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Trading off species protection and timber production in forests managed for multiple objectives

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Abstract. We address a multiobjective forest-management problem that maximizes harvested timber volume and maximizes the protection of species through the selection of protected habitat reserves. As opposed to reserving parcels of the forest for general habitat purposes, as most published works do, the model we present, and its several variants, concentrate on the preservation status of each one of the species living in the forest under study. Thus, all of the formulations we propose trade off harvested timber volume against the weighted number of preserved species. Each formulation represents a different management policy. Casting the models in a static setting allows us to analyze the effect of several management policies through computational experience with different forest-stucture – species relationships.

Introduction and literature review

Significant advances have been made over the last two decades in the development and application of optimization decision tools to support natural resource decisionmaking. The forestry field in particular has enjoyed a rich history in the utilization of optimization models to support decisionmaking. In a parallel vein, a significant amount of research has also been conducted in the conservation biology field to develop optimization approaches that can guide in the selection of parcels for protected habitat reserves. To date, these fields of model development and inquiry, forest management and habitat-reserve selection, have remained largely separate tracks of inquiry. Our research represents one of the first steps in bringing together these two areas of decisionmaking so that management options can be considered in concert rather than separately. Timber-management activities and habitat-reserve decisions can influence one another. Further, managing a parcel for one of these purposes is likely to preclude the ability to simultaneously achieve any level of benefits of the other objective. Since there are dependencies and impacts associated with these two types of management decisions, we suggest it is important that decision models be developed that can integrate these two facets of land-management decisionmaking.

In the application to forest management, many optimization decision models have been built to address timber harvest-scheduling applications. Such models can be used to specify the optimal spatial arrangement and temporal sequencing of timber-management activities for stands of the forest. Over the last two decades an active area in this field has been the development of spatially explicit harvest-scheduling models. One particular line of research that has emerged from this focus on spatially explicit forest models is the development of harvest-adjacency constraint sets. The purpose of the harvest-adjacency constraint was to preclude large timber-harvest openings by preventing harvest activities on neighboring parcels within specified time frames or exclusion periods. The spatial restrictions were designed to reduce or curtail adverse impacts on nontimber resources of the forest that were associated with large harvest openings. The development of the harvest-adjacency constraint can be traced through the research of Meneghin et al (1988), Torres-Rojo and Brodie (1990), Jones et al (1991), Yoshimoto and Brodie (1994), Murray and Church (1996), Snyder and ReVelle (1996a; 1996b), Murray (1999), Hoganson and Borges (2000), McDill and Braze (2000), and McDill et al (2002).

This line of inquiry has received a significant amount of attention for several reasons. One is the growing need for a landscape approach to forest management and the realization that activities in one region of a forest can impact others. The second motivation is from a mathematical and modeling standpoint, in that adjacency constraints have proven to be very confounding, often rendering problems intractable. McDill and Braze (2000) identify no fewer than fourteen different adjacency-constraint formulations that have been proposed in the literature. This search for alternative specifications of harvest-adjacency constraints was largely an effort to develop specifications of these spatial restrictions that would allow harvest-scheduling models with these restrictions to be solved to optimality within a reasonable amount of time.

The development and application of optimization models for habitat-reserve design and parcel-selection applications have also been active areas of research. Although many biological or ecological protection goals may exist, two objectives are commonly addressed: (1) maximize the number of species or habitat classes that can be represented within a limited number of sites, and (2) select the smallest number of sites to provide representation or coverage to all of the species of concern at least once.

Many reserve-design optimization models have been based upon two classic formulations from the facility-location literature: the location set covering problem (LSCP) (Toregas and ReVelle, 1973) and the maximal covering location problem (MCLP) (Church and ReVelle, 1974). The objective of the LSCP, when adapted to a reserve-design problem, is to select the smallest number of candidate habitat sites so that all species are covered or represented at least once by the selected set (Underhill, 1994). The objective of the MCLP is to select the set of candidate habitat-reserve sites that maximizes the number of individual species that are represented at least once in the selected set, given a specified number of parcels available for set-aside. Many authors, including Cocks and Baird (1989), Saetersdal et al (1993), Camm et al (1996), Church et al (1996), Willis et al (1996), Williams and ReVelle (1997; 1998), Csuti et al (1997), Snyder et al (1999), and Church et al (2000), have developed integer optimization models for reserve design.

These reserve-design optimization models all have at least one commonality, and that is that they deal exclusively with decisions on where to set aside land parcels for protected habitat status. Decisions on other land-management options, such as where or when to conduct vegetation management, were assumed to occur in a separate decision framework. In reality, better decisions might be made if multiple types of land-management decisions were jointly considered because they have the potential to impact each other. The US Forest Service is an example of a land-management organization that would be faced with both of these types of management decisions. The agency has a long-established program to identify areas in national forests for designation as protected Research Natural Areas (RNAs), as well as a commitment to meet demands for timber products (USDA, 1992). We suggest that models that integrate habitat-protection decisions with other land-management decisions could prove beneficial to public land managers and decisionmakers.

Snyder and ReVelle (1997) developed a two-objective integer optimization model that simultaneously addressed the selection of parcels for habitat and for timber harvesting. The model included harvest-adjacency constraints that prevented harvests from occurring next to one another as well as next to habitat areas. The model traded off acres of protected habitat against volume of harvested timber in a one-time-period model on a regular grid. In this model, harvesting and habitat protection could not occur simultaneously within the same land parcel, nor could they occur individually in adjacent parcels. The effect was to produce a nonharvested buffer around habitat blocks or groups of blocks, which in turn led to relatively compact selection of parcels for habitat status. However, the model did not include any requirements for representation of specific species or coverage from the parcels that were selected for protected habitat status, as is required in reserve-coverage formulations. Parcels were selected for habitat status, more upon the basis of the degree to which remaining parcels could be assembled to allow maximum timber harvests, rather than on the number or type of species that the selected parcels might protect.

It is to this area that our current research makes a contribution. We develop new, flexible $0-1$ integer optimization models in which decisions on both harvesting and habitat-reserve selections are made, subject to harvest-adjacency constraints. This extends the work by Snyder and ReVelle (1997) in that explicit consideration for coverage of species through the selection of habitat parcels is required. Thus, this research draws together the lines of research on both harvest-adjacency-constraint structure within the context of a harvest-scheduling model and reserve-design formulations within a single forest-management optimization decision model. The models presented cover a variety of policy and management questions, while trading off harvested timber volume against species preservation.

General definitions and issues

For the purposes of illustration, we deal with hypothetical forests that are represented as uniform grids of square, indexed, cells or parcels although, as we explain later, the model can be easily rewritten for nonuniform parcel shapes. Each parcel is the habitat of one or more indexed species. Preservation of a particular species is achieved if at least one cell containing that species is left uncut. Preservation policies can seek either mandatory preservation of all considered species, or preservation of as many species as possible for given bounds on area or number of protected habitat parcels.

Additionally, each parcel contains a certain volume of timber that can be harvested. If a parcel is harvested, we enforce the condition that adjacent parcels must remain uncut. The uncut buffer then performs a variety of functions. First, it provides habitat and/or a habitat corridor. These uncut parcels can also aid in the reseeding of cut parcels. In addition, adjacency conditions are also put in place to provide some measures of environmental protection because excessively large harvest openings can often lead to increased runoff and erosion, which can have detrimental impacts on both soil productivity and aquatic clarity and health. In the USA, maximum clear-cut opening sizes are enforced on federal forestlands for all of these reasons. We assume that the two management choices of habitat preservation and timber harvesting are mutually exclusive on any parcel. Further, we assume that the only timber-harvesting regime under consideration is clear-cutting, and that clear-cutting removes all habitat value for a parcel during the subsequent planning horizon.

An issue of concern for the models that we build here is the scale of the parcels being considered. Our model, which represents an initial effort on the problem, assumes that parcels to be protected and parcels to be cut are of the same size.

It may well be possible to alter the models to make size requirements for the two types of activities different and/or to apply the models to irregular systems of parcels, but we have not attempted that here. Many reserve-site-selection coverage models to date have assumed the size or suitability of parcels for purposes of preservation to be uniform. That is, the coverage-type models have assumed that a single reserve site would be sufficient to provide protection or coverage to any species of concern regardless of parcel size and/or species' habitat needs. Reserve-site-selection models have often utilized grid-based data with uniform coverage requirements, although recently some reserve applications have been applied to irregular systems of parcels (Fischer and Church, 2003) or to those with differential habitat area needs by species or ecosystem feature (McDonnell et al, 2002; Nalle et al, 2002). Thus, our initial approach to designating parcels for species protection through the use of a uniform template corresponds to much of the literature to date. At the same time, many of the harvest-scheduling optimization models have also utilized a uniform template of land parcels for management purposes. Hence, our usage of a uniform template fits within the context of many of the timber-harvest-scheduling and reserve-site-selection models developed to date. The issue that remains to be explored is whether or not parcel size is comparable for the two land uses.

When dealing with a regular grid of parcels, adjacency can be defined in multiple ways. Adjacent parcels can be defined as those that share a common edge, as parcels 1 and 2 in figure 1, or those that share a common point, as parcels 1 and 4 in the same figure.

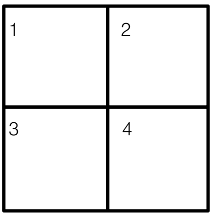


Figure 1. Adjacency

For our research we utilized both the edge and the point adjacency definitions. The effect of this adjacency condition is to force an uncut annulus around any harvested parcel. Other definitions of adjacency conditions can be developed that force a two-parcel or higher width buffer around any harvested parcel (Snyder and ReVelle, 1997).

The trade-off model

The following variables and parameters are defined:

i, I are the index and set of species;

j, J are the index and set of parcels;

$$y_j = \begin{cases} 1, & \text{if cell } j \text{ is harvested,} \\ 0, & \text{otherwise;} \end{cases}$$

$$x_j = \begin{cases} 1, & \text{if cell } j \text{ is reserved for habitat purposes,} \\ 0, & \text{otherwise;} \end{cases}$$

$$z_j = \begin{cases} 1, & \text{if cell } j \text{ remains uncut because of adjacency considerations,} \\ 0, & \text{otherwise;} \end{cases}$$

$$u_i = \begin{cases} 1, & \text{if species } i \text{ is preserved,} \\ 0, & \text{otherwise;} \end{cases}$$

N_i is the set of all parcels that contain species i;
n_i is number of parcels in the set N_i; in other words, the number of parcels containing species i;
V_j is the volume of timber that can be obtained if parcel j is harvested;
W_i is the optional weight on species i.

We address the situation in which species preservation is traded off against harvested timber volume on a regular grid of parcels for a one-time-period model. Objective Z_1 provides a measure of the harvested timber volume, to be maximized:

$$Z_1 = \sum_j V_j y_j \,. \tag{1}$$

The second objective (Z_2) measures species preservation, through the (weighted) number of preserved species. This weight could represent, for example, a measure of the scarcity, vulnerability, or 'importance' of a particular species. Its value could be set equal to unity if we had no special knowledge of the species' value for preservation. We seek to maximize

$$Z_2 = \sum_i W_i u_i \,. \tag{2}$$

The preservation variable u_i takes on the value of 1 if there is at least one reserved parcel that contains species i, expressed as

$$u_i \leqslant \sum_{j \in N_i} x_j \,, \qquad \forall i \,. \tag{3}$$

The right-hand side of equation (3) sums the number of reserved parcels that contain species i.

Adjacency constraints are added, which state that, if parcel j is harvested, then none of the parcels in the annulus around it can be harvested. These constraints, in their simplest pairwise structure, have the form:

$$y_j + y_k \leqslant 1, \qquad \forall (j, k) \text{ adjacent} \,.$$

Many researchers have found that representing adjacency constraints in this pairwise structure often leads to significant computational difficulties, and that more efficient constraint structures can be developed. We choose, then, to use adjacency constraints based upon the more compact 'block of four' adjacency constraints developed by Snyder and ReVelle (1996a; 1996b) and the clique constraints specified by Murray and Church (1996). For a regular grid these constraints are written as

$$\sum_{k \in S_j} y_k \leqslant 1, \qquad \forall j \notin \text{ east and south edges of the forest,} \tag{4}$$

where S_j is the set containing parcel j, the parcel immediately to the east of cell j, the parcel immediately to the southeast of parcel j, and the parcel immediately to the south of parcel j. The effect of using this specification of the adjacency condition is to reduce the number of constraints to one third of the number needed when the pairwise adjacency constraint structure is utilized. As a consequence, the "integer friendliness" found by Snyder and ReVelle (1996a), may be maintained. For irregular shaped forests, this constraint is written in a slightly different form.

As a consequence of these adjacency constraints, many parcels will remain uncut. However, not all of those uncut parcels may be strictly needed to achieve the species preservation represented by one of the objectives of the problem. The importance of explicitly selecting which parcels are to be left as reserves comes from the fact that those parcels not preserved but also not cut, might be cut later. In a dynamic formulation, this would have a bearing on the parcels selected for reserve status. To differentiate between parcels that remain uncut because they are chosen as habitat reserves and those that are left uncut because of adjacency constraints, we define variables x_j and z_j, respectively. Then, we formulate the model in such a way that its outcome will explicitly indicate the number and position of reserved parcels, as opposed to those parcels that are simply left uncut because of the adjacency constraints and assumed to function in a habitat capacity.

To enforce the fact that a parcel can be harvested, reserved, or left uncut, we use the following constraint:

$$x_j + y_j + z_j = 1, \qquad \forall j. \tag{5}$$

The complete reserve selection timber trade-off (ReSTT) model is the following:

$$\text{maximize } Z_1 = \sum_j V_j y_j , \tag{1}$$

$$\text{maximize } Z_2 = \sum_i W_i u_i ; \tag{2}$$

subject to

$$u_i \leqslant \sum_{j \in N_i} x_j , \qquad \forall i; \tag{3}$$

$$\sum_{k \in S_j} y_k \leqslant 1, \qquad \forall j \notin \text{ east and south edges of the forest}; \tag{4}$$

$$x_j + y_j + z_j = 1, \qquad \forall j; \tag{5}$$

$$y_j, x_j \in \{0,1\}, \qquad u_i, z_j \in [0,1], \qquad \forall i,j. \tag{6}$$

Constraint (6) enforces the integer nature of the variables.

In the ReSTT model, for parcels that are reserved as habitat, variable x_j will necessarily take the value 1, by virtue of constraint (3) and the maximization of objective Z_2. However, a parcel j that remains uncut only because of adjacency constraints could be represented in the solution to the problem by either a variable x_j equal to one, or a variable z_j equal to one, because for those parcels the model does not differentiate both variables. In order to introduce a difference between these types of uncut parcels, a secondary objective can be added and minimized, of the form:

$$\varepsilon \sum_j x_j , \tag{7}$$

where ε has a very small value. This secondary objective will force $x_j = 0$ for those parcels j that are not strictly required for preservation purposes. The value of ε needs to be small enough ($0 < \varepsilon < \min_i \{W_i\}$) to ensure that this objective remains secondary and it does not enter into competition with the preservation objective.

Note that, in this model, only the y_j and x_j variables need to be declared as binary; z_j and u_i do not actually need to be declared binary in order for them to solve with binary values. If variables y_j and x_j are binary, constraint (5) will force variable z_j to be binary. Also, variable u_i appears only in constraint (3) and in the preservation objective. Since this variable is maximized, it will take the highest value allowed by constraint (3). If variable x_j is binary, the right-hand side of constraint (3) will always have an integer value or a zero value. If the right-hand side is zero, the corresponding variable u_i will take necessarily the value zero. If the right-hand side has any integer value, the variable will take the value one, provided it is upper bounded by this value. Reducing the number of variables that must be declared binary may improve the computational efficiency of a $0-1$ integer programming model.

This model could be modified to address a different management situation, in which all species in a set S are required to have some degree of representation. The set S could contain all or some species. To model this situation we would force the variables u_i corresponding to the species in S to have the value one. For these species, constraint (3) becomes:

$$\sum_{j \in N_i} x_j \geqslant 1, \qquad \forall i \in S, \tag{8}$$

meaning that at least one parcel containing species i must remain uncut. The formulation is augmented by constraint (8) for the set S of species that must be preserved. If all species must be preserved, constraint (3) is simply replaced by constraint (8) and only the timber volume is maximized.

Also, an additional constraint could be added to the model to limit the number of reserved parcels. We model this policy in our formulation by adding the constraint:

$$\sum_{j} x_j \leqslant p\,. \tag{9}$$

Computational experience

We constructed a semihypothetical set of data for a 144-parcel square-grid forest. 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 them to create a 144-parcel (12×12) regular grid. No timber volume information was associated with or available for the parcels. Thus, for the purposes of our application, we generated several different hypothetical forest-volume scenarios to correspond to our grid of species presence–absence data. The distribution of the species is detailed in table 1.

Table 1. Species distribution in the 144-parcel, square-grid forest.

In how many parcels is each species present?

Histogram 1			Histogram 2		
number of parcels, c	species present in c parcels	percentage of the species living in c parcels	number of species, s	parcels containing s species	percentage of the parcels containing s species
1	41	35	1	54	38
2	22	19	2	33	23
3	12	10	3	14	10
4	6	5	4	9	6
5	7	6	5	10	7
6	5	4	6	4	3
7	3	3	7	5	3
8	5	4	8	1	1
9	2	2	9	2	1
10	3	3	13	2	1
13	1	1	14	1	1
14	1	1	15	1	1
18	1	1	17	2	1
19	1	1	18	2	1
21	1	1	20	3	2
22	2	2	23	1	1
28	1	1			
31	1	1			
34	1	1			

'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 $W_j = (a/n_i)$, where a is a constant of (140) and n_i is the number of parcels in which i is present.

The species distribution data did not include information on the harvestable timber volume in each parcel, giving us the opportunity to simulate different conditions. In the absence of inventoried timber volume, we generated timber-volume scenarios based upon possible relationships between timber volume in a stand and number of species in that stand. Our first approach was to assume that there is no relation between timber volume and the number of species in a parcel, assigning each parcel a random amount of timber volume. These random numbers range from 1 to 150.

As some correlation between timber volume (older trees) and amount of wildlife might exist, we generated a second hypothetical timber-volume distribution in which the number of species in a parcel was dependent on the timber volume, as in the equation $N_j = \alpha V_j + \beta$, where N_j is the number of species present in that parcel, V_j is the timber volume in parcel j, and α and β are parameters. Because we have information only on the dependent variable N_j, we simulated this scenario using the inverse equation:

$$V_j = \gamma N_j + \delta . \tag{10}$$

We used values $\gamma = 6.4$ and $\delta = 3.6$, so the timber volume in each parcel ranges from approximately 10 to 150. We call this case the proportional forest.

We also simulated a third forest condition, the intermediate case, in which the number of species in each parcel is related to the harvestable timber volume in a random proportion. As before, the independent variable is the timber volume; however, we use the following equation for estimating the timber volume:

$$V_j = \phi_j N_j , \tag{11}$$

where ϕ_j is a random number uniformly distributed between 3.2 and 9.6 (6.4 ± 3.2), for each parcel. In the particular instance we used, the timber-volume values ranged from 4 to 172 units.

Note that the total timber volumes in the three scenarios are not the same. These volumes did not need to be directly comparable as we were trying to demonstrate the effect that different timber – species relationships might have on the solution properties.

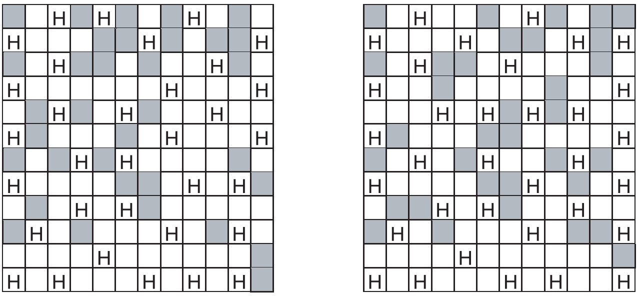
The resulting ReSTT model has 548 binary variables and 381 constraints. We solved the ReSTT model using the commercial linear integer optimization package CPLEX 7.1 (ILOG, 2001), on a Pentium III computer. The longest time taken by a run was 0.77 s, and all remaining runs took less than 0.3 s. Only one of the runs required branching (two integer nodes). All of the models were solved by the multiobjective weighting method. This method consists in putting a nonnegative weight on each objective and adding all weighted objectives to form a single objective function. The problem is solved repeatedly, changing each time the relative weights on the original objectives, and a trade-off curve is drawn. We used weights λ and $(1 - \lambda)$ on both objectives, where λ is between 0 and 1.

Developing timber-volume scenarios—uncorrelated case

The ReSTT model was solved many times for the uncorrelated case, incrementally varying the value of the weights on both objectives to produce a trade-off curve between the two objectives. Table 2 shows the results of these runs, and figure 2 shows the 'extreme', endpoint solutions when the weights are set to 1 and 0, respectively, for each of the objectives (for example, maximum timber volume, maximum number of

Table 2. ReSTT (reserve selection timber trade-off) model solutions on the uncorrelated 144-forest.

Timber volume	Preserved species	Number of reserved parcels	Weight on the preservation objective
3283	116	34	$\geqslant 0.4$
3373	115	35	0.3
3500	111	32	0.2
3576	108	32	0.1
3626	104	35	0.05
3631	102	34	$\leqslant 0.01$



(a) (b)

Figure 2. Random forest: (a) all 116 species preserved, timber volume = 3283; (b) maximum timber volume (3631), 102 species preserved. Harvested parcels are marked with an H. Reserved parcels (34) are shaded.

preserved species). In these figures, the harvested parcels are marked with an H, and the reserved parcels are shaded.

These results show that the maximum harvested timber volume attainable, 3631 units, can be achieved while simultaneously covering 102 species, or 88% of the total, figure 2(b). In order to preserve all 116 species, a 9.6% drop in timber volume ensues, figure 2(a). These findings suggest that it is relatively 'easy' to achieve coverage of many species without great sacrifices to the maximum harvested timber volume that could be achieved. This is a result, in some measure, of the adjacency conditions, which force uncut buffers. Note that many of the reserve parcels coincide with the adjacency buffer sites.

Even if the weight on the preservation objective is zero, the maximum harvestable timber volume is of course also limited by the adjacency constraints. In the previous example, the total timber volume in the 144 parcels is 10 821. However, the adjacency constraints limit the harvestable volume to at most 3631 volume units.

The upper curve in figure 3 (see over) shows the timber volume against number of preserved species trade-off for the uncorrelated or random forest. The bottom curve in figure 3 shows the number of reserved parcels for each Pareto-optimal (or noninferior) solution. Note that this number remains almost unchanged across the solutions. Furthermore, there is no clear trade-off between the number of reserved parcels and the remaining parameters. This is because the number of reserved parcels is being minimized as a secondary objective, with a very small weight, only to ensure that the model will keep them to the strictly needed amount, in favor of neither-cut-nor-reserved parcels, represented in the model by the variable z_j. Consequently, in each case, the model adjusts the number of reserved parcels to what is needed for the optimization of the preservation and timber-volume objectives.

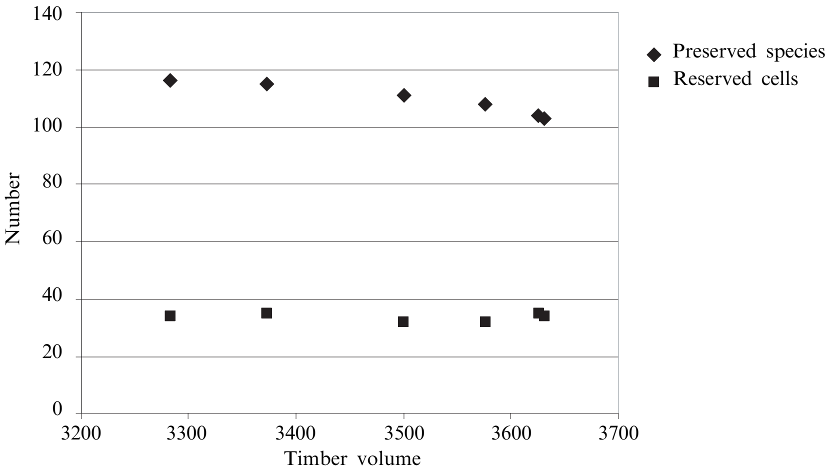


Figure 3. Trade-off curve for the uncorrelated forest.

Second hypothetical forest example—the 'proportional' forest

The trade-off in this case is much stronger between the two objectives than in the uncorrelated case. As before, the maximum harvested timber volume is limited by adjacency constraints. Table 3 and figures 4 and 5 show some results. Figure 5 shows the endpoint solutions of the curve, points A and B. Point A is shown in figure 5(a), and corresponds to the solution that covers all 116 species. Point B, shown in figure 5(b), corresponds to the solution with the highest possible harvested timber volume. Going from

Table 3. Representative values for the ReSTT (reserve selection timber trade-off) model solutions on the proportional 144-forest.

Timber volume	Preserved species	Number of reserved parcels	Weight on preservation
1200	116	34	0.4–0.99
1377	113	32	0.3
1444	110	32	0.2
1652	98	34	0.1
1880	76	33	0.05
1886	74	33	0.01

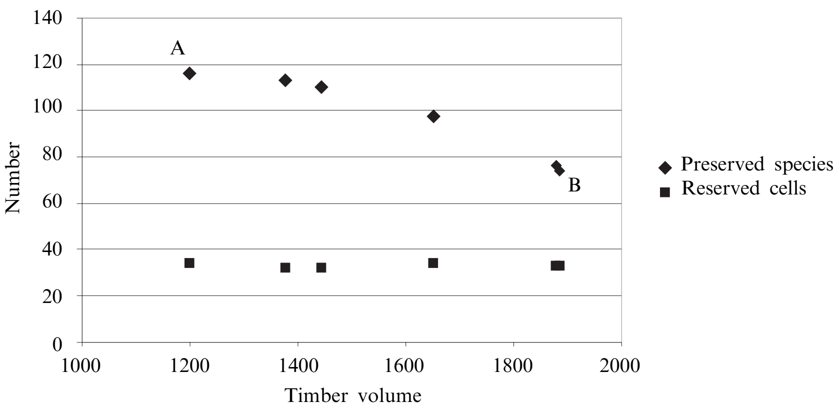
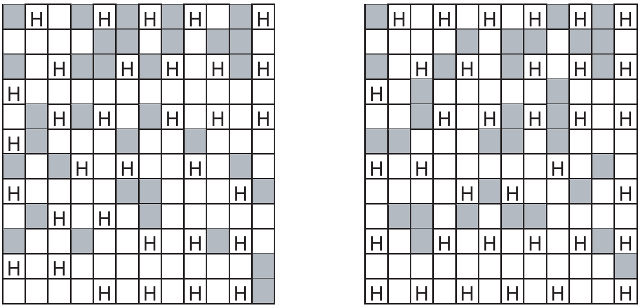


Figure 4. Trade-off curve for the proportional forest.



(a) (b)

Figure 5. Proportional forest: (a) all 116 species preserved, timber volume $=$ 1200; (b) maximum timber volume (1886), 74 species preserved. Harvested parcels are marked with an H. Reserved parcels are shaded.

point A to point B involves an increase of 36.4% in timber volume for a decrease in 42 (or 36.2%) of the total number of species.

Again, the number of reserved parcels does not change significantly across all solutions. This lack of variability in the total number of reserved parcels shows that, in our example, reserving a larger number of parcels for habitat purposes does not necessarily guarantee the preservation of more species, at least for the manner in which we defined preservation. This finding may be true for other cases in which wildlife distribution is similar to the one in our example, as presented in table 1.

Third hypothetical forest example—the ‘intermediate’ forest

Table 4 shows some solutions. With this set of data, 75 species, or 64.7% of the total, are protected when the timber-volume objective is at a maximum, of 1707 timber-volume units. In order to cover all 116 species a 33% drop in timber volume must be accepted. The trade-off curve is very similar to the curve for the proportional forest.

Table 4. Representative values for the ReSTT (reserve selection timber trade-off) model solutions on the intermediate 144-forest.

Timber volume	Preserved species	Number of reserved parcels	Weight on preservation
1142	116	34	0.4
1341	112	32	0.2–0.3
1452	103	32	0.1
1602	89	32	0.075
1698	77	32	0.05
1707	75	32	0.01

Effect of the adjacency constraints

Because the adjacency constraints limit the number of harvestable parcels, they alone allow the preservation of many species. In order to analyze the effect of these constraints on preservation, we relaxed them and tested the ReSTT model without constraint (4). The results are shown in table 5 and figure 6 (see over).

In table 5 the last row shows the case in which all the forest is cut and no species are preserved. The first row of the same table shows a solution in which all species are

Table 5. Representative values for the solutions of the ReSTT (reserve selection timber trade-off) model without adjacency constraints, on the intermediate 144-forest.

Timber volume	Preserved species	Number of reserved parcels	Weight on preservation
2100	116	34	0.999
2596	108	29	0.18
2701	102	25	0.15
2944	78	17	0.1
3109	57	15	0.09
3237	30	15	0.08
3353	9	7	0.05
3394	0	0	0.001

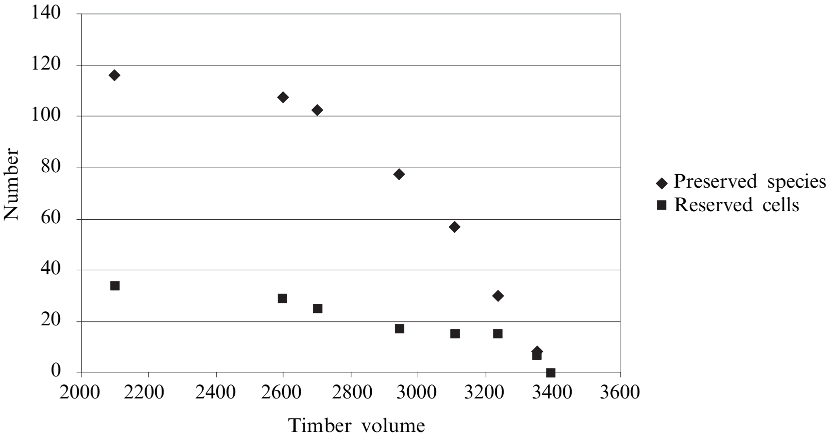


Figure 6. Trade-off curve for the intermediate forest, with no adjacency constraints.

preserved in 34 parcels. All the remaining parcels of the forest are harvested. So, for this case, the harvest-adjacency constraints result in a 38% reduction in harvested timber volume comparing the solutions with 116 to 0 preserved species. An important issue to note is that, by adding the adjacency constraints, even when the weight on the preservation objective is zero, 75 (65% of the total) species are preserved. Thus, although harvest-adjacency restrictions do not in and of themselves replace the need for explicit policies on species preservation, they nonetheless do provide some measure of habitat protection on their own.

Mandatory preservation

When solving the ReSTT model, the number of species that are preserved in the solution depends on the relative weights on the two objectives. If there is the need to preserve a particular set S of species, the mandatory preservation constraint (8) can be added before solving it. Alternatively, if an instance of the ReSTT model is run, and its solution does not include some species that need to be preserved, constraint (8) can be added for that specific species, and the problem solved again. Note, though, that adding the constraint for one species not only forces the preservation of that particular species, but it might also change the preservation status of other species in the solution.

Upper-bounding the number of reserved parcels

Except for the case in which the adjacency constraints are removed, all the runs show that there is neither a clear trade-off between the number of reserved parcels and the harvested timber, nor a clear relationship between the number of reserved parcels and the number of preserved species. The number of reserved parcels remains nearly constant in all runs. We might expect this same relationship to hold for other cases in which wildlife is distributed in a similar way as in our example. However, a policy-maker may be interested in knowing how many species could be protected for varying numbers of parcels that could be selected for reserve status. Although our models suggest for the datasets we used that around thirty-three parcels are typically needed to cover all species, one might not have either the budget or political consensus to select so many parcels at once or at all.

In order to analyze the performance of this policy, we tested a variant of the ReSTT model, in which we kept all the constraints and added constraint (9), which upper-bounds the number of reserved parcels. We call the resulting model, the ReSTT-p model. The dataset we used in this example was the 144-parcel 'intermediate' forest. The results are shown in table 6 and figure 7 (over), from which it is evident that, although the ReSTT-p models do not do as well when folded into the framework we are using (for example, they consistently produce solutions that are suboptimal with respect to our dual objectives), they belong to a different class of models, one in which the resources to designate parcels are strictly limited. In our models, we are trading off timber volume and species and there is no limit on the number of reserved parcels.

Table 6. Solutions of ReSTT-p (reserve selection timber trade-off) model with a limited number of reserves, on the intermediate 144-parcel forest. Limit on the number of reserves = 5 to 30.

Timber volume	Preserved species	Number of reserved parcels	Weight on preservation
1391	67	5	0.15 – 0.99
1476	63	5	0.12 (2 integer nodes, 0.05 s)
1592	55	5	0.1
1623	48	5	0.09
1707	33	5	0.01
1244	88	10	0.7 – 0.99
1362	85	10	0.2 – 0.6
1467	75	10	0.1
1677	50	10	0.075
1707	43	10	0.01 – 0.05
1244	102	20	0.6 – 0.99
1362	99	20	0.2 – 0.5
1449	91	20	0.1
1613	73	20	0.075
1707	62	20	0.01 – 0.05
1145	112	30	0.99
1345	110	30	0.3
1467	101	30	0.1
1698	75	30	0.05
1707	73	30	0.01

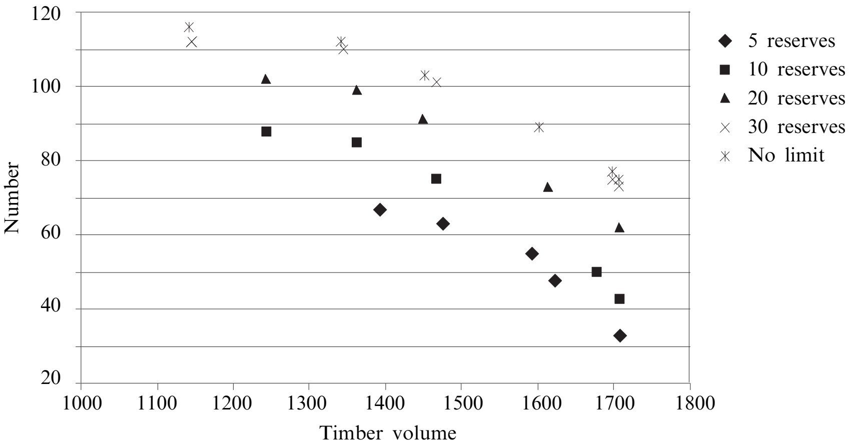


Figure 7. Trade-off curves for the ReSTT-*p* (reserve selection timber trade-off) model, intermediate forest.

Conclusions and future work

We develop new models that address the multiobjective problem of timber-volume maximization and species protection. In our research, as opposed to much of the previous reserve-site-selection coverage models, we explicitly select sites to preserve each species of interest, rather than just reserving general habitat for all species. We show that a model such as ReSTT that trades off harvested timber volume and number of preserved, weighted species is easy to solve and, if the resources for designating reserved parcels are not limited, allows the best figures for harvested timber volume and species preservation to be obtained for an almost fixed number of reserved parcels.

The casting of this formulation as a static problem is obviously a simplification of the dynamic nature of both the timber-resource and the harvest-scheduling problem. We view this research as the first step in the development of a temporal model that considers harvesting and reserve-selection decisions over a multiyear planning horizon. Future research will address this issue, as well as the issue of the different sizes or scales of the parcels to be protected and to be cut. We are working on models that would allow preservation and cutting at different scales.

We recognize that the use of a regular grid of parcels is also a simplification. The formulations developed in this paper can be modified for application to irregular parcel systems. Models dealing with such systems would differ from the presented models only in the adjacency constraints. The 'block of four' adjacency constraints utilized in this model can be generalized to 'block of s' constraints for each set of s mutually adjacent parcels (Snyder and ReVelle, 1996b). Further, we anticipate that our formulations should be solvable if applied to problems with more planning parcels. All of our runs with the 144-parcel grid solved in seconds with only a few required branch-and-bound nodes, making successful application to larger problems seem likely.

Future research may also include the development of models that concentrate on improving the survival probability of species through the protection of multiple parcels or a minimum habitat area for each species. Our models assumed that a single protected parcel was adequate protection for a species. In reality, different species will have different habitat and resource requirements that might translate into the need for multiple parcels or a minimum, contiguous area of habitat. Finally, an issue that this model does not address is that of the spatial arrangement of the reserve sites. Figures 2 and 5 illustrate that the selected habitat areas tend to be largely isolated parcels, with no real clustering between protected parcels or buffers between harvest and habitat areas. Although the ultimate ability of selected habitat areas to protect species successfully is a function of many factors, including size of the protected parcels and habitat needs of specific species, the value of isolated habitat parcels may be less than that of a more buffered, connected set of parcels. Future modeling efforts could focus on addressing issues of reserve compactness and contiguity in conjunction with a multiobjective harvesting – reserve model.

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References

Camm J, Polasky S, Solow A, Csuti B, 1996, "A note on optimal algorithms for reserve site selection" *Biological Conservation* **78** 353 – 355
Church R, ReVelle C, 1974, "The maximal covering location problem" *Papers in Regional Science* **71** 199 – 215
Church R, Stoms D, Davis F, 1996, "Reserve selection as a maximal covering location problem" *Biological Conservation* **76** 105 – 112
Church R, Gerrard R, Hollander A, Stoms D, 2000, "Understanding the tradeoffs between site quality and species presence in reserve site selection" *Forest Science* **46** 157 – 167
Cocks K, Baird I, 1989, "Using mathematical programming to address the multiple reserve selection problem: an example from the Eyre Peninsula, South Africa" *Biological Conservation* **49** 113 – 130
Csuti B, Polasky S, Williams P, Pressey R, Camm J, Kershaw M, Kiester A, Downs B, Hamilton R, Huso M, Sahr K, 1997, "A comparison of reserve selection algorithms using data on terrestrial vertebrates in Oregon" *Biological Conservation* **80** 83 – 97
Fischer D, Church R, 2003, "Clustering and compactness in reserve site selection; an extension of the biodiversity management area selection model" *Forest Science* **49** 555 – 565
Hoganson H, Borges J, 2000, "Impacts of the time horizon for adjacency constraints in harvest scheduling" *Forest Science* **46** 176 – 187
ILOG, 2001, CPLEX 7.1, http://www.ilog.com
Jones J, Meneghin B, Kirby M, 1991, "Formulating adjacency constraints in linear optimization models for scheduling projects in tactical planning" *Forest Science* **37** 1283 – 1297
McDill M, Braze J, 2000, "Comparing adjacency constraint formulations for randomly generated forest planning problems with four age – class distributions" *Forest Science* **46** 423 – 436
McDill M, Rebain S, Braze J, 2002, "Harvest scheduling with area-based adjacency constraints" *Forest Science* **48** 631 – 642
McDonnell M, Possingham H, Ball I, Cousins E, 2002, "Mathematical methods for spatially cohesive reserve design" *Environmental Modeling and Assessment* **7** 107 – 114
Meneghin B, Kirby M, Jones J, 1988, "An algorithm for writing adjacency constraints efficiently in linear programming models", in *1988 Symposium on Systems Analysis in Forest Resources* General Technical Report, RM-161, USDA Forest Service, PO Box 96090, Washington, DC 20090-6090, pp 46 – 53
Murray A, 1999, "Spatial restrictions in harvest scheduling" *Forest Science* **45** 45 – 52
Murray A, Church R, 1996, "Constructing and selecting adjacency constraints" *INFOR Journal* **34** 232 – 247
Nalle D, Arthur J, Sessions J, 2002, "Designing compact and contiguous reserve networks with a hybrid heuristic algorithm *Forest Science* **48** 59 – 68
Saetersdal M, Line J, Birks H, 1993, "How to maximize biological diversity in nature reserve selection: vascular plants and breeding birds in deciduous woodlands, western Norway" *Biological Conservation* **66** 131 – 138
Snyder S, ReVelle C, 1996a, "The grid-packing problem: selecting a harvesting pattern in an area with forbidden regions" *Forest Science* **42** 27 – 34
Snyder S, ReVelle C, 1996b, "Temporal and spatial harvesting of irregular systems of parcels" *Canadian Journal of Forest Research* **26** 1079 – 1088
Snyder S, ReVelle C, 1997, "Multiobjective grid packing model: an application in forest management" *Location Science* **5**(3) 165 – 180
Snyder S, Tyrrell L, Haight R, 1999, "An optimization approach to selecting research natural areas in National Forests" *Forest Science* **45** 459 – 469

Toregas C, ReVelle C, 1973, "Binary logic solutions to a class of location problems" *Geographical Analysis* **5** 145 – 155
Torres-Rojo J, Brodie J, 1990, "Adjacency constraints in harvest scheduling: an aggregation heuristic" *Canadian Journal of Forest Research* **20** 978 – 986
Underhill L G, 1994, "Optimal and suboptimal reserve selection algorithms" *Biological Conservation* **70** 85 – 87
USDA, 1992, "Preparing for the future: Forest Service research natural areas", FS-503, USDA Forest Service, PO Box 96090, Washington, DC 20090-6090
Williams J C, ReVelle C S, 1997, "Applying mathematical programming to reserve selection" *Environmental Modeling and Assessment* **2** 167 – 175
Williams J C, ReVelle C S, 1998, "Reserve assemblage of critical areas: a zero – one programming approach" *European Journal of Operations Research* **104** 497 – 509
Willis C K, Lombard A T, Cowling R M, Heydenrych B J, Burgers C J, 1996, "Reserve systems for limestone endemic flora of the Cape lowland fynbos: iterative vs. linear programming" *Biological Conservaiton* **77** 53 – 62
Yoshimoto A, Brodie J, 1994, "Comparative analysis of algorithms to generate adjacency constraints" *Canadian Journal of Forest Research* **24** 1277 – 1288