected values? *Journal of Experimental Psychology: Applied* 6:183–194.

Bond SD, Carlson KA, Keeney RL. 2008. Generating objectives: can decision makers articulate what they want? *Management Science* 54:56–70.

———. 2010. Improving the generation of decision objectives. *Decision Analysis* 7:238–255.

Brans J-P, Mareschal B. 2005. PROMETHEE methods. Pages 163–195 in Figueira J, Greco S, Ehrgott M, eds. *Multiple Criteria Decision Analysis: State of the Art Surveys*. Boston, MA: Springer.

Chan KMA, Guerry AD, Balvanera P, Klain S, Satterfield T, Basurto X, Bostrom A, Chuenpagdee R, Gould R, Halpern BS, Hannahs N, Levine J, Norton B, Ruckelshaus M, Russell R, Tam J, Woodside U. 2012. Where are *cultural* and *social* in ecosystem services? A framework for constructive engagement. *Bioscience* 62(8):744–756.

Coello Coello CA. 1999. A comprehensive survey of evolutionary-based multiobjective optimization techniques. *Knowledge and Information Systems* 1:269–308.

Daw TM, Coulthard S, Cheung WWL, Brown K, Abunge C, Galafassi D, Peterson GD, McClanahan TR, Omukoto JO, Munyi L. 2015. Evaluating taboo trade-offs in ecosystems services and human well-being. *Proceedings of the National Academy of Sciences* 112:6949–6954.

de Groot RS, Alkemade R, Braat L, Hein L, Willemen L. 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity* 7:260–272.

Edwards W. 1977. How to use multiattribute utility measurement for social decisionmaking. *IEEE Transactions on Systems, Man and Cybernetics* 7:326–340.

Edwards W, Barron FH. 1994. SMARTS and SMARTER: improved simple methods for multiattribute utility measurement. *Organizational Behavior and Human Decision Processes* 60:306–325.

Ehrgott M. 2005. Multiobjective programming. Pages 667–722 in Figueira J, Greco S, Ehrgott M, eds. *Multiple Criteria Decision Analysis: State of the Art Surveys*. Boston, MA: Springer.

Figueira J, Mousseau V, Roy B. 2005. ELECTRE methods. Pages 133–162 in Figueira J, Greco S, Ehrgott M, eds. *Multiple Criteria Decision Analysis: State of the Art Surveys*. Boston, MA: Springer.

Fiske AP, Tetlock PE. 1997. Taboo trade-offs: reactions to transactions that transgress the spheres of justice. *Political Psychology* 18:255–297.

Garrard GE, Rumpff L, Runge MC, Converse SJ. 2017. Rapid prototyping for decision structuring: an efficient approach to conservation decision analysis. Pages 46–64 in Bunnefeld N, Nicholson E, Milner-Gulland E, eds. *Decision-Making in Conservation and Natural Resource Management: Models for Interdisciplinary Approaches*. Cambridge, UK: Cambridge University Press.

Golovin D, Krause A, Gardner B, Converse SJ, Morey S. 2011. Dynamic resource allocation in conservation planning. *Proceedings of the AAAI Conference on Artificial Intelligence* 25:1331–1336.

Gould RK, Klain SC, Ardoin NM, Satterfield T, Woodside U, Hannahs N, Daily GC, Chan KMA. 2014. A protocol for eliciting nonmaterial values through a cultural ecosystem services frame. *Conservation Biology* 29:575–586.

Gregory R, Failing L, Harstone M, Long G, McDaniels T, Ohlson D. 2012. *Structured Decision Making: A Practical Guide to Environmental Management Choices*. Oxford, UK: Wiley-Blackwell.

Hammond JS, Keeney RL, Raiffa H. 2000. The even-swap method for multiple objective decisions. Pages 1–14 in Haimes YY, Steuer RE, eds. *Research and Practice in Multiple Criteria Decision Making*. Berlin: Springer.

Kangas A, Kangas J, Pykäläinen J. 2001. Outranking methods as tools in strategic natural resources planning. *Silva Fennica* 35:215–227.

Keeney RL. 1992. *Value-Focused Thinking: A Path to Creative Decisionmaking*. Cambridge, MA: Harvard University Press.

———. 2002. Common mistakes in making value trade-offs. *Operations Research* 50:935–945.

———. 2013. Identifying, prioritizing, and using multiple objectives. *EURO Journal on Decision Processes* 1:45–67.

Keeney RL, Raiffa H. 1976. *Decisions with Multiple Objectives: Preferences and Value Trade-Offs*. New York: John Wiley & Sons.

Langemeyer J, Gomez-Baggethun E, Haase D, Scheuer S, Elmqvist T. 2016. Bridging the gap between ecosystem service assessments and land-use planning through Multi-Criteria Decision Analysis (MCDA). *Environmental Science & Policy* 62:45–56.

Martin DM, Mazzotta M. 2018a. Non-monetary valuation using Multi-Criteria Decision Analysis: sensitivity of additive aggregation methods to scaling and compensation assumptions. *Ecosystem Services* 29:13–22.

———. 2018b. Non-monetary valuation using Multi-Criteria Decision Analysis: using a strength-of-evidence approach to inform choices among alternatives. *Ecosystem Services* 33:124–133.

Monat JP. 2009. The benefits of global scalinig in multi-criteria decision analysis. *Judgment and Decision Making* 4:492–508.

Retief F, Morrison-Saunders A, Geneletti D, Pope J. 2013. Exploring the psychology of trade-off decision-making in environmental impact assessment. *Impact Assessment and Project Appraisal* 31:13–23.

Roy B. 1991. The outranking approach and the foundations of ELECTRE methods. *Theory and Decision* 31:49–73.

———. 2005. Paradigms and challenges. Pages 3–24 in Figueira J, Greco S, Ehrgott M, eds. *Multiple Criteria Decision Analysis: State of the Art Surveys*. Boston, MA: Springer.

Runge MC, Bean E, Smith DR, Kokos S. 2011. Non-native fish control below Glen Canyon Dam: report from a structured decision-making project. US Geological Survey Open-File Report 2011-1012. http://pubs.usgs.gov/of/2011/1012/.

Saarikoski H, Mustajoki J, Barton DN, Geneletti D, Langemeyer J, Gomez-Baggethun E, Marttunen M, Antunes P, Keune H, Santos R. 2016. Multi-criteria decision analysis and cost-benefit analysis: comparing alternative frameworks for integrated valuation of ecosystem services. *Ecosystem Services* 22:238–249.

Saaty TL. 1980. *The Analytic Hierarchy Process*. New York: McGraw-Hill.

Saaty TL, Vargas LG. 2012. *Models, Methods, Concepts and Applications of the Analytic Hierarchy Process*. International Series in Operations Research and Management Science, edited by Hillier FS. Vol. 175. New York: Springer.

Satterfield T, Gregory R, Klain S, Roberts M, Chan KM. 2013. Culture, intangibles and metrics in environmental management. *Journal of Environmental Management* 117:103–114.

Satz D, Gould RK, Chan KMA, Guerry A, Norton B, Satterfield T, Halpern BS, Levine J, Woodside U, Hannahs N, Basurto X, Klain S. 2013. The challenges of incorporating cultural ecosystem services into environmental assessment. *Ambio* 42:675–684.

Srivastava J, Connolly T, Beach LR. 1995. Do ranks suffice? A comparison of alternative weighting approaches in value elicitation. *Organizational Behavior and Human Decision Processes* 63:112–116.

Tamiz M, Jones D, Romero C. 1998. Goal programming for decision making: an overview of the current state-of-the-art. *European Journal of Operational Research* 111:569–581.

Tetlock PE. 2003. Thinking the unthinkable: sacred values and taboo cognitions. *TRENDS in Cognitive Sciences* 7:320–324.

Tetlock PE, Kristel OV, Elson SB, Green MC, Lerner JS. 2000. The psychology of the unthinkable: taboo trade-offs, forbidden base rates, and heretical counterfactuals. *Journal of Personality and Social Psychology* 78:853–870.

Turner NJ, Gregory R, Brooks C, Failing L, Satterfield T. 2008. From invisibility to transparency: identifying the implications. *Ecology and Society* 13:7.

von Winterfeldt D, Edwards W. 1986. *Decision Analysis and Behavioral Research*. Cambridge, UK: Cambridge University Press.

Williams BK, Szaro RC, Shapiro CD. 2007. *Adaptive Management: The US Department of the Interior Technical Guide*. Washington, DC: Adaptive Management Working Group, US Department of the Interior.

Williams JC. 1998. Delineating protected wildlife corridors with multi-objective programming. *Environmental Modeling and Assessment* 3:77–86.

Williams PJ, Kendall WL. 2017. A guide to multi-objective optimization for ecological problems with an application to cackling goose management. *Ecological Modelling* 343:54–67.