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Selecting compact habitat reserves for species with differential habitat size needs

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Abstract

We propose a model for the design of protected habitat reserves, which maximizes the number of species represented at least once in a limited set of reserved sites or parcels. Most models for reserve design do not differentiate eligible habitat sites by their size. Also, they assume that protection is guaranteed through the selection of one site for any species, not taking into consideration that habitat needs vary from species to species. Our model acknowledges the fact that different species require reserves of different sizes, and that these reserves should be compact areas, as opposed to a set of disconnected parcels. Computational experience is shown on a landscape modeled as a regular grid, in which individual species require 1-, 2- or 4-parcel compact reserves. The results are compared to output from a Maximum Species Covering Model.

Keywords: Habitat protection; Species preservation; Multiobjective programming; Integer programming; Biodiversity

1. Introduction

Decision models, aimed at supporting the selection of sites for protected habitat status, have been under development for two decades. Beginning with the heuristic formulations of Kirkpatrick [1] and Margules et al. [2], researchers sought the "minimum reserve set," the smallest number of sites or parcels needed to represent all species at least once in the system of reserved sites. These iterative methods used an attractiveness score for each site, based on the identity and number of the species present. At each iteration, as an additional parcel entered the reserve set, the attractiveness score for parcels that remained available to enter the system was updated. Both Underhill [3] and Possingham et al. [4] recognized that the iterative methods were, in fact, seeking to solve the set covering problem, a problem already intensively studied in the field of mathematical programming. The set covering problem and its derivatives have been widely studied in the field of location science since the early 1970s.

In location science, these coverage problems have names: the location set covering problem [5] and the maximal covering location problem (MCLP) [6]. Both can be cast and solved as 0–1 linear optimization models. When modeled as a set covering formulation, the problem is one of selecting the minimum number of habitat reserve sites needed

✠We dedicate this paper to the memory of Professor Charles ReVelle who passed away on August 10, 2005.

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to provide protection or coverage to all species of interest (e.g., [7]). When modeled as a maximal covering type formulation, the problem is one of selecting eligible habitat sites for protection in order to maximize the number of species that are protected or covered by the set of selected sites subject to a limit on the number of sites that can be selected (e.g., [8–11]). This latter problem has been referred to as the maximal covering species problem [11] or the reserve site selection problem [12]. ReVelle, et al. [13] review many of these species protection models and relate them to comparable models in location science.

Several assumptions are often made when using such models. First, a species is considered covered or protected if any one of the sites containing that species is selected for protection. With this approach, sites eligible to cover any particular species are not differentiated based upon size, quality, land acquisition cost or other features. Further, the assumption is made that protection is guaranteed through the selection of one site for any species, not taking into consideration that habitat needs may vary from species to species. Thus, habitat site selection models have typically ignored the differential habitat needs for individual species and the differential ability of eligible habitat sites to provide protection to different species, although such needs and abilities may have been implicitly recognized in the designation of a site's eligibility to represent a particular species. The actual specification of what constitutes an eligible or adequate habitat reserve to insure long-term viability of individual species is beyond the scope of this paper, but is addressed by Kunin [14], Pressey and Logan [15], and Bassett and Edwards [16].

Some extensions and modifications of this general reserve site selection problem have been made. Ando et al. [17] and Polasky et al. [18] solved budget constrained versions of the reserve site selection problem, incorporating land values and opportunity costs of site acquisition. Snyder et al. [19] incorporated area of the potential reserves sites and constrained total area of the selected sites. Haight et al. [20] and Arthur et al. [21] developed probabilistic reserve site selection problems in which probabilistic coverage and expected coverage of species, respectively, was maximized subject to limits on the number of reserve sites that can be selected. Church et al. [22] developed a reserve site selection formulation in which site quality of eligible habitat sites was included, maximizing the quality of protection provided to the covered species subject to a limit on the number of sites that can be selected. However, all of these models still assumed that coverage could be guaranteed for any species by selecting one of the eligible sites containing that species.

More recently, reserve site selection models have started to appear in the literature in which coverage for a particular species or ecosystem element requires a minimum number or combined total area of eligible reserve sites to be selected. Church et al. [23] developed a reserve site selection model designed to select sites for biodiversity management areas in order to represent and protect as many biodiversity elements as possible given budget limitations, where a biodiversity element was a physical or biological feature of an area that serves as a metric of biodiversity. In that model, a constraint was included that stipulated that a biodiversity element was not considered covered unless or until a total minimum area containing that element was selected for protection over the set of selected sites. This model did not, however, require or enforce the selected sites for any biodiversity element to be contiguous or compact. Thus, the set of sites constituting coverage of any particular biodiversity element could be quite spatially dispersed.

To address this issue, Fischer and Church [24] modified the previous model to include a clustering objective. That is, the model seeks to minimize the outside perimeter of the selected set of reserves while still stipulating that any particular biodiversity element requires a minimum total area contained within selected sites before it is considered covered. In this modified model, overall clustering and contiguity is encouraged but not guaranteed for every selected site and biodiversity element. This model could be solved with exact solution methods, but reported solution times were high. Median solution time reported for two data sets was 11 h.

Nalle et al. [25] specified a similar problem of selecting sites for protection given that a minimum percentage of each habitat type was to be protected while considering compactness and contiguity and limits on the number of sites to protect. However, their problem was specified as a quadratic 0–1 optimization model, and solved using heuristic solution methods. McDonnell et al. [26] specified a similar reserve site selection problem, minimizing and trading-off reserve boundary length and total area while requiring a minimum area of conservation elements to be selected in order for that element to be considered covered. This model was cast as a nonlinear integer program and solved via simulated annealing. Both the Nalle et al. [25] and McDonnell et al. [26] papers applied their models to grid-based data. Finally, Williams and ReVelle [27] minimized the total number of sites (or the total area) needed for representation of all species within a reserve core. They promoted contiguity and compactness of the reserve by surrounding the core area with buffer zones.

While the four papers referenced above all minimize the perimeter of the selected set reserve sites, and as a consequence, implicitly encourage overall reserve compactness, none require or ensure that the minimum area needed for any

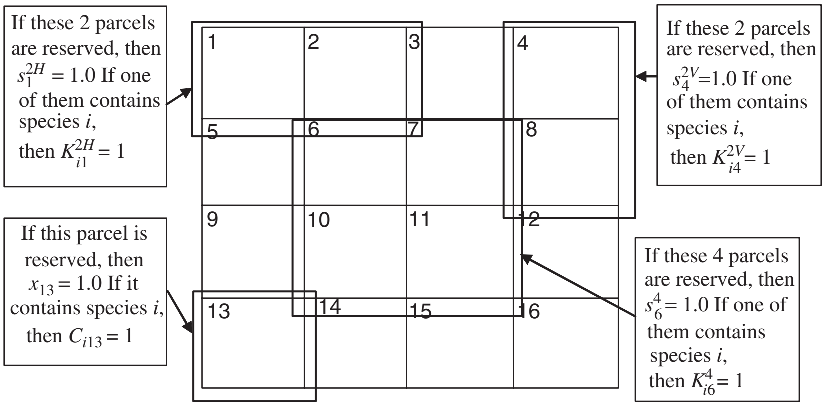

Fig. 1. Allowable reserve shapes: 4-parcel reserve, 2-parcel reserves and 1-parcel reserve.

of the individual species or ecosystem elements is assembled in a connected fashion. Coverage for individual species or landscape elements, as defined by these models, can still be met through a selection of an unconnected set of sites. It is here that our research makes a contribution. We develop a new reserve site selection coverage model that requires a minimum, contiguous area of eligible habitat be selected before a species is declared covered. Our model ensures that coverage for a species is met through the selection of a *locally* connected group of parcels whose combined area meets the minimum area requirement for each. Moreover, our model can be solved quickly using exact solution methods. However, it should be pointed out that the purpose of our model is not to ensure that the entire set of selected habitat reserves is necessarily compact and contiguous, but rather the assembled set of sites for any one particular species is contiguous.

2. Basic assumptions

In this section we analyze the basic assumptions for the model that we formally present in the next section. The basic objective of this model is to preserve as many species as possible, given that a limited number habitat sites can be reserved.

Our basic unit of habitat protection decision-making is a “parcel”. For a species to be preserved, clusters of contiguous or adjacent parcels must be reserved. These clusters are what we term habitat reserves. We consider that each species needs *at least* one reserve of a certain known, minimum number of parcels in order to be preserved. Some may require one parcel, while others require more than one. Species presence/absence data are known with certainty for each parcel. For the purposes of our analysis and illustrating the model, a grid-based system of parcels is utilized.

Several interpretations of multi-parcel habitat requirements are possible. Suppose a species i needs a minimum of four contiguous reserved parcels in order to be preserved. This could have at least two meanings. It could mean that a reserve of four parcels is needed in which the species is present in at least one of these parcels. Or it could mean that a reserve is needed that contains at least four contiguous parcels, *each* of which contains the species. We develop our model to address the first alternative, although it is easy to modify it to fit the second one.

Adjacency can have also several meanings, particularly if the landscape has been divided into gridded parcels. In this case, there is edge adjacency when two parcels share a side, and point adjacency when two parcels' corners touch each other. For the purposes of our analysis, we have chosen to use edge adjacency, although the model could be modified to consider other adjacency conditions.

3. Model with limited area units for preservation

The model we present uses predefined reserve shapes. To illustrate the capabilities of the model, we use three reserve configurations: four parcels in a square, two edge-adjacent parcels in either East–West (horizontal) or North–South (vertical) position, and individual parcels (Fig. 1). The basic model could be adapted to incorporate reserves of other sizes and shapes. The goal of this model is to maximize the weighted number of preserved species, when at most p parcels can be reserved.

The model is defined as

Sets

I_1 Set of all species i requiring just one parcel for preservation.
I_2 Set of all species i requiring two parcels for preservation.
I_4 Set of all species i requiring four parcels for preservation.

Parameters

C_{ij} 1 if j belongs to the set of parcels that contain species i.
K_{ij}^{2H} 1 if either parcel in the horizontal group of two reserved parcels (parcel j and the parcel at its right) contains species i. That is, $K_{ij}^{2H} = \text{Max}\{C_{ij}; C_{ij+1}\}$, where parcel $j+1$ is to the right of parcel j.
K_{ij}^{2V} 1 if either parcel in the vertical group of two reserved parcels (parcel j and the parcel below) contains species i. That is, $K_{ij}^{2V} = \text{Max}\{C_{ij}; C_{ij+B}\}$, where parcel $j+B$ is below parcel j. Note that the region is B parcels in width.
K_{ij}^{4} 1 if at least one parcel in the group of four reserved parcels (parcel j and the parcels to its east, south and southeast) contains species i. That is, $K_{ij}^{4} = \text{Max}\{C_{ij}; C_{ij+1}; C_{ij+B}; C_{ij+B+1}\}$. Here, $j+1$ is the parcel to the right, $j+B$ is the one below, i.e. adding a row, and so on.
W_i Positive weight on species i.
p Number of parcels that can be selected for protected habitat reserves.

Decision variables

x_j 1 if parcel j is selected for a habitat reserve, 0 otherwise.
s_j^4 1 if parcel j is the northwestern parcel of a set of four reserved parcels, 0 otherwise.
s_j^{2H} 1 if parcel j is the western parcel of a horizontal set of two reserved parcels, 0 otherwise.
s_j^{2V} 1 if parcel j is the northern parcel of a vertical set of two reserved parcels, 0 otherwise.
u_i 1 if species i is preserved, 0 otherwise.

$$\text{Max } Z = \sum_i W_i u_i$$

s.t.

$$u_i \leqslant \sum_j K_{ij}^4 s_j^4 \quad \forall i \in I_4, \tag{1}$$

$$u_i \leqslant \sum_j (K_{ij}^{2H} s_j^{2H} + K_{ij}^{2V} s_j^{2V}) \quad \forall i \in I_2, \tag{2}$$

$$u_i \leqslant \sum_j C_{ij} x_j \quad \forall i \in I_1, \tag{3}$$

$$\left.\begin{array}{l} s_j^4 \leqslant x_j \\ s_j^4 \leqslant x_{j+1} \\ s_j^4 \leqslant x_{j+B} \\ s_j^4 \leqslant x_{j+B+1} \end{array}\right\} \quad \forall j \notin \text{last row or column of the gridded landscape}, \tag{4}$$

$$\left.\begin{array}{l} s_j^{2H} \leqslant x_j \\ s_j^{2H} \leqslant x_{j+1} \end{array}\right\} \quad \forall j \notin \text{last column of the gridded landscape}, \tag{5}$$

$$\left.\begin{array}{l} s_j^{2V} \leqslant x_j \\ s_j^{2V} \leqslant x_{j+B} \end{array}\right\} \quad \forall j \notin \text{last row of the gridded landscape}, \tag{6}$$

$$\sum_j x_j = p, \tag{7}$$

$$x_j \in \{0, 1\}, \quad u_i, s_j^4, s_j^{2H}, s_j^{2V} \in [0, 1].$$

The objective maximizes the weighted number of preserved species. We use positive weights on species, representing their scarcity. The reader could be tempted to use negative weights on "undesirable" or invasive species. In this case, though, the model would not necessarily select reserves as to penalize these undesirable species or minimize their presence, because of the structure of the current formulation. Constraints (1)–(3) count as preserved ($u_i = 1$) only those species i for which there is at least one reserve of adequate size (4, 2 or 1, respectively) containing the species in one of its parcels. Constraints (1) apply to species with a 4-parcel habitat requirement. In constraints (1), variable u_i on the left side cannot take the value one unless the right side is equal to or greater than one, which will happen if:

(i) at least one variable s_j^4 in the summation is one, meaning that there is a reserve formed by parcel j and the parcels at its east, south and southeast, and
(ii) the corresponding K_{ij}^4 is also one, meaning that species i is present in at least one parcel of the cluster formed by parcel j and the parcels at its east, south and southeast.

Constraints (2) are similar, except in this case they apply to species with 2-parcel habitat requirements, and reserves can have either 2-parcel vertical or horizontal shapes. In constraints (3), a species requiring a single habitat parcel is considered covered, $u_i = 1$, if at least one of the eligible habitat parcels containing that species is selected for protection. These last constraints are typical of a MCLP [6]. Constraints (4) do not allow a 4-parcel cluster to be considered as a reserve ($s_j^4 = 1$), unless parcel j and the parcels at its east, south and southeast are reserved. Constraints (5) and (6) are the equivalent to constraints (4) for 2-parcel horizontal and 2-parcel vertical clusters. Constraint (7) limits the number of reserved parcels to p.

Note that although all variables must have values zero or one in the solution, there is no need to declare all these variables as integer or binary in the formulation. If variables x_i have binary values (zero or one), then variables s_j^4, s_j^{2H} and s_j^{2V} will necessarily take values zero or one, by virtue of constraints (4)–(6). Take for example, constraints (4): if all the parcels of the cluster are reserved, all the variables x on the right-hand side will be one, and variable s_j^4 can (and will) take its maximum possible value (one) if the reserve is useful for preservation purposes, that is, if a species i needs that particular reserve for being preserved. If one or more of the parcels of the cluster are not reserved, the variable s_j^4 will necessarily take the zero value.

Similarly, if variables s have values zero or one, variables u will necessarily take values zero or one, by virtue of constraints (1), (2) or (3). Since the right-hand sides of these constraints take only non-negative integer values, their left hand sides (variables u_i) can only take either value zero (if the right-hand side is zero) or one (if the right-hand side has an integer value different from zero).

Not having to declare all of the decision variables as binary is a computational advantage of the model. Recall that the most popular method for finding optimal solutions is the branch and bound algorithm. When this algorithm is used, as more variables need to be declared integer, the likelihood of the algorithm having to branch on these variables increases, and so does the solution time. In the ideal case in which none of the variables needs to be declared integer, the optimal solution is found just by solving the linear, continuous problem.

4. Computational experience

We constructed a set of data for a 144-parcel square-grid landscape with 116 species. The species' distribution was adapted from a dataset generated by the Chicago Region Biodiversity Council in 1995–2000 for a watershed in northeastern Illinois. We took the species' data and used it to create a 144 parcel (12 × 12) regular grid. "Scarcity" weights W_i were developed for each species, which were inversely proportional to the number of parcels in which the species was present, according to $W_i = [a/n_i]$, where a is a constant (144) and n_i is the number of parcels in which species i is present.

The relevant data for the landscape is shown in Table 1. The Table is divided into three parts. Each part shows the number of the species, its weight in the objective and the number of parcels needed for its preservation. We run the

Table 1
Species' data for the 144-parcel landscape

Species	Weight	No. of parcels
1	144	1
2	144	2
3	36	4
4	21	1
5	144	1
6	72	4
7	72	1
8	144	2
9	144	2
10	51	2
11	144	2
12	144	2
13	144	1
14	72	4
15	36	4
16	31	4
17	31	1
18	144	4
19	51	1
20	72	1
21	31	4
22	144	4
23	26	4
24	72	1
25	26	2
26	72	2
27	72	2
28	31	2
29	144	1
30	15	4
31	144	1
32	21	1
33	36	1
34	72	1
35	10	2
36	144	1
37	144	1
38	144	1
39	144	2
40	144	2
41	21	2
42	21	2
43	31	2
44	144	4
45	144	4
46	144	4
47	144	4
48	144	4
49	21	4
50	36	4
51	144	4
52	31	4
53	36	1
54	72	1
55	21	1
56	36	1
57	144	1

Table 1 (*contd.*)

Species	Weight	No. of parcels
58	51	1
59	51	1
60	51	2
61	51	2
62	72	2
63	72	2
64	144	2
65	72	2
66	51	1
67	21	4
68	72	4
69	15	4
70	15	4
71	72	4
72	144	1
73	21	1
74	51	4
75	72	4
76	26	4
77	144	4
78	72	4
79	72	4
80	144	4
81	144	4
82	51	1
83	72	1
84	72	1
85	51	1
86	72	2
87	144	2
88	144	2
89	10	2
90	72	2
91	144	2
92	144	2
93	10	1
94	5	1
95	144	1
96	10	1
97	26	1
98	144	1
99	144	1
100	5	1
101	31	1
102	51	2
103	144	2
104	5	2
105	15	2
106	21	4
107	26	4
108	10	4
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110	144	1
111	72	1
112	51	1
113	144	1
114	144	1
115	10	4
116	144	4

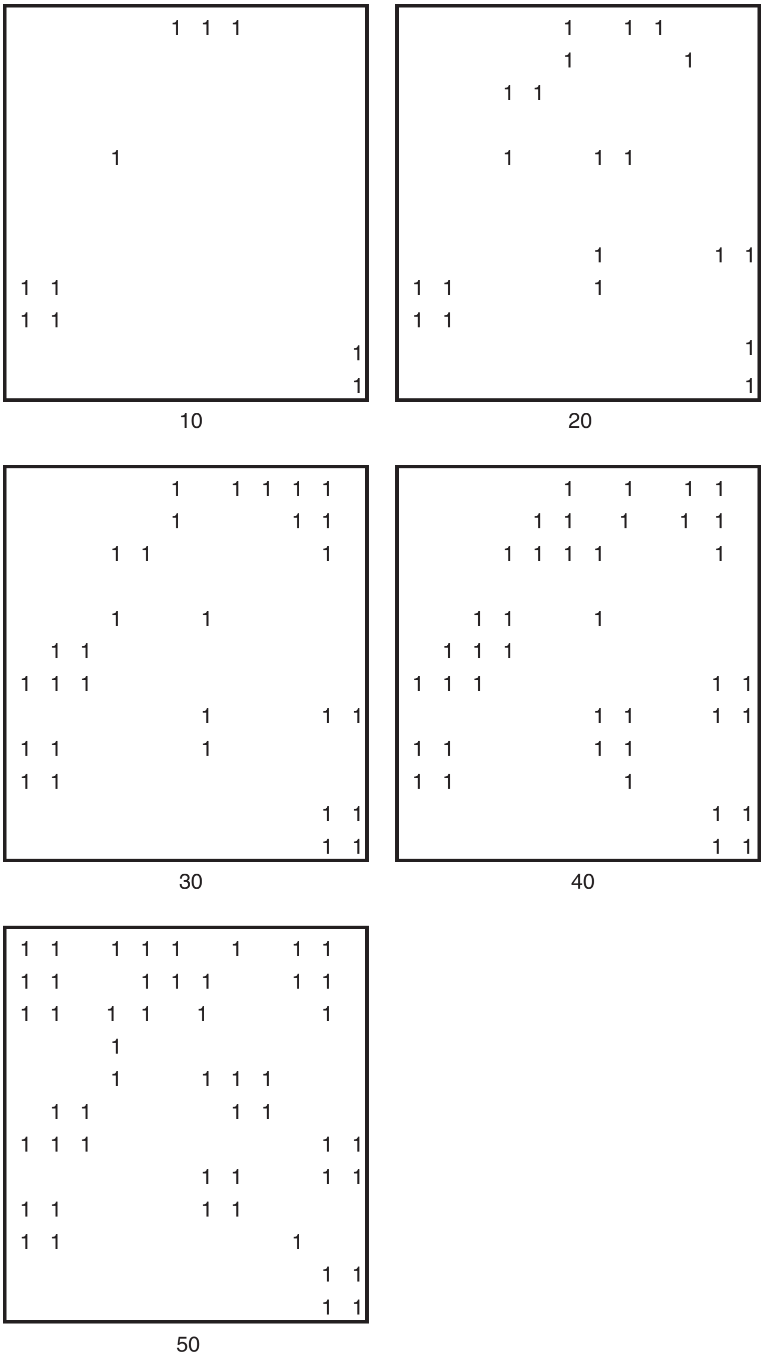

Fig. 2. Solutions for 10, 20, 30, 40 and 50 reserved parcels.

model for different maximum total numbers of reserved parcels, ranging from 10 to 54, using CPLEX 7.5, on a Pentium IV computer, 2400 MHz, 512 MB RAM.

Figs. 2 and 3 show some of the solutions.

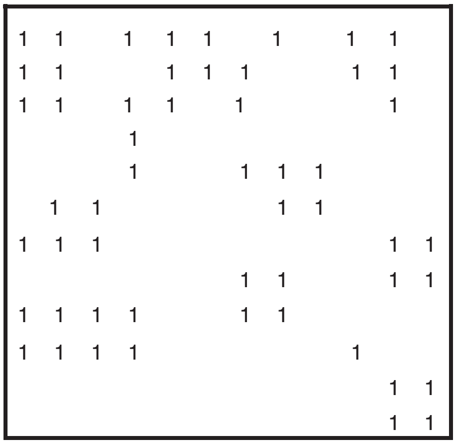

Fig. 3. Full protection for all 116 species with 54 parcels.

We observed that although the total reserved area is not fully connected or compact in the different solutions, the parcels tend to form clusters that are larger than the requirements of single species. For example, in the case of $p=54$, in which all 116 species are protected, eleven clusters are enough for these purposes, with sizes ranging from 1 to 12 parcels per cluster. This finding suggests that the model is selecting parcels for reserves to take advantage of the needs of species which are located close to one another or with similar habitat needs rather than simply selecting reserves for each species in isolation of the others. If the model was applied to a dataset with a set of species who had very similar habitat needs or which were located in parcels in close proximity to each other, the overall degree of compactness and contiguity of the selected reserves might be quite high. If, on the other hand, however, the habitat needs of the species of interest were either very different or spatially dispersed, then the overall set of reserves might appear much less globally compact and/or connected. Regardless, the model is selecting contiguous sets of parcels to meet individual species' habitat needs.

We also discovered a degree of consistency, or robustness, in the solutions. In examining Fig. 2, nine of the 10 reserved parcels in the first solution ($p=10$) are also present in the second solution ($p=20$). Exactly the same happens if we compare the solutions for 20 and 30 reserved parcels and for 30 and 40 parcels. When we compare the solutions for 40 and 50 parcels, there are four differing parcels. The reserves in the solution for 50 parcels are completely contained in the solution for 54 parcels. In this last case, we solved for 54 reserved parcels and then solved again, forcing the solution to contain the solution for 50 parcels (shown in the figure). These solutions are alternate optima, suggesting that alternate optima could also be found in some of the remaining cases. That is, we could search for alternate optimal solutions that always contain the fewest reserves for a given level of coverage. Additionally, instead of maximizing the weighted number of species, we could simply maximize the *number* of species. Note though, that both objectives are not the same. In fact, in the former, the model can choose to preserve fewer species of a higher "value" or weight, instead of maximizing just the number of species.

The consistency found in the results for different numbers of reserved parcels, suggests that, instead of building a reserve system at once, it is possible to distribute the cost of building a large reserve system over a period of years. During the first year, a few parcels would be reserved, and some more added on every following period. The intermediate reserve systems would then be nearly optimal, as well as the resulting final reserve, provided the conditions of the landscape do not change dramatically over the period of preservation.

Table 2 shows the run times and the solutions obtained for the example landscape. Fig. 4 shows the trade off between preserved species and reserved parcels.

Note that, when 10 parcels are reserved, more than half of the species are preserved. However, providing coverage to more species requires an increasingly larger investment in habitat reserves per species.

Next, we compare the results of our model to those of a conventional maximum species covering model (MSCM), using the same dataset. In the MSCM model, only one reserved parcel is needed in order for a species to be represented.

Table 2
Solutions obtained using the model

Parcels	Protected species	Objective	Run time (s)	Integer nodes
10	61	4341	2.09	22
15	70	5328	3.43	60
20	80	6089	2.67	206
25	92	6773	6.66	319
30	96	7308	11.88	1699
35	101	7827	17.95	1743
40	108	8295	12.81	949
45	111	8599	19.96	2449
50	115	8866	16.20	2172
54	116	9010	2.28	143

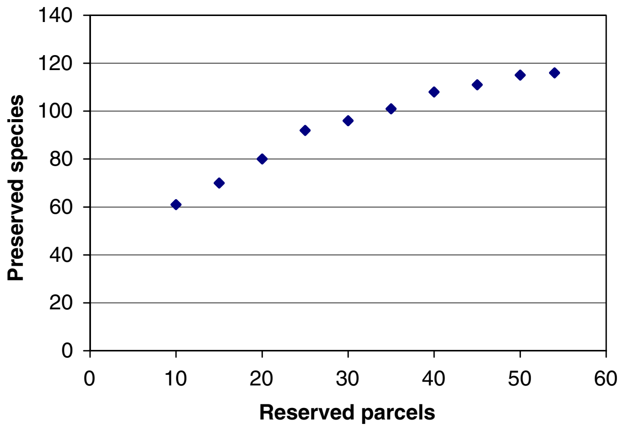

Fig. 4. Trade-off between reserved parcels and preserved species.

Using the same notation as before, the MSCM model is defined as follows:

$$\text{Max } Z = \sum_i W_i u_i$$

s.t.

$$u_i \leqslant \sum_j C_{ij} x_j \quad \forall i \in I, \tag{8}$$

$$\sum_j x_j = p, \quad x_j \in \{0, 1\}, \quad u_i \in [0, 1]. \tag{9}$$

Note that the MSCM model is a simplified version of the model presented in this paper, using only two of the constraint sets of our model.

The results of the runs using this last model are presented in Table 3.

In this case, no compact reserves of a size of four or more parcels were found, as shown in Fig. 5. In this figure, the shaded areas denote the only reserve clusters including at least four contiguous parcels.

Of the 38 species deemed covered through the MSCM and requiring four contiguous parcels, only species 3, 22, 52, 109 and 115 actually have their minimum area requirements met through the corresponding MSCM solutions. Also, out of the 33 species requiring two contiguous parcels for survival, only 17 actually have these habitat needs met although the solution of the MSCM model counts all 33 as preserved. These findings underscore the potential inadequacy of solutions generated via the traditional MSCM.

Table 3
Solutions obtained using the MSCM

Parcels	Species	Objective	Run time (s)	Integer nodes
10	88	5940	0.01	0
15	97	6907	0.01	0
20	102	7627	0.01	0
25	107	8347	0.02	0
30	112	8779	0.02	0
34	116	9010	0.01	0

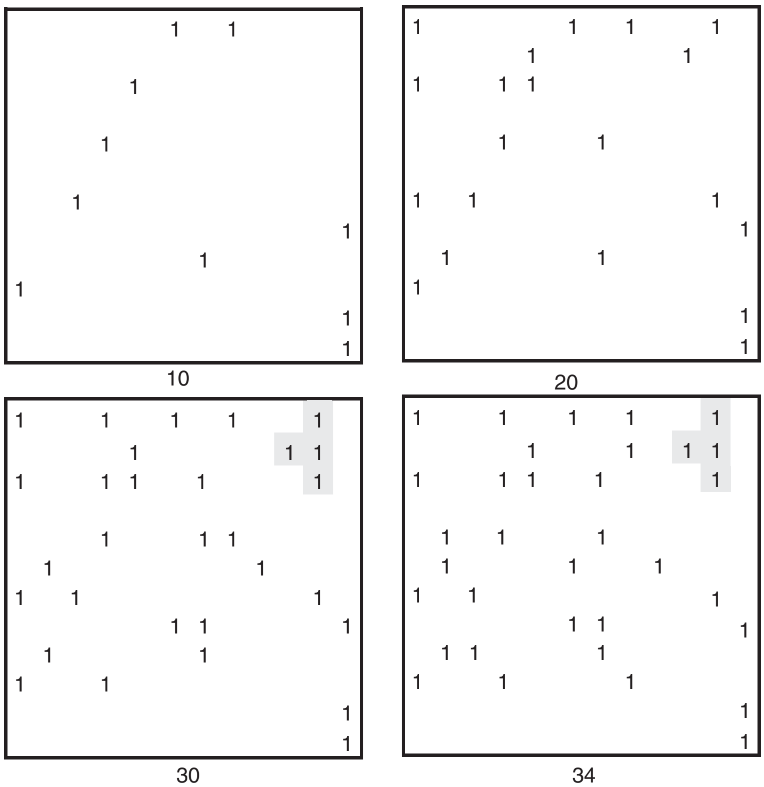

Fig. 5. Solutions for 10, 20, 30 and 34 reserved parcels, using the MSCM.

Comparing Figs. 3 and 5, consistency in the selection of reserved parcels *between* both models can be found. Note that, when solving the MSCM for $p = 10$, 20, 30 and 34, most of the selected parcels also appear in the solution in Fig. 3. This suggests that, at least for the data we used, there is a core group of habitat parcels, whose selection as reserves would meet different criteria, as represented by the MSCM and the new model.

We reiterate that the goal of the new model is not global connectedness, but the provision of large enough areas to fulfill individual species' preservation needs. Even though global connectedness is not sought, the reserves obtained using the new model are visually more connected and compact than the ones obtained by the MSCM when both models are solved for full species coverage. A future analysis could be done to determine how both models would compare if the 'full-preservation-solution' of the MSCM was resolved with 54 parcels to make it comparable to the full-preservation-solution of the new model. In order to do this comparison though, definitions and mathematical specifications of "connectedness" and "compactness" must be formalized. Additionally, trade-offs between global connectivity and reserve sizes for individual species' needs would need to be explored. It is our impression that connectedness is a conflicting objective with reserve area size for individual species' needs, at least in the case in which budgetary constraints set an upper bound on the number of parcels that can be reserved.

5. Conclusions

We develop and test a new approach to reserve selection. In this approach, the number of individual species represented or covered in selected habitat reserves is maximized, while insuring a reasonable preservation cost through a limit on the number of reserved parcels. Special consideration is given to the fact that, in order to be preserved, some of the species need areas for survival that are larger than individual parcels. Each species has its own minimum reserve size, measured in a number of basic-size parcels. We develop and solve a 0–1 linear optimization model for this situation and show computational experience that suggests the model will solve efficiently.

A number of enhancements could be made to the general model we outline in this paper. First, our model addresses contiguity in reserves for individual species, not contiguity over the entire set of protected parcels. Additional constraints or objectives could be included to enhance this global connectivity of the selected habitat sites. Second, other pre-defined shapes of habitat reserves could be defined and incorporated into the model. The example reserve configurations we utilized in this analysis were only meant to illustrate the capabilities of the model, and not to substitute for all habitat size and shape needs of species of interest. Other modifications could include the treatment of obnoxious or undesirable species or the construction of reserved paths through the area under study.

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