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Incorporating multiple criteria into the design of conservation area networks: a minireview with recommendations

Alexander Moffett and Sahotra Sarkar*

Biodiversity and Biocultural Conservation Laboratory, Section of Integrative Biology, and Department of Philosophy, University of Texas at Austin, 1 University Station, C3500, Austin, Texas, 78712–1180, USA

*Correspondence: Sahotra Sarkar, Biodiversity and Biocultural Conservation Laboratory, Section of Integrative Biology, and Department of Philosophy, University of Texas at Austin, 1 University Station, C3500, Austin, Texas, 78712-1180, USA. Tel: 1 (512) 232 7122; Fax: 1 (512) 471 4806; E-mail: sarkar@mail.utexas.edu

ABSTRACT

We provide a review of multicriteria decision-making (MCDM) methods that may potentially be used during systematic conservation planning for the design of conservation area networks (CANs). We review 26 methods and present the core ideas of 19 of them. We suggest that the computation of the non-dominated set (NDS) be the first stage of any such analysis. This process requires only that alternatives be qualitatively ordered by each criterion. If the criteria can also be similarly ordered, at the next stage, Regime is the most appropriate method to refine the NDS. If the alternatives can also be given quantitative values by the criteria, Goal Programming will prove useful in many contexts. If both the alternatives and the criteria can be quantitatively evaluated, and the criteria are independent of each other but may be compounded, then multi-attribute value theory (MAVT) should be used (with preferences conveniently elicited by a modified Analytic Hierarchy Process (mAHP) provided that the number of criteria is not large).

Keywords

Conservation area networks, multicriteria analysis, multicriteria decision-making (MCDM), reserve selection, systematic conservation planning.

INTRODUCTION

Biodiversity conservation does not occur in a sociopolitical vacuum (Sarkar, 2005). Rather, designating land for conservation competes with other social claims on land including human habitation, recreation, habitat transformation for agricultural or industrial development, biological and industrial resource extraction, etc. Moreover, though the selection of conservation areas has typically focused on the adequate representation of biodiversity surrogates (subsets of species, species assemblages, habitat types, environmental classes, etc.) within conservation area networks, the spatial organization of these networks is also critical to the persistence of biodiversity. Spatial criteria relevant to the design of conservation area networks (CANs) include size, shape, dispersion, connectivity, alignment and replication (Margules & Pressey, 2000; Sarkar, 2004). Consequently, the design of conservation area networks is a multicriteria decision problem that must accommodate many biological and sociopolitical criteria.

Over the last three decades the decision theory community has devised a wide variety of methods for multicriteria decision-making (MCDM). These range from heuristic multidimensional optimization algorithms to the well-developed multi-attribute value and utility theories (MAVT and MAUT) (Dyer *et al.*, 1992; Keeney & Raiffa, 1993; Dyer, 2005). Though conservation biologists have begun to use MCDM methods sporadically, to the best of our knowledge, there has yet been no systematic analysis of the appropriateness of various MCDM methods for CAN design. In this minireview, we initiate such analyses by surveying all major methods and applications of MCDM for CAN design.

CANs are often (though not always) constructed iteratively, that is, by selecting land units, one at a time, for inclusion in a potential network. Consequently, there exist two types of protocol for the incorporation of multiple criteria into CAN design: (1) *iterative* stage protocols in which all criteria are considered as each individual site is selected for potential inclusion in a CAN (Faith & Walker, 1996). In such a protocol, each site is a 'feasible alternative' or, in short, an 'alternative'; and (2) *terminal* stage protocols, in which a set of networks is initially selected, with each network satisfying specified biodiversity representation targets (Sarkar *et al.*, 2004a). Criteria other than biodiversity representation are then used to rank these networks, each of which comprises a feasible alternative. Terminal stage protocols privilege biodiversity representation over other criteria because the satisfaction of the representation targets, in principle, cannot be compromised. Iterative stage protocols typically do not privilege biodiversity representation: they allow trade-offs between this and other criteria. Whether an iterative stage or terminal stage protocol is appropriate is a partly subjective contextual decision, dependent on the perceived importance of biodiversity representation relative to that of the other criteria. Both protocols may

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Table 1 Criteria used in CAN design. The references are only to those studies that explicitly involve incorporation of multiple criteria into CAN design

Biological criteria	Sociopolitical criteria
Biodiversity surrogate representation*	Economic cost†
Size of individual units‡	Recreational value§
Total area¶	Human population**
Shape††	Future economic value‡‡
Dispersion§§	Scenic beauty¶¶
Connectivity***	Cultural heritage†††
Environmental impact‡‡‡	Educational value§§§
Accessibility¶¶¶	

*No additional references are included because every CAN design exercise in this Table includes the representation of biodiversity.
†Mendoza and Sprouse (1989); Laukkanen *et al.* (2002).
‡Sarkar *et al.* (2004b); Moffett *et al.* (2005).
§Mendoza and Sprouse (1989); Malczewski *et al.* (1997); Li *et al.* (1999); Huang *et al.* (2002); Villa *et al.* (2002); Ananda and Herath (2003); Herath (2004); Redpath *et al.* (2004); Janssen *et al.* (2005).
¶Rothley (1999); Noss *et al.* (2002); Sarkar *et al.* (2004b); Moffett *et al.* (2005).
**Malczewski *et al.* (1997); Sarkar *et al.* (2000); Faith *et al.* (2001); Sarkar and Garson (2004).
††Noss *et al.* (2002); Sarkar *et al.* (2004b); Moffett *et al.* (2005).
‡‡Kuusipalo and Kangas (1994); Berbel and Zamora (1995); Faith *et al.* (1996); Malczewski *et al.* (1997); Li *et al.* (1999); Faith *et al.* (2001); Huang *et al.* (2002); Laukkanen *et al.* (2002); Villa *et al.* (2002); Ananda & Herath (2003); Herath (2004); Huth *et al.* (2004); Redpath *et al.* (2004); Janssen *et al.* (2005).
§§Sarkar *et al.* (2004b).
¶¶Laukkanen *et al.* (2002); Bojórquez-Tapia *et al.* (2004); Redpath *et al.* (2004).
***Rothley (1999); Geneletti (2004); Sarkar *et al.* (2004b).
†††Redpath *et al.* (2004); Janssen *et al.* (2005).
‡‡‡Mendoza and Sprouse (1989); Malczewski *et al.* (1997); Li *et al.* (1999); Huang *et al.* (2002); Janssen *et al.* (2005); Phua and Minowa (2005).
§§§Li *et al.* (1999); Bojórquez-Tapia *et al.* (2004); Redpath *et al.* (2004).
¶¶¶Malczewski *et al.* (1997); Li *et al.* (1999); Sierra *et al.* (2002); Villa *et al.* (2002); Bojórquez-Tapia *et al.* (2004); Geneletti (2004); Redpath *et al.* (2004); Sarkar *et al.* (2004b); Moffett *et al.* (2005).

also be used in the same planning exercise with multiple criteria being used both for the iterative site selection stage and to decide between entire nominal networks of selected sites.

The methods we review can be used with either type of protocol. Since MCDM methods are based on an abstract characterization of the criteria, in what follows, we do not distinguish between biological and sociopolitical criteria except in Table 1 which lists the criteria that have previously been used in multicriteria CAN design. Section 2 describes how we identified the MCDM methods we review and surveyed the literature for applications to conservation planning. Section 3 describes the valuational framework and the methods (Sarkar, 2004; Sarkar & Garson, 2004). Section 4 reports our evaluations. We present our final recommendations in Section 5. Appendix S1 describes each method individually, along with its advantages, disadvantages, and examples of its use in conservation planning.

Selection criteria

We do not review methods that explicitly incorporate uncertainty in the decision-making process. With the exception of multi-attribute utility theory (MAUT; Keeney & Raiffa, 1993), these methods are still largely at early stages of development and thus not amenable to immediate use in conservation planning (see, for instance, Duenas & Mort, 2002; Millet & Wedley, 2002; Novikova & Pospelova, 2002). We also leave aside for later review methods that are explicitly designed for use by multiple decision-makers, those in which alternatives are formulated during the decision-making process, and those in which preferences may be dynamically updated during that process. Though these types of protocol clearly capture the informal process of much of conservation (and other) decision-making, they likewise remain insufficiently developed to justify immediate use in conservation planning. Figure 1 provides a flowchart of decision-making scenarios and identifies the type of MCDM methods discussed in this paper.

We used the following textbook surveys of MCDM to compile a list of 'major' methods: Hwang and Masud (1979); Hwang and Yoon (1981); Chankong and Haimes (1983); Yu (1985); Arrow and Raynaud (1986); Steuer (1986); von Winterfeldt and Edwards (1986); Stadler (1988); Bana e Costa (1990); Ringuest (1992); Vincke (1992); Keeney and Raiffa (1993); Yoon and Hwang (1995); Roy (1996); Kirkwood (1997); Gal *et al.* (1999); Miettinen (1999); Bouyssou *et al.* (2000); Triantaphyllou (2000); Belton and Stewart (2002); Collette and Siarry (2003); and Figuera *et al.* (2005). There exist many other MCDM methods that do not find their way into this review. For instance, while we review all methods that receive chapter-length treatment in the books used, we do not review every variant mentioned in them. We exclude those methods that require stronger assumptions than included methods without providing more precise rankings of the alternatives. Similarly, we do not review methods, such as several listed by Hinloopen *et al.* (1983a; p. 147), for which we could not find any documentation. Throughout we have retained the (often idiosyncratic) names of the methods given by their inventors rather than variants introduced by reviewers.

To search for applications to conservation planning, we performed keyword searches for each of the identified methods in all Blackwell, Elsevier and Kluwer journals. Additional keyword searches were performed on these journals using: 'multicriteria', 'multi-criteria', 'multiple criteria' and 'MCDM'. From the results of these searches, we compiled a list of those papers documenting the application of MCDM methods to the design of CANs. From this initial set, we retained only those articles that explicitly applied MCDM methods to the problem of representing biodiversity surrogates while taking other criteria into account. The lists of references in these papers were subsequently used to identify any further pertinent applications of MCDM techniques.

The valuational framework and the major methods

A decision scenario consists of a goal, Γ, a set of feasible alternatives (or, in short, alternatives), $A = \{\alpha_j: j = 1, 2, \dots, m\}$, a set of

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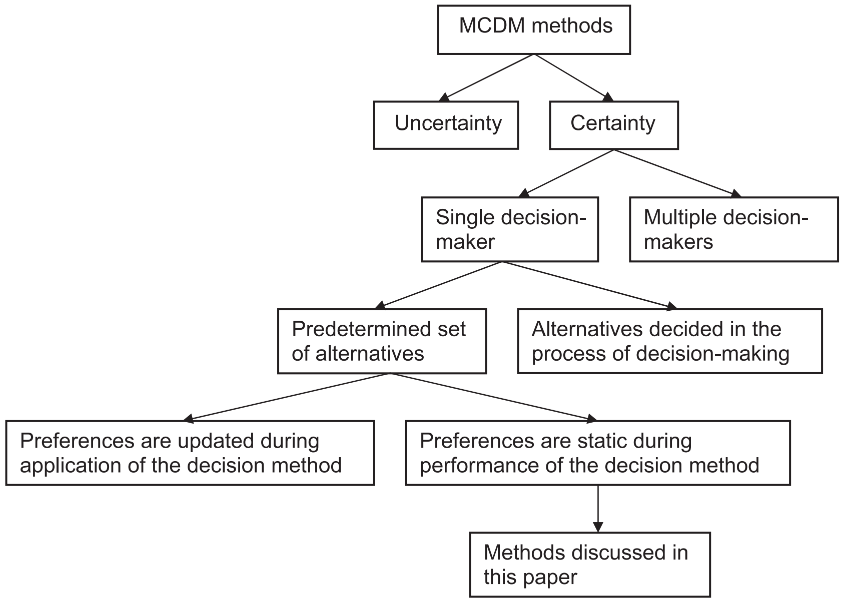

Figure 1 A flowchart of decision-making scenarios. For further discussion, see the text.

criteria, K = {κ_i: $i = 1, 2, \ldots, n$}, and the set of assumptions, Σ, specifying the ways in which A and K can be evaluated.

In the context of CAN design, the elements of A are: either (1) available land units or 'sites' for iterative stage protocols; or (2) potential CANs satisfying representation targets for terminal stage protocols. For the former protocols, K must include biodiversity representation as a criterion in our context. For the latter, K will typically not include biodiversity representation again. The remaining criteria in K may be the same for the two protocols, consisting of both biological (shape, size, dispersion, connectivity, alignment, etc.) and sociopolitical (cost, cultural value, educational value, etc.) criteria.

The goal, Γ, may be the selection of a single 'best' alternative or the selection of a subset of alternatives with or without an ordering. The set of assumptions, Σ, will include whether qualitative or quantitative values can be assigned to an alternative by each criterion, and whether these values can be aggregated across criteria. Due to the wide range of possibilities we do not attempt to provide a formal characterization of Γ or Σ.

By definition, an MCDM method allows the evaluation of A on the basis of K. Available MCDM methods vary both in the assumptions required for their use and in the extent to which they rank alternatives in A on the basis of K (Figuera *et al.*, 2005). The precision of the ranking provided by a method depends on the strength of the assumptions in Σ: the stronger the assumptions, the more specific the ranking. Each method represents a trade-off between the wish to make weak assumptions and the hope to produce a maximally detailed ranking, that is, a total quantitative ranking of the alternatives. A useful taxonomy of methods for MCDM is thus produced by organizing the methods on the basis of the strength of assumptions in Σ. Such a taxonomy allows a decision-maker to select the most appropriate method for a particular decision scenario given what is required by Γ and what can be assumed on account of Σ — see Fig. 2. Here, we only discuss those 19 methods in Fig. 2 that were identified by our criteria (in Section 2); a discussion of the other methods in Fig. 2 is provided in Appendix S1. Explicit reasons for excluding these methods are discussed during the evaluative assessment of the next section.

In constructing a taxonomy of MCDM methods, we begin with the minimal assumption that each alternative can be qualitatively ordered or ranked by each criterion, that is, given any two alternatives, α_e and α_f, and a criterion, κ_l, α_e is either better than, as good as, or worse than α_f by κ_l. (More formally, every criterion introduces a linear (or full) weak order on A. The order is *weak* because α_e can be as good as α_f; in a *strong* order, α_e would be either strictly better than or strictly worse than α_f.) Note that such an assumption of ordinal or qualitative order is weaker than an assumption of quantitative order (that is, quantitative values being assigned). Without this assumption, any attempt to use a criterion to assess an alternative becomes incoherent. This minimal assumption allows the use of three methods (in addition to ELECTRE IV, which we only discuss in Appendix S1):

(1) non-dominated set (NDS) computation. For any two alternatives, α_e and α_f, α_e dominates α_f, or $\alpha_e \succ \alpha_f$ if and only if α_e outperforms α_f on the basis of at least one criterion and performs at least as well as α_f on the basis of all the criteria. The NDS is then the following set of optimal alternatives, {α_j: $(\forall i)\neg(\alpha_i \succ \alpha_j)$}, which are not dominated by any alternative (Sarkar & Garson, 2004). (Note that we will use different symbols ($\succ$, $\succ'$, $\succ''$, etc.) to denote orderings produced in different ways by the different methods.)

(2) Maximin, which ranks the alternatives by comparing each alternative on the basis of its worst ranking under the criteria (Yoon & Hwang, 1995); and

(3) Maximax, which produces a ranking of the alternatives by comparing each alternative on the basis of its best ranking under the criteria (Yoon & Hwang, 1995).

These methods may not rank alternatives in A with sufficient precision to satisfy the goal Γ of a given decision scenario. Three

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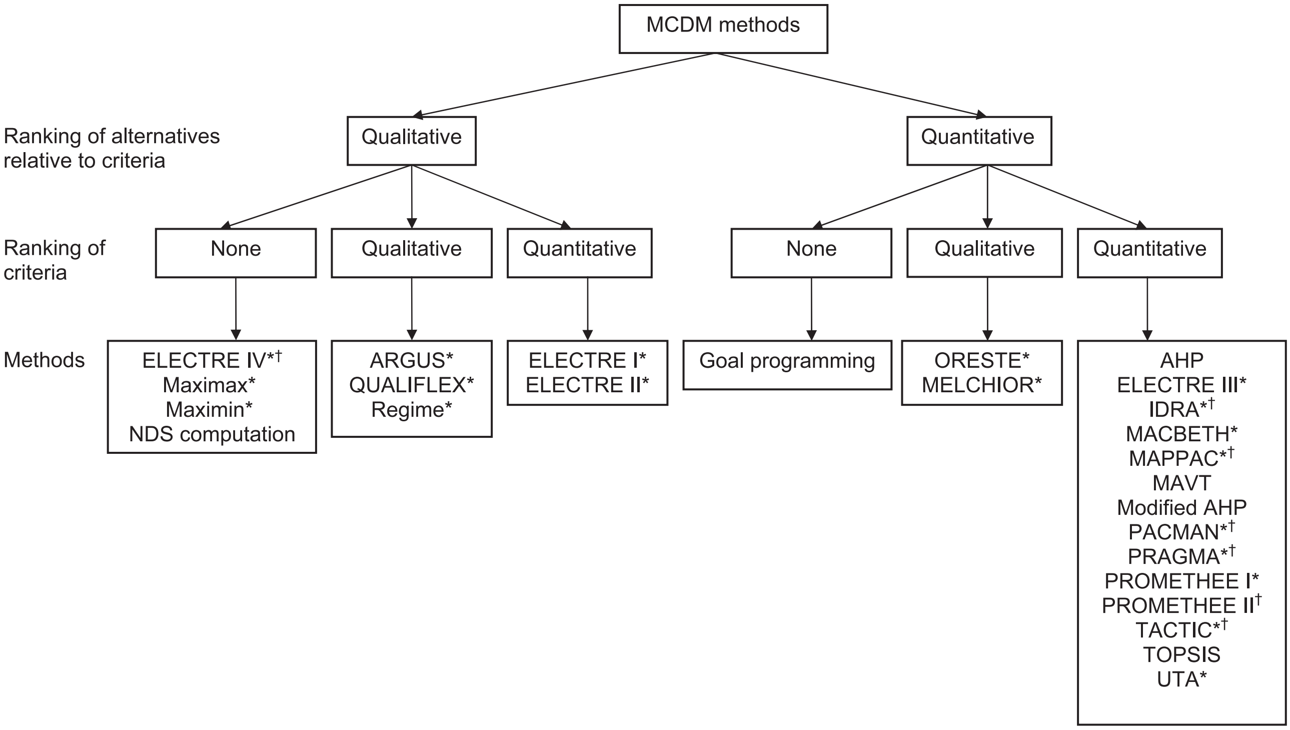

Figure 2 A taxonomy of MCDM methods based on requirements placed on criteria and alternatives. To keep the figure simple, we have eschewed repetition. Throughout, whenever there is a branch, all hanging lists on the left can also be included in the corresponding lists to its right. Thus, it is possible to use NDS computation when there is a qualitative or quantitative ranking of preferences and when the alternatives can also be quantitatively ranked, it is possible to use Regime when there is a quantitative ranking of preferences and when the alternatives can also be quantitatively ranked, and so on. A '*' indicates that this method has never been used in conservation planning; a '†' indicates that the method is only discussed in Appendix S1.

additional methods are available if we add to Σ the assumption that a qualitative evaluation of the criteria is also possible:
(4) Regime. For any two alternatives, α_e and α_f, let K^+ equal the set of criteria in K according to which α_e outperforms α_f and let K^- equal the set of criteria in K according to which α_f outperforms α_e. In Regime, $\alpha_e \succ' \alpha_f$ if and only if $K^+ \neq \emptyset$ and there exists an injective map from K^- to K^+ by which each criterion in K^- is mapped to a more important criterion in K^+. The set of optimal alternatives is then $\{\alpha_j: (\forall i)\neg(\alpha_i \succ' \alpha_j)\}$ (Hinloopen *et al.*, 1983a);
(5) Qualiflex. For each criterion, κ_i, an ordinal value, λ_{ij}, is assigned to each alternative, α_j, representing the rank value of α_j with respect to κ_i. For each κ_i the set of all $m!$ possible rankings of alternatives is produced with μ_{jk} equal to the position of α_j in the k-th such ranking. Let $C_{ik}(\alpha_e, \alpha_f)$, the concordance index associated with the comparison of α_e and α_f with respect to κ_i and the k-th ranking, be defined by $C_{ik}(\alpha_e, \alpha_f) = 1, 0, -1$, respectively, for the three cases, $[(\lambda_{ie} > \lambda_{if}) \wedge (\mu_{ek} > \mu_{fk})] \vee [(\lambda_{ie} < \lambda_{if}) \wedge (\mu_{ek} < \mu_{fk})]$, $[(\lambda_{ie} = \lambda_{if}) \wedge (\mu_{ek} = \mu_{fk})]$, and otherwise. Let C_{ik}, the overall concordance index associated with κ_i and the k-th ranking, be defined by $C_{ik} = \sum_{\alpha_e, \alpha_f \in A} C_{ik}(\alpha_e, \alpha_f)$. The C_{ik} is calculated and aggregated on the basis of a qualitative ordering of the criteria to produce an overall concordance index, C_k, for each ranking. The ranking with the greatest C_k is the optimal one (Paelink, 1976); and
(6) ARGUS begins with qualitative pairwise comparisons of the alternatives on the basis of each criterion and then imposes an order on the criteria. It calculates the number of criteria by which one alternative is better than another, and then compounds the ordinal rankings of the alternatives and these criteria to produce a final ranking of the alternatives (de Keyser & Peters, 1994).
Many more methods become available if we further strengthen our assumptions. Add to Σ the assumption that each criterion, κ_i, can be assigned a quantitative weight, ω_i. Then there are two more methods:
(7) ELECTRE I. For any two alternatives, α_e and α_f, $\alpha_e \succ'' \alpha_f$ if and only if α_e outperforms α_f on the basis of a sufficiently important set of criteria, with the importance of a set of criteria measured by the sum of their weights, while α_f outperforms α_e only on the basis of a sufficiently unimportant set of criteria. Using this outranking relation, the set of optimal alternatives is defined as $\{\alpha_j: (\forall i)\neg(\alpha_i \succ'' \alpha_j)\}$ (Roy, 1968); and
(8) ELECTRE II, which defines both a weak and a strong outranking relation and uses both relations to provide a ranking of the alternatives in A (Roy & Bertier, 1973).

Next, suppose we assume that a quantitative value can be assigned to each alternative on the basis of each criterion. This is a critically important assumption which, if justifiable in a decision scenario, provides a wide range of powerful methods. There are at least two sources of uncertainty which may prevent such an attribution:

imprecise definition of alternatives, and imprecise measurability of the alternatives. In the context of CAN design, the former problem is rarely relevant; alternatives are well-defined, either as individual sites or as entire sets of selected sites. The question of measurability remains. Some sociopolitical criteria such as economic cost and some spatial design criteria such as the size of selected units are relatively easily quantified. Others, including sociopolitical criteria such as social cost or forgone opportunity costs, as well as spatial design criteria, such as shape or connectivity, are not easily quantifiable. Consequently, we often have more confidence in results produced by the qualitative evaluation of the alternatives than in results dependent on quantitative analyses. This is what generates interest in the left branch of the tree in Fig. 2, although, if we either elicit quantitative preferences or otherwise approximate qualitative rankings by quantitative values (sometimes called 'pseudo-metric' values) many computationally more straightforward MCDM methods become available (Hinloopen *et al*., 1983b).

If we include in Σ only the assumption that a quantitative value can be assigned to each alternative on the basis of each criterion (and thus nothing about the ranking of the criteria) this makes available one more method:

(9) Goal Programming. A value, v_{ij}, is assigned to each α_j on the basis of each κ_i, a goal, γ_i, is assigned to each criterion representing the minimal acceptable level of performance of an alternative relative to κ_i, and an optimal set of alternatives is defined as $\{\alpha_j: (\forall i)(v_{ij} \geq \gamma_i)\}$.

If we now add to Σ the assumption that a qualitative rank can be assigned to each criterion, there are two additional methods:

(10) Oreste, which uses the qualitative ranking of the criteria to rank the performances of each of the alternatives with respect to each criterion (thus requiring the comparison of, for example, the performance of α_e on the basis of κ_g with the performance of α_f on the basis of κ_h) and uses this ranking to rank the alternatives in A (Roubens, 1982); and

(11) MELCHIOR, which uses the quantitative values assigned to the alternatives to define notions of strict and weak preference, depending on assumed threshold values for preferences, and exploits these definitions, in conjunction with the qualitative ranking of the criteria, to rank the alternatives in A through a complicated algorithm (Leclercq, 1984).

A wealth of MCDM methods becomes available if Σ includes the assumption that a quantitative value can also be assigned to each criterion. At this point, a new distinction becomes important: namely, whether the evaluations along the different criteria can be compounded or not. If there is no compounding, a method is called an 'outranking' method. ELECTRE III and PROMETHEE I are two such methods, as are all the methods discussed earlier. If compounding takes place, essentially, what is calculated is a value function that summarizes the total performance of each alternative by aggregating its performance with respect to each of the criteria. (Another way of interpreting this assumption is that all criteria are assumed to be commensurable with each other (Sarkar, 2005): they may be measured on the same value scale.) Assuming that an aggregate value function can be produced amounts to a commitment to some version of the standard economic model of preferences. It allows the co-option of all the techniques that have been developed for the elicitation of preferences, etc., but is also subject to the standard objections to the economic model of rationality (Arrow & Raynaud, 1986). The alternative methods available differ in how they estimate this value function.

If we are unwilling to add to Σ the assumption that the criteria can be compounded, two new methods are available:

(12) ELECTRE III, which is similar to ELECTRE II but allows the use of 'pseudo-criteria' (which rank alternatives in intervals, rather than at points) besides true criteria. This may result in a more precise ranking of the alternatives in A than that provided by ELECTRE II (Roy, 1978); and

(13) PROMETHEE I, which constructs a unique value function for each criterion, uses these functions to assign a quantitative value to each alternative on the basis of each criterion, and then uses these values, in conjunction with criteria weights, to rank the alternatives in A (Brans & Vincke, 1985).

If we are willing to embrace aggregation, six new potentially important methods become available (while we relegate discussion of six others to Appendix S1):

(14) the multiple attribute value theory (MAVT), which constructs a unique value function for each criterion, assigns quantitative weights to the criteria on the basis of comparison between two alternatives and aggregates the product of criterion weights and alternative values under each criterion (Dyer & Sarin, 1979; Keeney & Raiffa, 1993);

(15) the Analytic Hierarchy Process (AHP), which uses pairwise comparisons of the alternatives to assign a value to each alternative on the basis of each criterion, assigns weights to the criteria on the basis of a second set of pairwise comparisons and assigns overall values to the alternatives by aggregating these values (Saaty, 1980);

(16) the modified Analytic Hierarchy Process (mAHP), which constructs a linear value function for each criterion, assigns a quantitative weight to each criterion using the pairwise comparisons of the AHP, aggregates the single criterion value functions on the basis of the assigned weights and uses the resultant function to assign a quantitative value to each alternative (Dyer, 1990; Sarkar *et al*., 2004b; Moffett *et al*., 2005);

(17) MACBETH, which uses comparisons made between pairs of alternatives on the basis of each criterion to produce a linear program that is then solved to produce an aggregate value function consistent with the comparisons (Bana e Costa & Vansnick, 1994);

(18) TOPSIS, which constructs an *n*-dimensional Euclidean space with each criterion along an axis, assigns a point in this space to each alternative based on its performance by each criterion, does the same for a point supposed to represent a hypothetical optimal alternative and ranks each alternative on the basis of its distance from this optimum (Yoon & Hwang, 1995); and

(19) UTA, which likewise constructs a value function on the basis of a linear program, with the program here constructed on the basis of the ranking of a subset of A (Jacquet-Lagreze & Siskos, 1982).

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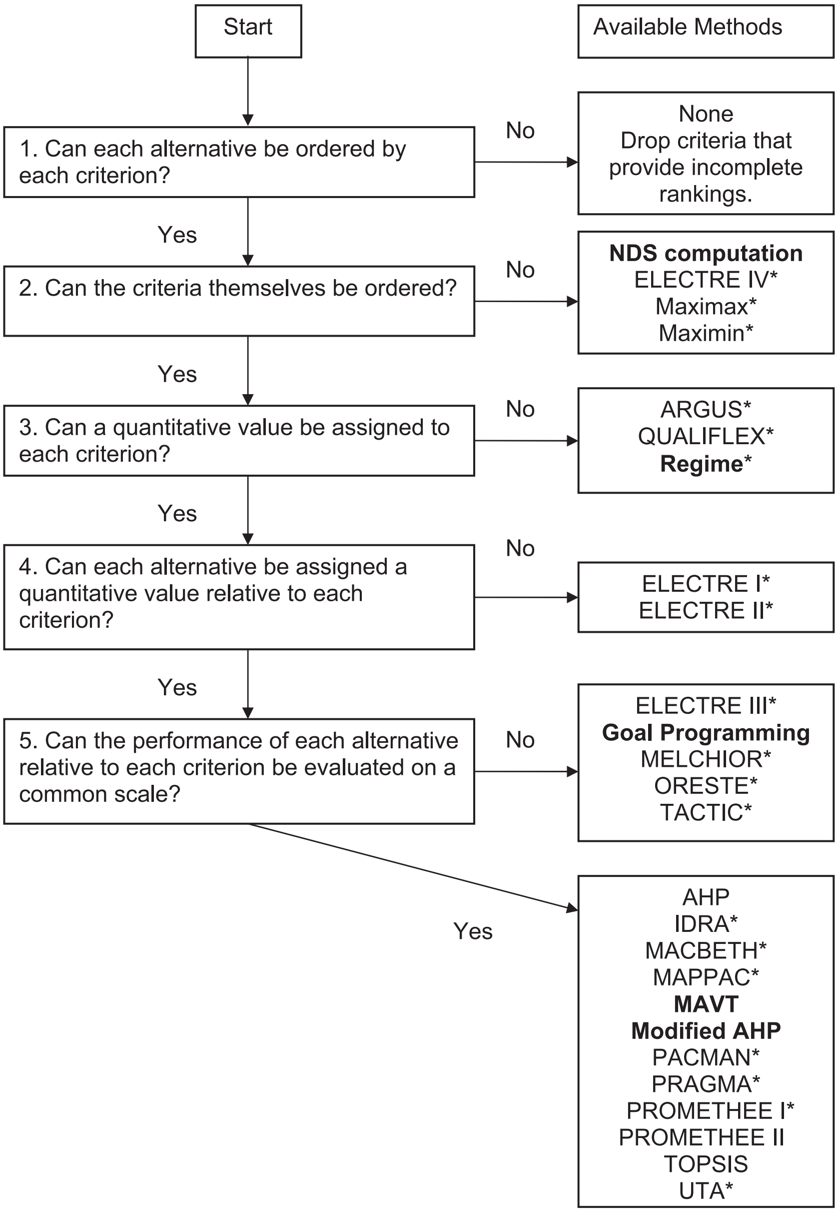

Figure 3 A decision procedure for the selection of an existing MCDM method. A '*' indicates that this method has never been used in conservation planning; methods indicated in bold are recommended in Section 5. For further discussion, see the text.

Critical appraisal

The Appendix discusses all the 26 methods we found, gives sufficient details for their use, lists each of their advantages and disadvantages individually, as well as some of the software packages available to use them — our coverage of software packages is not intended to be comprehensive (for more detail see Figueira *et al.*, 2005). In the text, we only mention those software packages that have been used for conservation planning; once again, our coverage is not comprehensive — we are not attempting a review of software here. Figure 3 shows a decision procedure that can be used to guide the selection of an MCDM method for conservation planning.

The method that is best in the sense of making the least assumptions is NDS computation. The evaluation of a set of alternatives through the calculation of the NDS has the following advantages: (1) it requires only that each criterion induce a weak linear ordering on the alternatives, and thus does not require (a) the assignment of quantitative values to the alternatives, (b) an evaluation of the relative importance of the criteria, or (c) an independence assumption requiring that the preferences for values on one criterion are not influenced by values on the other criteria; (2) it introduces no subjective information into the decision-making process other than that required to produce the weak orderings of the alternatives; and (3) its results are compatible with those of any other rational decision procedure. Moffett *et al.* (2005) describe how the MULTCSYNC software package enables NDS computation and is designed for use with a terminal stage protocol for CAN selection. The other methods that do not make any stronger assumptions, MaxiMax and MaxiMin, do not have such

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a justification; ELECTRE IV (Roy & Hugonnard, 1982), which is relegated to the Appendix, besides not having such a justification, is also inordinately complicated.

In a terminal stage protocol, if the number of non-dominated alternatives is small, the non-dominated alternative set can be presented to political decision-makers who can then select among these alternatives on the basis of considerations beyond those that have been modelled (Sarkar & Garson, 2004). However, the cardinality of the NDS typically increases with the number of criteria (Sarkar & Garson, 2004). In many decision scenarios, the cardinality of this set will be too high to turn over to decision-makers. In such scenarios, the identification of the preferred alternative from this set will require further analysis of the alternatives. Moreover, in iterative stage protocols, computing the NDS at each iteration may result in sets of large cardinality. In such circumstances, we must further refine the NDS. But this will require at least the ordinal ranking of the criteria.

The Regime method provides the natural first strategy to eliminate some alternatives in the NDS. Because this method has never been used in conservation planning, it is impossible to assess the likelihood that it will suffice to decrease sufficiently the size of the final set of preferred alternatives. ARGUS requires compounding of rankings of alternatives and criteria by a method that is open to the charge of being *ad hoc*. Qualiflex is also open to this charge, as well as to a similar one for assuming that each pairwise comparison of the ranking of alternatives has the same value. The situation in which the criteria can be plausibly quantitatively ordered but the alternatives can only be qualitatively ordered — that is, the domain of the ELECTRE I and the ELECTRE II methods — remains unknown in conservation planning.

Turning to situations in which the alternatives receive quantitative values, Goal Programming is the only method that has been used in which the criteria are not ranked at all. Essentially this is a heuristic optimization method. There are situations in which this is clearly useful when the relevant performance thresholds can be satisfactorily specified. Both HYPERLINDO and LINDO/386 5.3 (Lindo Systems, 1995) are software packages that have been used for Goal Programming in the context of conservation planning (Berbel & Zamora, 1995; Rothley, 1999). Oreste requires the comparison of the value of one alternative by one criterion with the value of another alternative by some other criterion — it is unclear that such comparisons can be meaningfully made. MELCHIOR may be useful but is inordinately complicated; the threshold values for preferences that it assumes may also be criticized for being *ad hoc*.

If both criteria and alternatives are assigned quantitative values, the most important questions are: (1) whether the criteria are independent of each other in the technical sense required by MAVT (the criteria themselves must exhibit mutual difference independence; see Dyer, 2005); and (2) whether the different criteria can be aggregated. If these conditions are met, then there is no conceptual reason not to use MAVT. EXPERT CHOICE (Expert Choice, 1995) and DEFINITE (Janssen *et al.*, 2001) are software packages for MAVT which have been used for conservation planning (Bojórquez-Tapia *et al.*, 2004; Geneletti, 2004). If we can assume independence but not aggregativity, then outranking methods such as ELECTRE III and PROMETHE I look promising. However, ELECTRE III has never been used in the context of conservation planning and PROMETHEE I has only been used with an artificial data set (Drechsler, 2004). (Surprisingly, the weaker PROMETHEE II has been used in this context; see Laukkanen *et al.*, 2002.) No further assessment of the merits of these methods in this context is at present possible.

However, eliciting the preferences required to use MAVT can be complicated and time-consuming. The AHP helps by enabling the easy elicitation of the relevant information about preferences by paired comparisons on a ratio scale (provided that the number of criteria is not too high in which case pairwise comparisons may also become onerous). The AHP has been immensely popular in conservation planning (see Table 2). EXPERT CHOICE (Expert Choice, 1995) and MULTCSYNC (Moffett *et al.*, 2005) are among software packages implementing AHP that have been used in conservation planning (Malczewski *et al.*, 1997; Ananda & Herath, 2003; Bojórquez-Tapia *et al.*, 2004; Sarkar *et al.*, 2004b). However, the AHP is open to theoretical criticism because it allows rank reversal: the ranking of any two alternatives may be reversed when a new alternative (even a dominated alternative) is brought into consideration (Dyer, 1990). Thus it violates the independence of irrelevant alternatives axiom of decision theory (Arrow & Raynaud, 1986). The modified AHP (mAHP) avoids this problem and produces rankings consistent with the results of MAVT but by using the simpler preference elicitation process of the AHP — this is its major strength. However, such an elicitation process may become cumbersome if there are a large number of criteria. The MULTCSYNC software package (Moffett *et al.*, 2005) implements the mAHP in a way that is suited for CAN design.

MACBETH, TOPSIS and UTA all assume the independence and aggregativity conditions. They differ from the MAVT and AHP in how they carry out aggregation. MACBETH and UTA are alternative methods to construct an aggregate value function; conceptually there is no reason to use either over MAVT or mAHP. TOPSIS is another such method and is also open to the further criticism that its hypothetical optimum is not a feasible alternative, and therefore, distances from it may be meaningless. (For a use of TOPSIS in conservation planning see Phua & Minowa, 2005.)

If the preferences do not even approximately satisfy the independence condition or the aggregativity condition, then the use of mAHP or any other method for evaluating utility or value functions becomes suspect. If the independence condition is satisfied but the aggregation condition is not, outranking methods such as ELECTRE III and PROMETHEE I may be the only option.

IDRA (Greco, 1997), MAPPAC (Matarazzo, 1990), PACMAN (Giarlotta, 1998) and PRAGMA (Matarazzo, 1988) are all pairwise criterion and comparison approach (PCCA) methods. We relegate these to Appendix S1 because they make at least as strong assumptions as MAVT but only produce ordinal rankings of the alternatives. PROMETHEE II is weaker than PROMETHEE I and there is no motivation to use it. Nevertheless, in the context of conservation planning, it has been used by Laukkanen *et al.*

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Table 2 Applications of multicriteria methods to biodiversity conservation planning

Reference	MCDM methods	Criteria	Region	Protocol	Software
Anselin *et al.* (1989)	AHP	Duck species; wader species; passerine species	Sweden	Terminal	Not specified
Mendoza and Sprouse (1989)	AHP; MAXIMIN	Net present value; recreation value; wildlife; volume of timber; erosion	USA	Iterative and Terminal	Not specified
Kuusipalo and Kangas (1994)	AHP	Net income during first 10 years; net income during second 10 years; value of stands after 20 years; old forest species; young forest species; species dependent on hardwood	Finland	Terminal	Not specified
Berbel and Zamora (1995)	Goal Programming; NDS computation	Income; roe deer population	Spain	Iterative and Terminal	HYPERLINDO
Faith *et al.* (1996)	Goal Programming*	Forestry suitability; biodiversity	Australia	Iterative	DIVERSITY and LUPIS
Malczewski *et al.* (1997)	AHP; Goal Programming	Presence of wells; market accessibility index; number of heads; density of roads; vegetation type; number of hotel rooms; water accessibility; distance to cities; distance to coral reef; distance to roads; presence of oak and oak-pine forest; presence of natural forest coverage; distance to tourist facilities; slope, distance to airports; volume of water; access time; number of visitors; number of fishing boats; distance to high production wells; level of industrialization; total population; altitude	Mexico	Iterative and Terminal	EXPERT CHOICE
Li *et al.* (1999)	AHP	Local inhabitants' resource requirements; tourism and scientific research; environmental quality; accessibility	China	Terminal	Not Specified
Rothley (1999)	NDS computation; MAVT	Connectedness; area; number of rare plant species	Canada	Terminal	LINDO/386; SIGMA PLOT
Sarkar *et al.* (2000)	NDS computation	Area; population; biodiversity	USA	Terminal	Not specified
Faith *et al.* (2001)	Goal Programming*	Timber production; agricultural potential; land use intensity; human population; biodiversity	Papua New Guinea	Iterative	TARGET
Huang *et al.* (2002)	AHP	Fuel wood; timber wood; fruit; fodder; hunting; food; cash; vegetable; soil erosion; water; nitrogen-fixing	Tanzania	Terminal	Not specified
Laukkanen *et al.* (2002)	AHP; PROMETHEE II	Net income; biodiversity; monetary value of future timber production; scenic beauty; wild berry yield	Finland	Terminal	Not specified
Noss *et al.* (2002)	MAVT	Area; species representation; boundary length; protects imperiled local-scale species; vulnerable and declining bird species; coarse-scale and regional-scale aquatic species; plant communities; vegetation types; geoclimatic classes; aquatic habitats; focal species	USA	Iterative and Terminal	Not specified
Sierra *et al.* (2002)	MAVT	Biodiversity; habitat loss; exposure to human activities; endemism and conservation status of bird species	Ecuador	Iterative	Not specified
Villa *et al.* (2002)	AHP	Natural value of coastal environment; value for commercial exploitation; recreational value; accessibility and potential disturbance; natural value of marine environment	Italy	Iterative	Not specified
Ananda and Herath (2003)	AHP	Timber; biodiversity; recreation	Australia	Terminal	EXPERT CHOICE
Bojórquez-Tapia *et al.* (2003)	AHP; TOPSIS	Elevation; aridity; aspect; nearness to streams; slope; vegetation type	Mexico	Iterative	Not specified
Memtsas (2003)	MAVT; NDS computation; TOPSIS	Number of species; total species rarity; total site richness; total site rarity	Crete	Terminal	LINGO

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Table 2 Continued

Reference	MCDM methods	Criteria	Region	Protocol	Software
Bojórquez-Tapia *et al.* (2004)	AHP; MAVT	Dark area; scenic quality; environmental education; access; black tail dear; cougar; small mammals; condor; trout; herps; mixed conifer; meadows; Jeffrey pine; Pinyon; oak; chaparral; springs; meadows; enclosures; grasslands	Mexico	Iterative	EXPERT CHOICE
Drechsler (2004)	PROMETHEE I	Expected population lifetime of four bird species	None: Artificial scenario	Terminal	Not specified
Geneletti (2004)	MAVT	Rarity; isolation; dimension; exposure to disturbance	Italy	Iterative	DEFINITE
Herath (2004)	AHP	Conservation value; business investment; recreation visitor days; extent of river red gum; number of bird species	Australia	Terminal	Not specified
Huth *et al.* (2004)	MAVT	Yield; canopy opening; species composition	Malaysia	Terminal	Not specified
Redpath *et al.* (2004)	MAVT	Keepers jobs; conservation jobs; other jobs; tourism; hunting; grants; taxes; protected species; protected areas; access regulations; education; research; community viability; management; tradition; enjoyment by owner; enjoyment by others; heather cover; heather burns; access routes; tree cover; grazed area; appearance; vegetation; vertebrates; invertebrates; red grouse; raptors; fox, corvid and stoats; hares; sheep; dear; waders and other birds	UK	Terminal	Not specified
Sarkar and Garson (2004)	NDS computation	Area; accessibility; connectivity; human population	USA and Ecuador	Terminal	MULTCSYNC
Sarkar *et al.* (2004b)	AHP; modified AHP; NDS computation	Area; connectivity; dispersion; size of individual units; accessibility	Ecuador	Terminal	MULTCSYNC
Janssen *et al.* (2005)	MAVT	Water purification; water retention; peak storage; flood storage; carbon retention; greenhouse gas emissions; flora diversity; fauna diversity; cultural heritage; agriculture; recreation	Holland	Terminal	DEFINITE
Moffett *et al.* (2005)	AHP; modified AHP; NDS computation	Area; accessibility; connectivity; human population	Ecuador	Terminal	MULTCSYNC
Phua and Minowa (2005)	Modified AHP; TOPSIS	Species diversity; ecosystem diversity; landslide prevention; drought prevention; flood prevention	Malaysia	Iterative	Not specified

*This is our interpretation of the method used; no theoretical justification of the method is provided in the text. See the discussion in the text (at the end of Section 4).

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(2002); see our discussion of PROMETHEE I for a description of the method. TACTIC (Vansnick, 1986) offers nothing that is not offered by the ELECTRE family of methods (Martel & Matarazzo, 2005). These two methods have therefore also been relegated to Appendix S1.

Finally, many heuristic procedures for CAN selection implicitly carry out *ad hoc* multiple criterion incorporation during an iterative stage protocol. For instance, a large class of algorithms belong to a family explicitly introduced by Margules *et al*. (1988) in which sites are iteratively selected to maximize complementarity (the number of biodiversity surrogates in them that have not yet met their representation targets). In many of these algorithms, ties between sites are broken using an adjacency rule: sites adjacent to those that are already selected are given preference (Nicholls & Margules, 1993; Sarkar *et al*., 2002). The use of this rule results in larger individual units in a CAN and it can therefore be regarded as incorporating size in a MCDM process with representation being qualitatively (or ordinally) preferred over size (a design criterion). Similarly, cost (a socio-economic criterion), along with representation, is incorporated in the TARGET software package (Faith *et al*., 2001), whereas boundary length along with biodiversity representation is incorporated in the MARXAN software package (Possingham *et al*., 2000) based on simulated annealing. These methods are *ad hoc* in the sense that there is no systematic procedure used to assess the ranks of the criteria and are reliable only insofar as their robustness is tested through sensitivity analysis. In practice, robustness of the results over varied weights has sometimes been encouraged to ameliorate some of this arbitrariness (Faith, 1995). These methods have not been included in this review because they are not formal MCDM methods.

Discussion and recommendations

We emphasize that multiple criterion incorporation should begin with the computation of the NDS at least in the case of terminal stage protocols — this is why this method has received most emphasis throughout this review. All it requires is ordinal ranking of the alternatives by the criteria. We have not attempted here a systematic assessment of which of the criteria that are likely to be used in conservation planning (for instance, those in Table 1) only permit a straightforward ordinal rather than quantitative ranking. However, it is clear that many, such as shape, scenic value, cultural heritage and educational value, fall into this category; this situation underscores the utility of NDS computation. Since most of the applications to CAN design listed in Table 2 use terminal stage protocols to incorporate multiple criteria, but do not compute the NDS, this recommendation suggests a reform of much of contemporary practice in conservation planning.

If the NDS is not small enough to be presented to political decision-makers, we must minimally assume that the criteria can also be ordinally ranked. This sets the stage for the use of Regime. We emphasize that this method merits further exploration because its use requires only a qualitative ranking of the alternatives and the criteria and makes no further *ad hoc* assumptions. Since this method has never been used in conservation planning, it is impossible to assess the likelihood that, in a given decision scenario, it will significantly reduce the number of preferred alternatives from those in the NDS. It is unfortunate that, to the best of our knowledge, no publicly available software package implements Regime. We plan to rectify this situation in the CONSNET 1.1 software package (Aggarwal *et al*., unpublished data).

If we can assume that the alternatives are quantitatively ranked by the criteria, and assume nothing about the relative value of the criteria, we are in the potential realm of Goal Programming. This method is clearly valuable when thresholds for each criterion can be satisfactorily specified. It has already been used with some success in our context (Berbel & Zamora, 1995) and we predict its increased use in the future.

Beyond this, before any more good MCDM methods become available, we must assume that both alternatives and criteria can be quantitatively ranked and the criteria are independent of each other. We then have two outranking methods, ELECTRE III and PROMETHEE I, the performance of which in our context remains unknown but merits exploration. Finally, if we also assume that the criteria can be compounded, we recommend the use of MAVT. We also suggest that the value function be constructed using the mAHP which allows a convenient elicitation of preferences from a user unless the number of criteria is very large. There is no advantage to using the original AHP which suffers from the rank reversal problem mentioned earlier.

We conclude by noting that several MCDM methods that can potentially be usefully deployed in conservation planning have either never been used (Regime, ELECTRE III, PROMETHE I) or used very rarely (NDS computation, Goal Programming). Meanwhile, some methods that are of questionable merit in this context have been uncritically used (PROMETHEE II and TOPSIS). We hope that this review will help remedy this situation.

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SUPPLEMENTARY MATERIAL

The following material is available to download from www.blackwell-synergy.com/loi/ddi

Appendix S1 A list of the assumptions, advantages, disadvantages, applications to CAN design and available software packages for each of the 26 MCDM methods discussed in this review.

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