ARTICLE IN PRESS

DTD 5

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Environmental Modelling & Software ■■ (2004) ■■■–■■■

Environmental Modelling & Software

www.elsevier.com/locate/envsoft

MultCSync: a software package for incorporating multiple criteria in conservation planning

Alexander Moffett, Justin Garson, Sahotra Sarkar*

Biodiversity and Biocultural Conservation Laboratory, Section of Integrative Biology, University of Texas at Austin,
1 University Station, #C0930, Austin, TX 78712-1180, USA

Abstract

MultCSync is a software package designed to aid incorporation of multiple criteria into conservation planning though it can be used in other similar contexts. During such planning, conservation area networks are selected primarily to represent biodiversity but must: (i) incorporate spatial design criteria such as size, dispersion, and connectivity of individual areas; and (ii) negotiate competing social claims on land use including recreation, resource extraction, and development. The social claims can also usually be modeled as (potentially incompatible) criteria to be simultaneously optimized along with the spatial design criteria. MultCSync enables the prioritization of alternative networks on the basis of such criteria after all biodiversity representation targets are satisfied. It begins by computing the set of non-dominated alternatives. If this set is sufficiently small, these alternatives can be presented to political decision makers. However, if this set is intractably large, further prioritization among the non-dominated alternatives is necessary. MultCSync accomplishes this prioritization using the Analytic Hierarchy Process (AHP) as well as a modification of the AHP in accordance with multi-attribute value theory (MAVT). MultCSync is freely downloadable via the world wide web and can be used in conjunction with different place prioritization software packages.

Keywords: Multiple criteria decision making; MCDM; Analytic Hierarchy Process; AHP; Multiple attribute value theory; MAVT; Reserve network selection

Software availability

Name of software: MultCSync

Developers: Justin Garson, Alexander Moffett, and Sahotra Sarkar

Contact address: Biodiversity and Biocultural Conservation Laboratory, Section of Integrative Biology, University of Texas at Austin, 1 University Station, #C0930, Austin, TX 78712-1180. E-mail: sarkar@mail.utexas.edu

Year first available: 2004

Hardware required: Any IBM compatible PC

Software required: Microsoft Windows (NT4/95/98/2000/XP); graphic output requires Gnuplot, which is available freely from http://www.ncftpd.com/download/.

Programming language: Microsoft Visual C++ 6

Program size: 536 KB

Availability: Freely downloadable with manual and supporting material from http://uts.cc.utexas.edu/~consbio/Cons/ResNet.html.

Available since: July 2004.

Online documentation: http://uts.cc.utexas.edu/~consbio/Cons/ResNet.html.

---

* Corresponding author. Tel.: +1 512 232 7122; fax: +1 512 471 4806.

E-mail address: sarkar@mail.utexas.edu (S. Sarkar).

1364-8152/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envsoft.2004.10.001

1. Introduction

A standard strategy for biodiversity conservation consists of the selection of conservation area networks (CANs): sets of places such as national parks and reserves at which conservation plans are implemented (Margules and Pressey, 2000). CANs are selected to represent desired features of biodiversity such as species (generically called "biodiversity surrogates") at least up to specified targets, for instance, 10% of a species' range (Margules et al., 1988). Additionally, well-designed CANs incorporate spatial criteria such as the size and shape of individual areas, their dispersion over the landscape, and their connectivity. Moreover, CAN selection occurs in the context of many other social claims on land use besides biodiversity conservation. These include use for recreation, habitat transformation for agricultural or industrial development, biological and industrial resource extraction, etc. CANs are typically initially selected as economically as possible, that is, by representing biodiversity surrogates up to their targets in the smallest possible total area (Sarkar et al., 2004b). A central task of systematic conservation planning is to find a CAN that not only adequately represents surrogates but: (i) incorporates the spatial design criteria; and (ii) performs as optimally as possible with respect to the social claims on land use.

In what follows, each CAN that satisfies the biodiversity representation targets constitutes a "feasible alternative" or, in short, an "alternative". Given a set of feasible alternatives, both the spatial design criteria and the competing social claims on land use can be modeled as criteria each of which assigns at least an ordinal rank, and preferably a quantitative value, to every such alternative. These criteria are often incompatible in the sense that they cannot all be fully optimized simultaneously. For instance, preserving land for its wilderness value is incompatible with converting it for agricultural use. Selecting the "best available" alternative involves computing "trade-offs" between all the spatial design and social criteria.

A wide variety of techniques exist for such computations ranging from heuristic multi-dimensional optimization algorithms to the well-developed multi-attribute value and utility theories (MAUT and MAVT) (Dyer et al., 1992; Keeney and Raiffa, 1993; Dyer, 2004). The MultCSync software package implements three of these techniques for use in conjunction with place prioritization software packages that ensure biodiversity surrogate representation. These packages include ReSNet (Kelley et al., 2002; Sarkar et al., 2002), Marxan (Ball and Possingham, 2000), and C-Plan (Pressey, 1999). Each of these packages implements a different set of algorithms for selecting a CAN.

MultCSync begins by computing the subset of "non-dominated" alternatives in the set of feasible alternatives. An alternative, α_j, dominates another alternative, α_i, if α_j is better than α_i by at least one criterion, and no worse than α_i by any of the criteria. An alternative is "non-dominated" if no other alternative dominates it. Non-dominated alternatives are thus straightforwardly preferable to the dominated ones (Arrow and Raynaud, 1986): there is no criterion by which any dominated alternative is better than any non-dominated alternative. The set of non-dominated alternatives corresponds to the Pareto optimal sets of traditional economic analysis (Keeney and Raiffa, 1993). 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 between them on the basis of considerations beyond those that have been modeled.

However, typically, the cardinality of the non-dominated alternative set increases rapidly with the number of criteria (Sarkar and Garson, in press). In this circumstance, the non-dominated alternative set may be intractably large for use during decision-making process. It then becomes imperative to refine the non-dominated alternative set, that is, rank the non-dominated alternatives, so that some of them can be eliminated. This requires establishing preferences between the criteria and compounding this information with the rankings of the alternatives according to the criteria.

MultCSync provides three refinement protocols: (i) it allows less important criteria to be dropped sequentially, leading to either (a) a new revised non-dominated set or (b) the elimination of some alternatives from the existing non-dominated set; (ii) it allows the use of the Analytic Hierarchy Process (AHP) (Saaty, 1980) to produce a ranking of all the criteria and uses it to rank the non-dominated alternatives; and (iii) it provides a modification of the AHP which brings it in accordance with multi-attribute value theory (MAVT) (Kamenetzky, 1982; Belton, 1986; Dyer, 1990; Salo and Hämäläinen, 1997). The AHP has routinely been used in the context of CAN design and selection, though without first excluding dominated members of the feasible alternative set (Anselin et al., 1989; Kangas, 1993; Li et al., 1999; Mendoza and Prabhu, 2000; Schmoldt et al., 2001; Clevenger et al., 2002; Villa et al., 2002; Ananda and Herath, 2003; Hill et al., 2004). However, as will be noted in Section 2, the standard AHP has the counter-intuitive property of allowing rank reversal of existing alternatives when new alternatives are introduced (Kamenetzky, 1982; Dyer, 1990). MultCSync's method (iii) avoids this problem. The initial explicit computation of the non-dominated alternative set as well as methods (i) and (iii) mentioned above make MultCSync unique among existing software packages for multi-criteria decision making that are generally accessible. (For a review, see Belton and Stewart (2002).) Past software packages that also allow the explicit computation of non-dominated sets include VISPA (Colorni and Laniado, 1986) but this package is not generally accessible.

2. Background

MultCSync uses two distinct structures: (i) a set of feasible alternatives, $A = \{\alpha_j: j = 1, 2, \ldots, m\}$; and (ii) a set of criteria, $K = \{\kappa_i: i = 1, 2, \ldots, n\}$. Each α_j must be assigned a value, ν_{ij}, indicating the performance of the α_j relative to each κ_i. The values ν_{ij} can indicate: (a) only an ordinal ranking of the α_j relative to each κ_i; or (b) a definite quantitative value on the basis of some metric for each criterion. In the following discussion it will be assumed that lower values are preferred to higher ones, that is, the desired optimum for each criterion is its minimum. (This restriction does not constitute a limitation of the methods being developed because a maximization problem is naturally converted to a minimization problem by sign reversal.)

Given the ν_{ij}, the set of non-dominated elements of A can be defined as follows: for all alternatives, α_e and α_f, $e \neq f$, α_e dominates α_f or $\alpha_e \succ \alpha_f$ if and only if:

$$(\exists i)\left(\nu_{ie} < \nu_{if}\right) \wedge (\forall k)\left(\nu_{ke} \leq \nu_{kf}\right). \tag{2.1}$$

A non-dominated alternative, α_n, is one such that $(\forall d)\neg(\alpha_d \succ \alpha_n)$. Sarkar and Garson (in press) developed a computationally efficient (polynomial-time) algorithm for computing the non-dominated set. MultCSync incorporates that algorithm. Note that the identification of non-dominated alternatives only requires a total ordinal ranking of the alternatives according to each criterion; it does not require the assignment of quantitative values.

When the set of non-dominated alternatives is large, these alternatives must be further ranked with respect to each other. The AHP computes a unique ranking provided two conditions hold: (i) each alternative in A has a definite quantitative value according to each criterion in K (that is, ordinal ranks are no longer sufficient); and (ii) all the criteria in K have quantitative values on a ratio scale (Saaty, 1980).

Condition (i) is satisfied by eliciting from the user quantitative values for the ν_{ij}. For many criteria, such as area, economic cost, etc., this is unproblematic because they are measured on a quantitative scale. However, for others, including connectivity, social cost, etc., assigning such values requires economic valuation techniques that are controversial, especially in the context of biodiversity conservation (Norton, 1987; Sarkar, 2004). However, this problem cannot be avoided and users of MultCSync (or any other method based on the AHP, MAUT, or MAVT) should note potential pitfalls (Roy, 1971).

Satisfaction of condition (ii) requires elicitation of an $(n \times n)$-matrix, $M = (\mu_{ij})$, of pairwise comparisons on a ratio scale of the relative importance of the criteria: μ_{ij} is the multiplicative factor by which κ_i is more important than κ_j. (Therefore, $\mu_{ij} = 1/\mu_{ji}$.) The components of the eigenvector with the highest eigenvalue of $\mathbf{M}$ assigns a priority value to each κ_i. First, the ν_{ij} are normalized between 0 and 1 (Saaty, 1980):

$$\nu'_{ij} = \frac{\nu_{ij}}{\sum_{j=1}^{m} \nu_{ij}}. \tag{2.2}$$

All alternatives can then be ranked using the equation:

$$\text{rank}(\alpha_i) = \sum_{i=1}^{n} \omega_i \nu'_{ij} \tag{2.3}$$

where ω_i is the ith component of the eigenvector of $\mathbf{M}$ with the highest eigenvalue.

Given the normalization described in Eq. (2.2), it follows that the normalized values, ν'_{ij}, depend on the sum, $\sum_{j=1}^{m} \nu_{ij}$, which, in turn, depends on the number of alternatives in A. As a result, such a normalization allows for the possibility of rank reversal, by which the rank ordering of the elements in A changes as a result of the introduction of a (possibly dominated) alternative into A (Kamenetzky, 1982).

The possibility of rank reversal can be avoided by a modification of the AHP which uses a different method of normalization that is independent of the cardinality of A. The modification proposed by Dyer (1990) uses the equation:

$$\nu'_{ij} = \frac{\nu_{ij} - \min[\nu_{ij}]}{\max[\nu_{ij}] - \min[\nu_{ij}]} \tag{2.4}$$

where " $\min[\nu_{ij}]$" and " $\max[\nu_{ij}]$", respectively, are the minimum and maximum possible values ν_{ij} for κ_i. This normalizes the ν_{ij} between 0 and 1 in a way that avoids reference to the cardinality of A, thereby preventing the ν'_{ij} from changing with the addition of new alternatives. MultCSync implements both the standard AHP and the modification described here. The question whether rank reversal constitutes a problem remains controversial (Saaty, 1990)—consequently, MultCSync leaves both options, of using Saaty's original method and Dyer's modified method, available to the user.

3. Program description

MultCSync 1.0 consists of a single executable file (MultCSync.exe) that can be downloaded anywhere onto the user's hard drive. The program is opened by double clicking on the executable file. Graphic output requires the prior instillation of Gnuplot (http://www.ncftpd.com/download/). The MultCSync interface is composed of a main interface containing eight menu options along with a progress window that informs the user about the options that are currently activated. Functions are performed by selecting from amongst the menu options.

3.1. Input

The v_{ij} form an $(n \times m)$-matrix, **N**. In MultCSync, the matrix **N** is stored as a text file, which is the basic input file required for both the determination of non-dominated alternatives and the use of the subsequent refinement protocols. This text file is the only input file required to calculate the non-dominated set of alternatives, Δ. The text file containing **N** can either be constructed within MultCSync, or externally, by using a standard text editor. To use the AHP and its modification, a further input file is required, containing the matrix, **M**, of pairwise comparisons of the criteria.

3.2. Running MultCSync

There are two main operations associated with MultCSync: (i) the selection of the non-dominated set, Δ, and (ii) the further refinement of Δ.

3.2.1. Determining Δ

In order to determine Δ, both the file paths of the text file containing **N** and a text file to store the output set must be specified. Δ is then calculated by selecting "Execute NDS" from under the "Execute" option of the main menu. If Δ is found to be sufficiently small by inspection, no further refinement is necessary.

Once Δ has been calculated, a two-dimensional graphical representation of this set can be projected onto the screen using Gnuplot. Such a projection represents each alternative by a point, plotted on the basis of two different criteria, with each axis of the graph representing one of the criteria (see Fig. 1 which corresponds to the example discussed in Section 4). Different projections can be generated for each pair of criteria in K.

3.2.2. Refining Δ

After calculating Δ, the user may discover that it is too large for a given purpose and must therefore be further refined. There are three ways to do this:

(i) To refine Δ, some criteria may be excluded from further consideration. Because the size of Δ typically increases with the number of criteria (Sarkar and Garson, in press), this process generally results in a smaller Δ. MultCSync allows for: (a) the refinement of Δ through use of the "Refine Non-Dominated Set" option (under "Execute")—the user must specify the criteria to be excluded, along with the name of the text file to be used in storing the refined non-dominated alternative set, and a new Δ will be calculated starting with the present one; or (b) the revision of Δ through use of the "Revise Non-Dominated Set" option—the

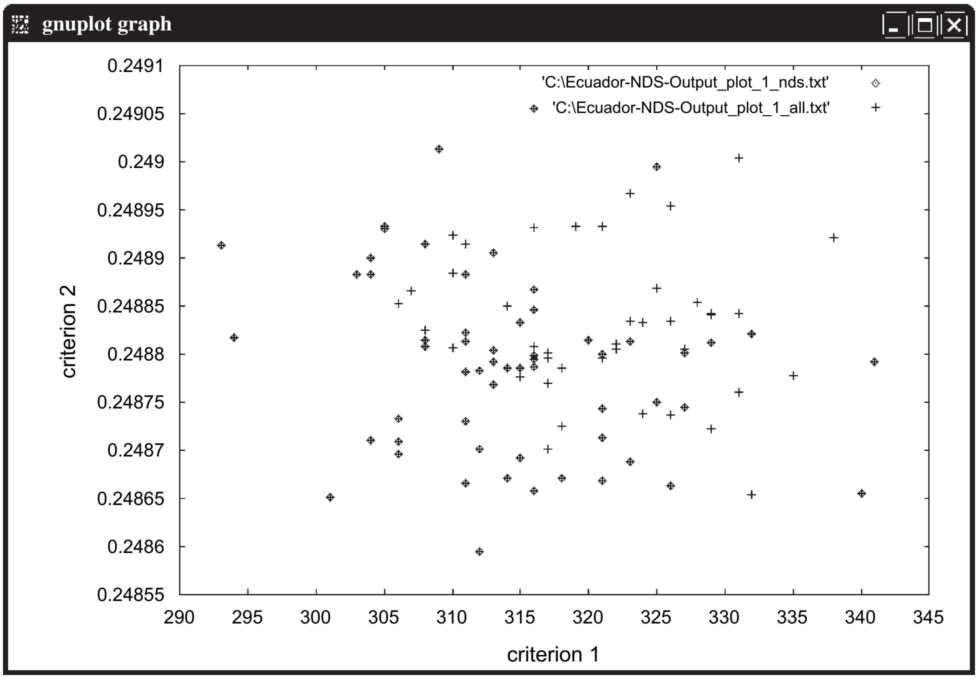

Fig. 1. Two-dimensional plot created by Gnuplot, representing 100 different alternative CANs using a data set from continental Ecuador. The two criteria plotted are the aggregate number of conservation areas (x-axis) and the inverse of the average area of each conservation area (y-axis). To maximize cohesiveness, the aggregate number of conservation areas was minimized while maximizing the average area of the conservation areas.

user must specify the criteria to be excluded and Δ is computed again from the original set A. The two options—excluding alternatives from the current Δ and calculating a new Δ from scratch—may produce different results (Sarkar and Garson, in press). Note that using this method requires a judgment that some criteria are less important than others (and can, therefore, be eliminated). The user can make this determination independently or use the elicitation process of the AHP (see method [ii] below) to prioritize the criteria.

(ii) The second method to refine Δ uses the AHP. Given a file containing a matrix **N**, the priorities of the alternatives are determined by first identifying the priority of each κ_i represented in **N** on a ratio scale. These priorities are calculated on the basis of a matrix of pairwise comparisons, which is stored as a text file. This text file can be constructed either by using a text editor, or within MultCSync. When the second option is chosen, for each required comparison, MultCSync produces a dialog box eliciting the comparison, along with a display of the matrix of pairwise comparisons, updated with each successive comparison. Once the matrix, **M**, of pairwise comparisons has been constructed, MultCSync assigns priorities to each of alternative on the basis of Eq. (2.3), using Eq. (2.2) to normalize the v_{ij}. MultCSync calculates the eigenvalues and eigenvectors using all four heuristic algorithms described by Saaty (1980, p. 19). It identifies the algorithm that achieves the best consistency ratio (CR) (see below). The rank ordering of alternatives is then produced by ordering the alternatives on the basis of their assigned priorities. Note that: (a) the elicited priorities of the criteria can also be used to drop those with the lowest values (to follow method [i] above); and (b) the elicited priorities may not be consistent. MultCSync reports the consistency ratio (CR) statistic of Saaty (1980). The CR statistic provides a measure of the probability that the results obtained may have arisen at random. Saaty (1980) recommends that only results with a CR ≤ 0.1 be used. If this requirement is not satisfied the user should repeat the elicitation process to generate a new **M**.

(iii) The third method to refine Δ uses the modified version of the AHP proposed by Dyer (1990) and is described in Section 2. Under this method, MultCSync again assigns priorities to each alternative on the basis of Eq. (2.3), but uses Eq. (2.4) instead of Eq. (2.2) for normalization.

3.3. Output

MultCSync is capable of generating the following five different types of output files: (i) a text file containing the non-dominated alternative set; (ii) a text file detailing the priorities assigned to each criterion, along with the CR statistic of **M**; (iii) a text file providing a rank ordering of a set of alternatives, in conjunction with the assigned priorities used to establish this ordering; (iv) a text file containing the information necessary to graph a set of alternatives using Gnuplot; and (v) a text file maintaining a log of all data entered in a given MultCSync run, as well as the file paths of all specified input and output files. All these output files can be opened without exiting MultCSync, thus allowing feedback from the output to guide subsequent use of the protocols.

4. An example

The use of MultCSync in conservation planning will be illustrated by an example describing the application of the software to the evaluation of CANs in continental Ecuador (a more detailed treatment of this example is found in Sarkar et al. (2004a)).

4.1. Generating a set of feasible alternatives

In this example, the set, A, of feasible alternatives was generated as follows. A $2 \times 2\ \text{km}^2$ raster grid was used to divide continental Ecuador into 61 554 cells. All anthropogenically transformed cells were removed leaving 37 272 cells available for incorporation into a CAN. Forty-six major vegetation types were used as biodiversity surrogates and the probabilistic expectation of each surrogate was calculated for each cell. A target of representation for each surrogate was set to 10% of the untransformed area in which that type occurred and the ResNet software package (Garson et al., 2002) was used to select a minimum set of cells that meet the representation targets; the selection was initiated using cells within the existing Ecuadorian national reserve system (NRS). Cells were selected on the basis of rarity and complementarity, with ties broken first on the basis of adjacency, and finally by lexical order. ResNet was run 100 times on 100 randomized re-orderings of the data set. Due to the impact of lexical order on cell selection, each re-ordering of the data set resulted in the selection of a different set of cells by ResNet. The set of 100 different CANs generated in this way was the set of feasible alternatives.

4.2. Selecting the criteria

To evaluate this set of 100 CANs, six criteria were used: (i) the aggregate number of conservation areas; (ii) the average area of each conservation area; (iii) the variance of the areas; (iv) the aggregate distance of the selected cells to existing units of the NRS; (v) the aggregate distance to anthropologically transformed areas; and (vi) the total area of the selected cells. Criteria (i), (iii), and (v) were interpreted as representations of the cohesiveness of the CANs, with lower values representing higher cohesion. Criterion (ii) was likewise interpreted as a representation of the cohesiveness of the CANs, though with lower values representing lower cohesion. Criterion (iv) was interpreted as a measure of risk with lower values representing an increased risk of habitat destruction. Finally, criterion (vi) was interpreted as a representation of the cost of acquisition of the CANs, with lower values representing lower cost. To maximize cohesion while minimizing both cost and the risk of habitat destruction, the values associated with criteria (i), (iii), (v), and (vi) were unaltered, while the inverse was taken of the values associated with criteria (ii) and (v). An optimal CAN was thus interpreted as one which minimized each of these updated values.

4.3. Calculating non-dominated alternatives

A (100×6)-matrix, **N**, was constructed with entry v_{ij} equal to the value of the jth alternative with respect to the ith criterion. **N** was stored in a text file and input into MultCSync, which was used to calculate the set of non-dominated alternatives, Δ, as defined by Eq. (2.1). Out of the 100 alternatives included in A, MultCSync identified 58 as non-dominated. A list of these alternatives was saved as a text file. Fig. 1 shows the graphical output from two of the criteria.

4.4. Evaluating the criteria

To calculate the weight associated with each criterion, each criterion was compared with each other criterion with regard to their importance to the attainment of an ideal CAN. These pairwise comparisons were quantified on a scale of 1/9 to 9 and their values were recorded in a (6×6)-matrix. This matrix was stored in a text file and input into MultCSync, which was used to calculate the eigenvector of the largest eigenvalue associated with the matrix. This eigenvector was used to assign weights to each of the criteria, as shown in Table 1.

4.5. Ranking the alternatives

MultCSync was used to normalize the entries of **N** over the interval (0,1), according to Eq. (2.4). The maximum and minimum values used in this process were determined on the basis of the range of values found in A. Using these normalized values, in conjunction with the weights assigned to the criteria, MultCSync ranked the alternatives in Δ using Eq. (2.3). Both the weights associated with the criteria and the rank order of the alternatives were saved as text files.

Table 1
The calculation of weights for each of the six criteria used to evaluate CANs in continental Ecuador

$$\begin{pmatrix} 1 & 1/2 & 9 & 3 & 6 & 7 \\ 2 & 1 & 9 & 9 & 4 & 9 \\ 1/9 & 1/9 & 1 & 1/5 & 1/6 & 1/2 \\ 1/3 & 1/9 & 5 & 1 & 1/3 & 4 \\ 1/6 & 1/4 & 6 & 3 & 1 & 2 \\ 1/7 & 1/9 & 2 & 1/4 & 1/4 & 1 \end{pmatrix} \Rightarrow \begin{pmatrix} 0.298983 \\ 0.440912 \\ 0.025251 \\ 0.082314 \\ 0.111190 \\ 0.041351 \end{pmatrix} \Rightarrow \begin{matrix} \omega_1 = 0.0298983 \\ \omega_2 = 0.440912 \\ \omega_3 = 0.025251 \\ \omega_4 = 0.082314 \\ \omega_5 = 0.111190 \\ \omega_6 = 0.041351 \end{matrix}$$

The matrix was constructed by comparing the importance of each criterion with that of every other criterion on a scale of 1/9 to 9. Entry (i, j) then represents the ratio by which criterion i is evaluated to be more important than criterion j. For example, criterion 1 (the aggregate number of conservation areas) is evaluated to be half as important as criterion 2 (the average area of each conservation area); thus, the entry (1, 2) = 1/2. The adjoining vector is the eigenvector with the highest eigenvalue of the matrix; eigenvector components are normalized such that they sum to 1. The weight of the ith criterion, ω_i, is set equal to the ith entry of the eigenvector.

The decision to employ a modified version of the AHP resulted in the identification of a different rank ordering of alternatives than would have been identified had the standard version of the AHP been used. This difference underscores the fact that the user must carefully consider the decision to use either the standard or the modified version of the AHP.

5. Final notes

MultCSync makes three innovations relevant to the selection of CANs during systematic conservation planning:

(i) MultCSync is the only generally accessible software package that allows the explicit computation of the non-dominated set Δ. While Rothley (1999) and others (e.g., Sarkar et al., 2000) have advocated the use of non-dominated sets to incorporate multiple criteria into CAN selection, those software packages that explicitly compute them (for instance, VISPA) are not yet generally accessible. (Moreover, VISPA is a DOS software package with limited options for interaction with the user.) However, most algorithms used for multi-criteria decision making typically give a higher preference to non-dominated alternatives over dominated ones. Computing Δ is important because it only requires an ordinal ranking of the alternatives by each criterion which is less problematic than the elicitation and valuation techniques required to obtain the quantitative values required for the subsequent refinement of Δ. If Δ is sufficiently small for use by decision makers, no further analysis is necessary;

(ii) the method of sequentially dropping criteria to decrease the cardinality of Δ is new. This method allows an easy exploration of contexts in which a user is uncertain about whether some criterion is as important as the others. If the criterion in question makes a significant difference to the results obtained, then more effort should be directed towards investigating the presumed relevance of that criterion. Using this criterion is a rudimentary qualitative form of sensitivity analysis. The ranking of criteria using the AHP or its modification can guide the choice of criteria to be eliminated at this stage;

(iii) though there are many software implementations of the AHP (for instance, Expert Choice (2000), Logical Decisions (2003), Web-HIPRE (Mustajoki et al., 2004)), none among those that are freely available explicitly implement the modification that avoids rank reversal and makes the AHP consistent with MAVT. However, Expert Choice and Web-HIPRE are partial exceptions insofar as they allow the user to select parameters that may ensure the absence of rank reversal though this is not an explicit option.

Acknowledgments

We thank Jim Dyer for discussions.

References

Ananda, J., Herath, G., 2003. The use of the Analytic Hierarchy Process to incorporate stakeholder preferences into regional forest planning. Forest Policy and Economics 5, 13–26.

Anselin, A., Miere, P., Anselin, M., 1989. Multicriteria techniques in ecological evaluation: an example using the Analytic Hierarchy Process. Biological Conservation 49, 215–229.

Arrow, K.J., Raynaud, H., 1986. Social Choice and Multicriterion Decision-Making. The MIT Press, Cambridge, MA.

Ball, I.R., Possingham, H.P., 2000. MARXAN (V 1.8.2) User's Manual. http://www.ecology.uq.edu.au/marxan.htm.

Belton, V., 1986. A comparison of the Analytic Hierarchy Process and a simple multi-attribute value function. European Journal of Operational Research 26, 7–21.

Belton, V., Stewart, T., 2002. Multiple Criteria Decision Analysis: An Integrated Approach. Kluwer, Dordrecht.

Clevenger, A., Wierzchowski, J., Chruszcz, B., Gunson, K., 2002. GIS-generated, expert-based models for identifying wildlife habitat linkages and planning mitigation passages. Conservation Biology 16, 503–514.

Colorni, A., Laniado, E., 1986. A software package for environmental impact assessment. In: Zannetti, P. (Ed.), Envirosoft 86: Proceedings of the International Conference on Development and Application of Computer Techniques to Environmental Studies. Computational Mechanics Publication, Southampton, pp. 745–756.

Dyer, J., 1990. Remarks on the Analytic Hierarchy Process. Management Science 36, 249–258.

Dyer, J., 2004. MAUT-multiattribute utility theory. In: Figueira, J., Greco, S., Ehrgott, M. (Eds.), State of the Art in Multiple Criteria Decision Analysis. Kluwer, Dordrecht.

Dyer, J.S., Fishburn, P.C., Steuer, R.E., Wallenius, J., Zionts, S., 1992. Multiple criteria decision making, multiattribute utility theory: the next ten years. Management Science 38, 645–654.

Expert Choice, 2000. Expert Choice 2000 2nd Edition for Groups, Home page: http://www.expertchoice.com/.

Garson, J., Aggarwal, A., Sarkar, S., 2002. ResNet Ver 1.2 Manual. Biodiversity and Biocultural Conservation Laboratory, University of Texas, Austin.

Hill, M., Braaten, R., Veitch, S., Lees, B., Sharma, S., 2004. Multi-criteria decision analysis in spatial decision support: the ASSESS analytic hierarchy process and the role of quantitative methods and spatially explicit analysis. Environmental Modelling & Software, in press, doi:10.1016/j.envsoft.2004.04.014.

Kamenetzky, R., 1982. The relationship between the Analytic Hierarchy Process and the additive value function. Decision Sciences 13, 702–713.

Kangas, J., 1993. A multi-attribute preference model for evaluating the reforestation chain alternatives of a forest stand. Forest Ecology and Management 59, 271–288.

Keeney, R.L., Raiffa, H., 1993. Decisions with Multiple Objectives: Preferences and Value Tradeoffs. Cambridge University Press, Cambridge, UK.

Kelley, C., Garson, J., Aggarwal, A., Sarkar, S., 2002. Place prioritization for biodiversity reserve network design: a comparison of the SITES and ResNet software packages for coverage and efficiency. Diversity and Distributions 8, 297–306.

Li, W., Wang, Z., Tang, H., 1999. Designing the buffer zone of a nature reserve: a case study in Yancheng biosphere reserve, China. Biological Conservation 90, 159–165.

Logical Decisions, 2003. Logical Decisions for Windows. Version 5.1, Home page: http://www.logicaldecisions.com/.

Margules, C.R., Pressey, R.L., 2000. Systematic conservation planning. Nature 405, 242–253.

Margules, C.R., Nicholls, A.O., Pressey, R.L., 1988. Selecting networks of reserves to maximize biological diversity. Biological Conservation 43, 63–76.

Mendoza, G., Prabhu, R., 2000. Multiple criteria decision making approaches to assessing forest sustainability using criteria and indicators: a case study. Forest Ecology and Management 131, 107–126.

Mustajoki, J., Hämäläinen, R.P., Marttunen, M., 2004. Participatory multicriteria decision support with Web-HIPRE: a case of lake regulation policy. Environmental Modelling and Software 19, 537–547.

Norton, B.G., 1987. Why Preserve Natural Variety? Princeton University Press, Princeton.

Pressey, R.L., 1999. Applications of irreplaceability analysis to planning and management problems. Parks 9, 42–51.

Rothley, K.D., 1999. Designing bioreserve networks to satisfy multiple, conflicting demands. Ecological Applications 9, 741–750.

Roy, B., 1971. Problems and methods with multiple objective functions. Mathematical Programming 1, 239–266.

Saaty, T.L., 1980. The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill, New York.

Saaty, T.L., 1990. An exposition of the AHP in reply to the paper 'Remarks of the Analytic Hierarchy Process'. Management Science 36, 259–268.

Salo, A., Hämäläinen, R., 1997. On the measurement of preferences in the Analytic Hierarchy Process. Journal of Multi-Criteria Decision Analysis 6, 309–319.

Sarkar, S., 2004. Conservation biology. In: Zalta, E.N. (Ed.), The Stanford Encyclopedia of Philosophy, Summer 2004 ed. http://plato.stanford.edu/archives/sum2004/entries/conservation-biology/.

Sarkar, S., Aggarwal, A., Garson, J., Margules, C.R., Zeidler, J., 2002. Place prioritization for biodiversity content. Journal of Biosciences 27 (S2), 339–346.

Sarkar, S., Garson, J. Multiple criterion synchronization (MCS) for conservation area network design: the use of non-dominated alternative sets. Conservation and Society, in press.

Sarkar, S., Moffett, A., Sierra, R., Fuller, T., Cameron, S., Garson, J., 2004a. Incorporating multiple criteria into the design of conservation area networks. Endangered Species Update 21, 100–107.

Sarkar, S., Pappas, C., Garson, J., Aggarwal, A., Cameron, S., 2004b. Place prioritization for biodiversity conservation using probabilistic surrogate distribution data. Diversity and Distributions 10, 125–133.

Sarkar, S., Parker, N.C., Garson, J., Aggarwal, A., Haskell, S., 2000. Place prioritization for Texas using GAP data: the use of biodiversity and environmental surrogates within socioeconomic constraints. Gap Analysis Program Bulletin 9, 48–50.

Schmoldt, D., Kangas, J., Mendoza, G., Pesonen, M. (Eds.), 2001. The Analytic Hierarchy Process in Natural Resource and Environmental Decision Making. Kluwer Academic Publishers, Boston.

Villa, F., Tunesi, L., Agardy, T., 2002. Zoning marine protected areas through spatial multiple-criteria analysis: the case of the Asinara island national marine reserve of Italy. Conservation Biology 16, 515–526.