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DESIGNING BIORESERVE NETWORKS TO SATISFY MULTIPLE, CONFLICTING DEMANDS

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Abstract. Reserve designers typically strive to create reserves that satisfy a variety of potentially conflicting criteria. Rather than optimizing with respect to just one criterion, reserve planners are likely to seek some compromise. To facilitate bioreserve design, I propose the use of multiobjective programming to identify these compromise alternatives, and then the use of the simple multiattribute rating technique to rank these alternatives and to explore the sensitivity of the rankings to the relative value placed on the individual criteria. An example is provided for the selection of a reserve system in Nova Scotia, Canada, based on three criteria: (1) connectedness, (2) area, and (3) rare species representation. First, multiobjective programming was used to reduce the set of over 15 000 potential reserve-system alternatives to a list of 36 candidate systems representing the optimal trade-offs among the three criteria. The simple attribute-rating technique was then used to identify a single best solution for an arbitrary set of relative criteria values and to test the robustness of this solution to changes in relative preferences for the criteria. The techniques presented here can simplify the evaluation of reserve alternatives, enabling planners to refocus their efforts on the complex biological, social, and economic aspects of reserve design.

Key words: biodiversity preservation; bioreserve design; multiobjective programming; Nova Scotia reserve network; reserve selection; selection algorithms, reserves; simple multiattribute rating technique.

Introduction

The growing concern over the conservation of biotic diversity has generated intense interest in the design of reserves and reserve networks to act as a final repository of much of the world's biota (Newmark 1995). Numerous biological criteria have been suggested by which reserve sites can be identified and evaluated. A review by Margules and Usher (1981) found that the most common criteria were diversity, rarity, and naturalness. However, new criteria are continually suggested (Soulé and Simberloff 1986, Vane-Wright et al. 1991, Witting and Loeschcke 1995). Additionally, nonbiologically motivated appeals may add to the list of criteria. For example, reserves may also be used for recreation (e.g., hunting, camping, and hiking) and for the generation of revenue. Such additional uses may be in direct conflict with the biological goals for the reserve.

It is unlikely that any reserve or reserve network can satisfy all of these demands simultaneously. Instead, reserve planners are forced to choose some alternative that provides a favorable compromise between the competing demands. But as the number of candidate reserve designs and the number of desired criteria increase, evaluation of candidate designs may become difficult. I present here two methods—multiobjective programming, (MOP; Cohon 1978) and the simple multiattribute rating technique (SMART; Edwards 1971)—that can be used to support the design of reserves and reserve networks with respect to multiple, potentially conflicting criteria. First, MOP is used to reduce the set of all potential reserve networks to a subset representing the optimal trade-offs among criteria. These trade-offs are explicitly quantified. So, for example, a reserve planner who must balance a trade-off between preserving total plant species richness and the number of rare animal species knows exactly the increase in plant species representation gained for a decrease in animal species representation. SMART is then used to rank the candidate networks and to test the sensitivity of the rankings to the relative importance ascribed to the criteria. To demonstrate their use, the methods are applied to the selection of a reserve network in Nova Scotia, Canada.

Background

Given the wide variety of conservation demands, limitations on suitable reserve locations, and ubiquitous economic constraints, each reserve or reserve network is expected to serve a disparate variety of purposes. For example, Goldsmith (1987) describes the selection process of a single network of forest nature reserves in Nova Scotia, Canada, that will contain a high number of plant species, a high number of rarities, have a high number of large-diameter trees, and have a large area. Turpie (1995) examines potential conservation sites for waterbirds in South Africa based con-

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currently on species richness, total number of birds, conservation status of represented birds, and the percentage of regional populations protected.

Unfortunately, it is unlikely that any single design can satisfy all goals simultaneously. There exists the potential for goals to be related in a manner that can be exploited to the planner's advantage. For example, reserve area has been suggested to be positively correlated with species richness and negatively correlated with extinction rates (MacArthur and Wilson 1967, Newmark 1995). Therefore, by increasing size, reserves may perform more favorably with respect to each of these criteria. In some instances, a criterion such as species richness could serve as a reasonable surrogate for a more fundamental currency of biodiversity value such as character richness (Williams 1999).

But it is more typical that performance with respect to one goal comes at the expense of the others. Irregular reserve boundaries may promote edge species but jeopardize interior species by exposing them to higher predation risk (Suarez et al. 1997). The relative value of one large reserve or several small reserves has been debated for 20 yr (see Russell 1994) and continues to attract interest (Erwin et al. 1995). Money not spent "up front" for the purchase of reserve lands could be used later for monitoring or management. In these instances, the multiple goals of a reserve can not be encompassed by some single surrogate (e.g., area). Instead, the planner is forced to select some favorable compromise design to the trade-offs that exist between the criteria.

If the number of reserve alternatives and/or the number of design criteria are small, the trade-offs among the criteria may be straightforward. But when the complexity of the design problem increases, planners must turn to more quantitative decision approaches (Church et al. 1996). Earlier methods may be grouped loosely into two classes: indexing schemes (Purdie et al. 1986, Rapoport et al. 1986, French 1994) and iterative techniques (Margules et al. 1988, Bedward et al. 1992, Nicholls and Margules 1993, Underhill 1994, Williams 1999). With indexing schemes, potential reserves or reserve networks are scored according to some mathematical combination of their ratings with respect to a defined set of criteria. For example, the "score" for a potential reserve network may be simply the sum total of the rare plant and rare animal species represented by the network. With iterative techniques, a logical heuristic is used to assemble combinations of reserves. Margules et al. (1988) describe a four-step algorithm for creating a reserve network with the smallest number of sites representing all, or as many, species as possible. Indexing schemes and iterative techniques are attractive for their speed and ease of use. However, these selection algorithms may produce sub-optimal results (Lomolino 1994, Underhill 1994, Csuti et al. 1997).

More recently, mathematical programming techniques, such as integer programming, have been used to address reserve design problems (Cocks and Baird 1989, Sætersdal et al. 1993, Camm et al. 1996, Church et al. 1996). Only mathematical programming methods guarantee an optimal (efficient) solution (Church et al. 1996) (though differences from iterative solutions are small [Williams et al. 1996, Csuti et al. 1997, Williams 1999]). Yet, the multi-criteria nature of reserve design problems rarely has been addressed by the mathematical programming approaches. Mathematical program formulations of reserve design problems have typically only included one criterion at a time, e.g., maximize the number of species represented, or maximize the number of ecosystem types represented (Church et al. 1996, Kiester et al. 1996). But the results produced by these single-criterion analyses may not meet the reserve planner's needs. For example, single-criterion optimization analysis may identify the reserve network with the highest endangered-species representation, or it may identify the reserve network with the highest ecosystem representation, but what are the trade-offs between species richness and ecosystem richness? In other words, what, if any, are the reserve alternatives that represent a compromise between these two criteria? The alternatives that offer intermediate levels of the design criteria may be more interesting to the reserve planner than the alternatives that maximize only one criterion at a time.

Indexing schemes and iterative techniques explicitly incorporate multiple criteria. However, the reserve-planner's trade-off preferences for the various criteria must be established a priori. These methods then produce a single best solution to the given set of preferences. To identify other potential trade-off solutions, new preferences must be defined for which new single best solutions are then determined. In the case of indexing schemes, perpetually sub-optimal alternatives may be scored repeatedly and needlessly. For iterative techniques, new logical rules must be created for each new set of trade-off preferences. Hence, sensitivity analysis of trade-off preferences can be inefficient and cumbersome. Indices also require the conversion of all criteria into some common currency, for example money (Hampicke 1994). But reserve planners may be unwilling or unable to find an agreeable common currency.

The first goal of this paper is to demonstrate, by way of example, the use of multiobjective programming (MOP; Cohon 1978) to support the design of reserve networks. MOP allows for a simple, realistic representation of the multicriteria reserve design problem. Through MOP, a multitude of potential reserve design alternatives are "screened" with respect to any number of criteria to yield a reduced set of candidate alternatives representing the optimal, intermediate, trade-off alternatives with respect to the criteria. Further, trade-offs between the criteria are explicitly quantified so that the reserve planner knows exactly the losses on all other criteria that result from gains on one criterion. These trade-offs among the criteria are reported in the inherent currency of the criteria (no conversion to a common currency), without the need to elaborate any preferences for the criteria a priori. MOP can be viewed as a more generalized formulation of a single-objective mathematical program for which the single-criterion program is just a special case. This technique has been used for other land-allocation problems (Schilling et al. 1980, Gilbert et al. 1985) and has been suggested as appropriate for reserve design (Church et al. 1996).

The second goal of this paper is to demonstrate, continuing with the same example, the use of a quantitative decision-analysis technique, the simple multiattribute rating technique (SMART; Edwards 1971) to evaluate the candidate reserve designs. The end result of the MOP analyses of reserve alternatives is a list of candidate plans, the implicit assumption being that the reserve planner is left to make the final selection. If the number of candidate plans and the number of design criteria are small, it may be easy to compare the candidates and make a final selection. But as the number of candidate plans and the number of criteria increase, ranking of the alternatives becomes less obvious and the use of a decision-support technique such as SMART can be informative. SMART is essentially an indexing scheme and therefore has similar limitations as other selection algorithms described above. But SMART offers a tractable manner in which to explore the sensitivity of the rankings to the relative value placed on the criteria. Before considerable effort is expended trying to define relative values for the criteria precisely, a planner can gain some indication of which criteria are most critical. For the reserve selection example described below, SMART is only applied after all inefficient alternatives have been eliminated through MOP.

Both of the techniques discussed are theoretically based and computationally rigorous. Software to perform these analyses is readily available, user friendly, inexpensive, and typically performs an automated sensitivity analysis. The incorporation of such decision-support techniques can enable planners to refocus their efforts on the complex biological, social, and economic aspects of reserve design.

Methods

The general formulation and solution of an MOP for the reserve network design

Consider a reserve design problem for which one needs to fulfill a list of conservation-oriented and recreational needs through the establishment of a reserve network. The locations and descriptions of potential reserve sites are known and some subset of these locations will be selected to form the network. One must also take into account particular restrictions that constrain the potential network alternatives. To begin, for each potential reserve i, an integer variable, x_i, is used to represent the decision of whether to include the reserve in the network ($x_i = 1$ means that the reserve is included; $x_i = 0$ means that the reserve is not included). The criteria for the network (the conservation and recreation needs) are then stated as a set of equations, written generally as

$$\text{Max (or Min) } Z_j = \sum_{i=1}^{n} c_i x_i \qquad j = 1, \ldots, k \tag{1a}$$

where Z_j is a design criterion (e.g., maximize area), k is the number of design criteria, n is the number of potential reserve sites, and c_i is a coefficient. Note that this formulation requires that the criteria be stated in the form of linear functions. Certain criteria, such as species richness or budgetary goals, can often be stated readily as linear equations. But criteria also may be decidedly nonlinear in form. Techniques for handling nonlinear criteria are addressed in *Discussion*, below.

The next step is to stipulate the restrictions on the network alternatives as a set of mathematical constraints. Examples of typical constraints are budgetary restrictions, limits on the total number of reserves in the network, or minimum numbers of species that must be represented. The constraints are stated mathematically as

$$\sum_{i=1}^{n} a_{ij} x_i \leq b_j \qquad j = 1, \ldots, n \tag{1b}$$

where b_j is some limiting constraint, n is the number of constraints, and a_{ij} is a coefficient.

Finally, the integer restriction on the network variables is stated as

$$x_i = 0, 1 \qquad i = 1, \ldots, n. \tag{1c}$$

This equation establishes that either the reserve is included in the network or it is not; reserves cannot be partially included. The set of alternative reserve combinations is generated by solving this set of equations. The solution consists of a set of x_i values for each optimal, intermediate trade-off network indicating which reserves are included in each network. Many software packages are available to solve MOPs (e.g., Lindo/386 5.3 [Lindo Systems 1995]). While real-world reserve design problems may entail a large number of constraints and criteria, a simple example is sufficient to illustrate the solution logic of MOP.

Consider the selection of a network of two reserves from a set of five potential locations (for a total of $\binom{5}{2} = 10$ potential reserve network alternatives) constrained by a maximum budget, B. The following two criteria are of interest:

$$\text{Max } Z_1 = \sum_{i=1}^{10} a_i x_i \tag{2a}$$

$$\text{Min } Z_2 = \sum_{i=1}^{10} c_i x_i \tag{2b}$$

where Z_1 is the area of the network, Z_2 is the total cost of procuring the network, a_i is the area of reserve i, c_i

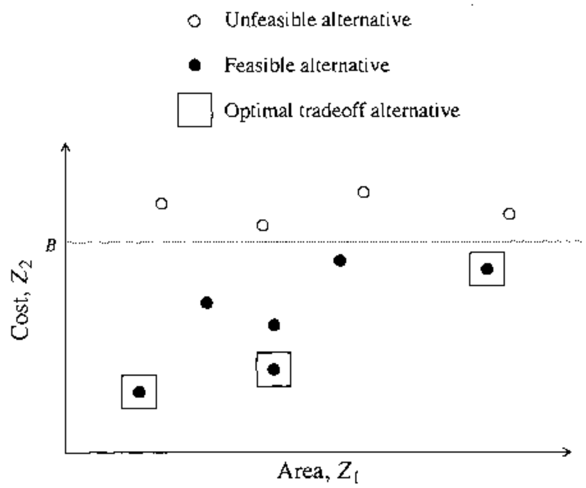

FIG. 1. Budgetary constraint (B) and reserve network alternatives graphed with respect to two design criteria: reserve area and cost. Of the 10 possible networks, those that cost more than the budget allows are unfeasible.

is the cost of reserve i, and x_i, is used to represent the decision of whether to include reserve i in the network. The budgetary constraint is written as

$$\sum_{i=1}^{10} c_i x_i \leq B. \tag{2c}$$

Finally, the integer restriction on the network variables is stated:

$$x_i = 0,\ 1. \tag{2d}$$

To solve an MOP the constraints are used to exclude unfeasible alternatives. The optimal trade-off alternatives are then identified from the remaining feasible alternatives. The solution process can be illustrated graphically for this simple problem. Because there are only two criteria, the 10 network alternatives can be graphed with respect to their performance on each of the two criteria (Fig. 1). The budgetary constraint is also indicated on this graph, and it eliminates four alternatives that are too expensive. The optimal trade-off alternatives are then distinguished as the feasible networks for which there is no other network that can provide more area at a similar or lower cost (or equivalently, there is no other network that is less expensive with equal or larger area). In this case there are three optimal trade-off solutions identified from the six feasible alternatives. No further consideration needs to be given to the remaining three non-optimal feasible alternatives. The final network selection can be made from this reduced set of optimal trade-off alternatives based on the relative value placed on the criteria. For real reserve designs with >2 criteria, a graphical solution is no longer possible. But the solution logic of this simple problem is identical to that for the more complex problems.

An example reserve network selection problem

The example application describes the selection of a reserve network in Nova Scotia, Canada (Goldsmith 1987). The goal is to identify a system of 5 forest nature reserves from a set of 20 potential reserves to supplement the already-existing two national parks (the existing parks are not considered in the identification of the new reserve system). The reserve alternatives are to be evaluated according to three criteria: (1) maximize the total connectedness of the reserve system (where "connectedness" is defined as the inverse of the distance between the reserves), (2) maximize the total area of the reserve system, and (3) maximize the number of rare plant species represented. These criteria are typical of reserve design scenarios and demonstrate MOPs accommodation of criteria that are measured in different currencies. The criteria are stated mathematically as

$$\text{Max } Z_1 = \sum_{i=1}^{t} (1/d_i)y_i \tag{3a}$$

$$\text{Max } Z_2 = \sum_{i=1}^{n} a_i x_i \tag{3b}$$

$$\text{Max } Z_3 = \sum_{i=1}^{f} r_i \tag{3c}$$

where Z_1 is the total connectedness, t is the total number of possible "connections" (the corridors between the included reserves, in this example $t = \binom{20}{2} = 190$), d_i is the distance between any two included reserves, y_i is an integer variable whose value is 1 if both endpoints of corridor i are included and 0 if not; Z_2 is the total area of the set of included reserves, n is the number of potential reserve locations (in this example $n = 20$), a_i is the area of reserve i, x_i is an integer variable whose value is 1 if the reserve is included and 0 if not; Z_3 is the total number of rare plant species represented, f is the total number of rare plant species (in this example $f = 25$), and r_i is an integer variable whose value is 1 if at least one reserve that contains species i is included and 0 if not.

The next step is to create the constraints in the form of Eq. 1b that describe the reserve problem. For this example problem, the only restriction is that the reserve system is limited to five reserves. This constraint is stated as

$$\sum_{i=1}^{n} x_i \leq 5. \tag{3d}$$

Additional constraints are now added to ensure that the variables used to describe the problem will perform as expected and that the solutions are not nonsensical. First, because a reserve or corridor can appear only once in any reserve system,

TABLE 1. Results of MOP (multiobjective programming) analysis: optimal trade-offs among candidate reserves for the three-criteria Nova Scotia reserve-design example.

Network identification no.	Connectedness, Z_1†	Area, Z_2 (ha)	No. of rare species, Z_3
1	29.01	1922	21
2	32.13	2043	17
3	35.59	1919	21
4	38.4	2040	17
5‡	40.88	2046	15
6	45.31	2004	17
7	45.56	2001	17
8	46.72	2043	15
9	48.89	2040	16
10	57.84	2043	14
11	61.87	1974	17
12	63.18	1965	19
13	64.56	1962	20
14	73.04	2040	14
15	77.52	1965	18
16	79.14	2027	15
17	81.92	1923	19
18	83.05	1974	15
19	85.32	1962	18
20	88.11	1903	16
21	138.96	1853	21
22	142.27	1997	14
23	149.12	1775.4	21
24§	150.49	194.4	22
25	152.82	240.4	21
26	156.07	237.4	21
27	184.18	1957	12
28	188.95	1896	19
29	193.97	358	19
30	206.86	280.34	20
31	213.72	361	17
32	223.34	358	17
33	231.67	1741	13
34	262.09	272	17
35	283.62	247	11
36‖	304.91	206	11

† Z_1 = 1/distance between reserves (in kilometers).
‡ Area-maximizing alternative.
§ Species-maximizing alternative.
‖ Connectedness-maximizing alternative.

$$x_i \leq 1 \qquad i = 1, \ldots, n \tag{3e}$$

$$y_i \leq 1 \qquad i = 1, \ldots, t. \tag{3f}$$

Next, because a species i is either represented ($r_i = 1$) or it is not ($r_i = 0$),

$$r_i \leq 1 \qquad i = 1, \ldots, f. \tag{3g}$$

To ensure that a connection is included only if both endpoints are included,

$$y_i \leq x_{\text{startingreserve}} \qquad i = 1, \ldots, t \tag{3h}$$

$$y_i \leq x_{\text{endingreserve}} \qquad i = 1, \ldots, t. \tag{3i}$$

To ensure that a rare species is added to the rare-species total only if at least one reserve containing the species is included,

$$r_j \leq \sum_{i \in B_j} x_i \qquad j = 1, \ldots, f \tag{3j}$$

where B_j is the set of reserves that contains species j. Finally, to ensure that reserves, connections, and species are either included or not included (no partial inclusions are allowed),

$$x_i, y_j, r_k = \text{integer}$$

$$i = 1, \ldots, n;\ j = 1, \ldots, t;\ k = 1, \ldots, f. \tag{3k}$$

The constraint method (Cohon 1978, Cohon and Rothley 1997) with the software package Lindo/386 5.3 (Lindo Systems 1995, Raja et al. 1997) (Table 1 and Fig. 2A) was used to solve the MOP defined in Eqs. 3a–3k. MOP analysis screens all possible reserve system combinations against the criteria and constraints (Eqs. 3a–3k). The "solution" of the MOP is then the reduced set of reserve system alternatives that represent the optimal, intermediate combinations with respect to the criteria. The contouring function in Sigma Plot (Jandel Corporation 1994) was used to generate the three-dimensional surface containing the reserve system alternatives to reveal the trade-off relationships among the alternatives (Fig. 2B).

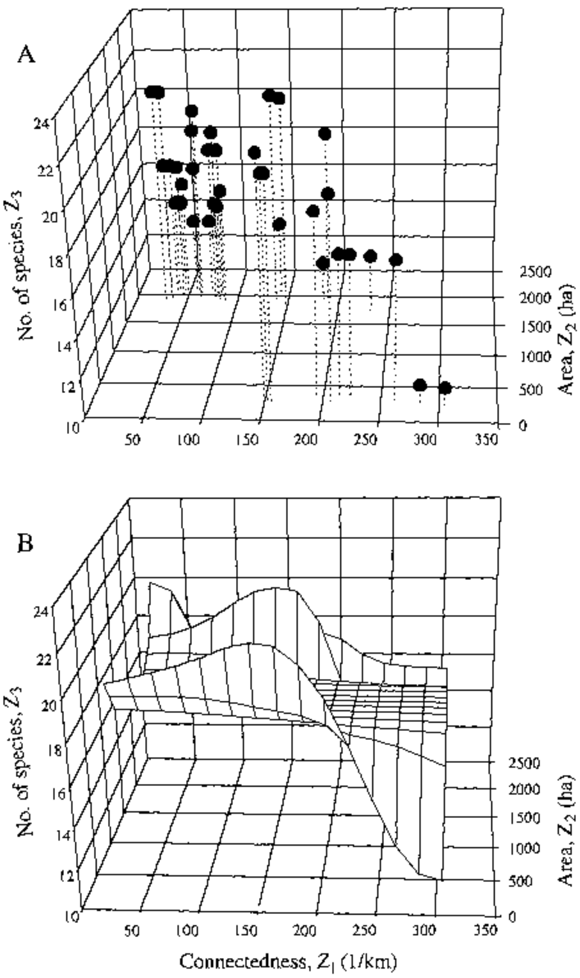

FIG. 2. (A) Optimal trade-off alternatives (●) for Nova Scotia reserve system graphed with respect to the three design criteria: reserve connectedness, reserve area, and number of rare plant species included. (B) A contour surface passing through the optimal alternatives, highlighting the trade-offs among the alternatives.

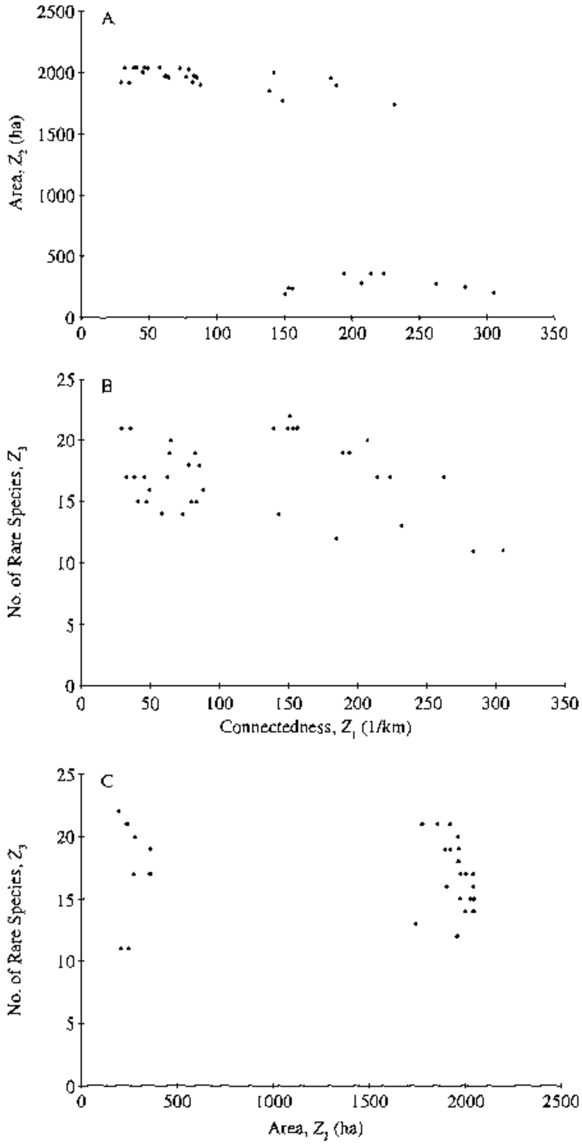

FIG. 3. Optimal trade-off alternatives for Nova Scotia reserve system graphed with respect to (A) area vs. connectedness, (B) number of rare species vs. connectedness, and (C) number of rare species vs. area.

Results of MOP analysis

The product of the above MOP analysis is a set of 36 reserve-system alternatives (reduced from a possible $\binom{20}{5}$ = 15 504 combinations). Three of these alternatives are the systems that are optimal with respect to each criterion considered individually (i.e., the connectedness-maximizing plan, the area-maximizing plan, and the rare-species-maximizing plan). The other 33 solutions represent the optimal, compromise alternatives. They are optimal in the sense that for each alternative, there is no other feasible alternative that offers a higher level of one of the criteria, without also providing a lower level of at least one of the other criteria. Each of the 15 468 alternatives that was eliminated from the final set is non-optimal and therefore can be removed from consideration.

Plots of the optimal alternatives with respect to two criteria at a time highlight the trade-offs between them (Figs. 3A–C). The plot of area vs. connectedness shows that the candidate networks form two clusters with respect to these two criteria (Fig. 3A). Larger area networks (>1500 ha) range in connectedness from 29.01 to 231.67. Smaller area networks (<1500 ha) range in connectedness from 150.49 to the 304.91 (the connectedness-maximizing alternative). Perhaps if these were the only two criteria of interest, the network in the larger area cluster that provided the highest level of connectedness would provide a good compromise solution. Note that some of the points in the smaller area cluster appear to be non-optimal with respect to

TABLE 2. Overall scores (from Eq. 4) for the five candidate reserve networks with the highest connectedness scores (from Table 1).

Network identification no.	Criteria weighting	
	Approx. equal†	Favoring connectedness‡
32	0.554	0.683
33	0.727	0.744
34	0.583	0.774
35	0.512	0.785
36	0.528	0.835

† In Eq. 4: $\lambda_1 = 0.33$, $\lambda_2 = 0.33$, $\lambda_3 = 0.34$.
‡ In Eq. 4: $\lambda_1 = 0.75$, $\lambda_2 = 0.1$, $\lambda_3 = 0.15$.

the points in the higher area cluster. If these were the only two criteria of interest, these points would in fact be non-optimal and would not need be considered. Their inclusion is the result of the consideration of the third alternative. The plot of number of rare plant species represented vs. connectedness shows little clustering (Fig. 3B). High levels of connectedness can be acquired while maintaining a large species representation. The plot of number of rare plant species represented vs. area again shows the network alternatives forming two clusters (Fig. 3C). The smaller area alternatives produce species representation ranging from 22 (the species-representation-maximizing solution) to 11 species. The larger area alternatives produce species representation ranging from 21 to 13 species. It is noteworthy that the species-maximizing solution has a very small area. Perhaps if these were the only two important criteria, the network in the larger area cluster that provided the highest level of species representation would provide a good compromise solution.

It would be reasonable at this point to discontinue the quantitative analysis and begin to deliberate a final reserve from the reduced set of alternatives. This list is a manageable size and the trade-offs between the alternatives can be seen clearly from the graphs of the alternatives with respect to the criteria. But even with only three criteria, a ranking of the 36 alternatives is not obvious.

SMART Analysis

Subsequent to the MOP analysis, one may be faced with a list of alternatives from which a final choice must be made. While the planner may value some criteria more than others or may even be able to rank the criteria, ascribing absolute values to the criteria may be difficult. The simple multiattribute rating technique (SMART; Edwards 1971) can be used to rank the alternatives and, as is appropriate for this example, to explore the sensitivity of the ranking of the alternatives to changes in the values placed on the criteria. Continuing with the previous example, consider the list of 36 reserve-system designs for which the connectedness, area, and number of rare plant species represented are known. The SMART technique scores each design according to an additive value function of the form

$$v = \sum_{i=1}^{k} \lambda_i v_i(Z_i) \qquad (4)$$

where Z_i is a design criterion, k is the number of design criteria, λ_i is the relative value placed on criterion i, and v_i is the individual value function for criterion i.

The first step is to establish an individual value function, v_i, for each criterion. The individual value function provides a consistent means by which each alternative's performance with respect to the criterion can be translated into a numerical index score reflecting the planner's relative value for that level of performance. A variety of methods are available for creating an individual value function, varying in their degree of rigor. For example, one technique would be to directly assign a value (e.g., from a scale of 1 to 10) for each feasible criterion score. This direct scoring may be appropriate for criteria for which performance scores are non-numerical (e.g., if the number of rare species represented was categorized as "low," "medium," or "high"). Cohon and Rothley (1997) describe in detail the midvalue splitting technique (Keeney and Raiffa 1976, Goodwin and Wright 1991) by which a continuous value function is quantified explicitly through a series of questions designed to elicit a planner's values for all possible levels of the criteria. No single method is correct. Instead, planners should use the method that produces an individual value function that most accurately represents their values. In all cases, the logic by which the individual value function is created should be recorded in detail.

For this example problem, because each alternative already has a numerical value for each criterion, we will just normalize (rescale according to an index ranging from 0 to 1, range chosen arbitrarily) to form the numerical index scores. It is important to note that using normalization, there is an implicit assumption that our "value" for the level of each criterion increases linearly with the increasing value of that criterion. For example, an assumption of linearity implies that 20 represented species is twice as valuable as 10 species. If this weighting is not desired, or if it is desirable to test the sensitivity of any results to the assumption of linearity, then techniques that allow for the creation of nonlinear individual value functions, such as the midvalue splitting technique, should be used.

The next step is to assign values (λ_i) to each criterion. Again, these values can simply be assigned directly or can be deduced in a quantitative manner (Cohon and Rothley 1997). For this example, we will simply assign starting values with essentially equal weights ($\lambda_1 = 0.33$, $\lambda_2 = 0.33$, $\lambda_3 = 0.34$), but note that these values need not be the true and final values and that the sensitivity of the solution to these values placed on the criteria will be fully explored (also note that while it

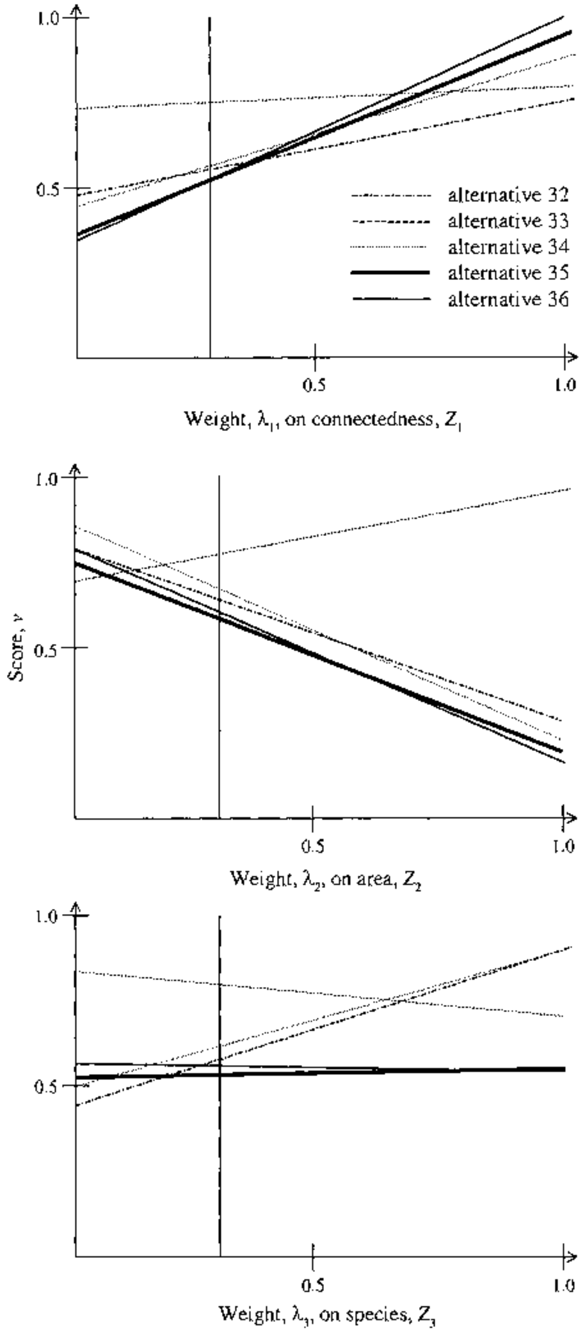

FIG. 4. Sensitivity-analysis graphs showing the overall scores (v) of the reserve alternatives as a function of the weightings ($\lambda_1 = 0.33$, $\lambda_2 = 0.33$, $\lambda_3 = 0.34$) placed on (A) connectedness, (B) total area, and (C) number of species.

is convenient to chose weights that sum to 1, it is not necessary).

Now that all of the parameters of Eq. 4 have been fixed, each network alternative is scored according to Eq. 4. For clarity, assume that a reserve planner in this example is very concerned with connectedness and only willing to consider the reserve networks with the top five connectedness scores (Table 1, alternatives 32–36). The overall scores for these alternatives according to Eq. 4 are shown in Table 2. The highest ranked alternative using the starting criteria values ($\lambda_1 = 0.33$, $\lambda_2 = 0.33$, $\lambda_3 = 0.34$) is alternative 33, a reserve system offering relatively low levels of connectedness and a small number of rare species but a very large area.

But how robust is this answer? To answer this question, Fig. 4, presents samples of the sensitivity analysis available as part of the SMART technique; it shows how the rankings of the alternatives vary with changing criterion values. The vertical lines on the graphs indicate the current weight placed on each criterion. The slanted lines represent the total scores for each alternative as a function of the weight placed on each criterion. For example, consider the sensitivity analysis for connectedness (Fig. 4A). At the solid vertical line representing $\lambda_1 = 0.33$, the dotted line representing alternative 33's score is higher than any of the other alternatives score lines. In fact, alternative 33's line is higher than the lines representing the scores of the other alternatives for all connectedness values ranging from 0 to ~0.65. If the planner were to value connectedness higher than 0.65, alternative 36 would be the highest ranked alternative. This makes sense as alternative 36 has the highest connectedness score. Fig. 4B shows that only for very low area values is alternative 33 not ranked the highest. This is logical given the large area of alternative 33 relative to the others. Finally, alternative 33 is top-ranked for species weights lower that 0.65; otherwise alternatives 32 and 34 nearly tie for top score (Fig. 4C). This is reasonable given their identical high levels of species representation. This sensitivity analysis suggests that for the initial criteria weights, this answer is fairly robust. If the planner placed relatively equal value on all three criteria, then alternative 33 is a good choice. However, given the reserve designer's proclivity for connectedness, it is useful to try a set of weights that more heavily favor connectedness (e.g., $\lambda_1 = 0.75$, $\lambda_2 = 0.1$, $\lambda_3 = 0.15$) and reexamine the results. Now alternative 36 has the highest ranking (Table 2). Sensitivity analysis shows that at these weights, the results are not as robust as for the first set of weights (Fig. 5). For example, by changing the weighting on area from 0.1 to 0.2 the highest ranked alternative would change from alternative 36 to alternative 33. But if these new weights reflect the reserve-planner's preferences for these criteria more accurately, then alternative 36 is more likely to satisfy the reserve-planner's aspirations.

DISCUSSION

Reserve networks are often expected to satisfy multiple, potentially conflicting demands. Rather than optimizing with respect to just one criterion, reserve planners are likely to seek some compromise. Multiobjective programming (MOP) is used to identify these compromise alternatives. In the example, I reduced a set

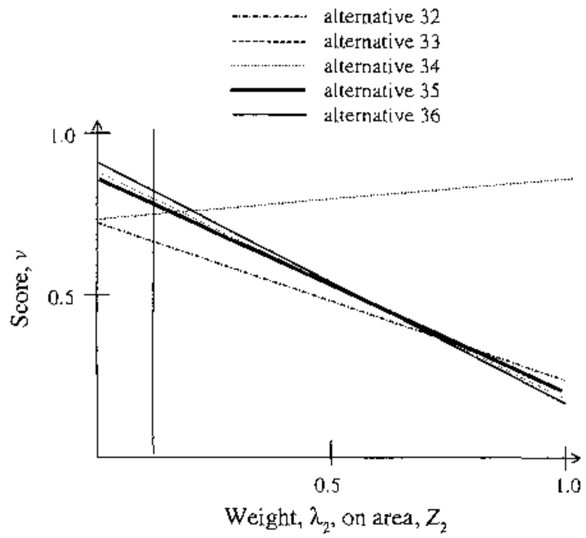

FIG. 5. Sensitivity-analysis graph showing overall score (v; Eq. 4) of the reserve alternatives as a function of the new weightings ($\lambda_1 = 0.75$, $\lambda_2 = 0.1$, $\lambda_3 = 0.15$).

of >15 000 potential reserve networks to a list of 36 candidate networks representing optimal trade-offs among three criteria (analyses took ~2 d). No decisions regarding the criteria were required to perform this reduction. MOP simply eliminates inefficient alternatives to produce a set of dominant candidates. The trade-offs among the criteria were explicitly quantified, so that the "costs" of improvement with respect to any criterion are known. I then used the simple multiattribute rating technique to rank these optimal alternatives according to the relative value placed on the individual criteria. Sensitivity analysis tests the robustness of the rankings and identifies the criteria on which the rankings are most dependent.

The example provided here described a "fixed-site" problem, for which the set of discrete candidate reserves has been clearly delineated (Cocks and Baird 1989). Similar techniques may also be applied to the "floating-site" problem for which the overall area in which the reserves are to be created is delineated but not the boundaries of the individual candidate reserves (Williams 1993).

A fundamental assumption for the MOP general formulation provided here is that all criteria and constraint equations are linear. Solutions for problems with nonlinear equations are available but they are more complex and computationally intensive. To simplify the problem, methods of linear approximation are available that transform the nonlinear criterion functions into a linear form (Steuer 1986, Schmitz et al. 1998).

The techniques described here are intended to be exploratory rather than dictatorial. Given the inherent uncertainty in the design criteria (e.g., what size reserve can secure the persistence of a large-bodied carnivore?), even a reserve design deemed optimal by MOP is not guaranteed to perform successfully. If there is any difficulty or uncertainty associated with the execution of the techniques described in this paper, it may be helpful to explore related procedures. Time permitting, it is always advisable to compare the results of competing methods to increase confidence in any final decision.

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