Geographical Analysis ISSN 0016-7363

Cost-efficient Reserve Site Selection Favoring Persistence of Threatened and Endangered Species

Bertrand Hamaide,[1] Justin C. Williams,[2] Charles S. ReVelle[3]

[1]Faculté des Sciences Economiques, Sociales et Politiques, Facultés Universitaires Saint-Louis, Brussels, Belgium, [2]Program in Systems Analysis and Economics, Department of Geography and Environmental Engineering, The Johns Hopkins University, Baltimore, MD, [3]Program in Systems Analysis and Economics, Department of Geography and Environmental Engineering, The Johns Hopkins University, Baltimore, MD

This article formulates and tests set covering and related models with spatial characteristics for selecting sites that provide habitat for species that are identified as ''critical'' (e.g., typically threatened, endangered, or rare), thereby enhancing their persistence. The first two models presented require the creation of a core area for each critical species and a buffer zone surrounding the core, with and without being constrained to include at least one representation of each and every common (i.e., noncritical) species. The final model aims at minimizing costs of protecting predetermined numbers of common species while all critical species remain covered and buffered. These models are implemented for occurrence data of terrestrial mammals in Oregon. They enable, among other things, a comparison between the budgetary impacts of reserve networks with and without buffering rings for critical species, and a determination of the marginal cost of common species protection.

Introduction

The models termed species set covering problem (SSCP) and maximal covering species problem (MCSP) are counterparts of location models (ReVelle, Williams, and Boland 2002) respectively developed in 1971 and 1974 and termed location set covering problem and maximal covering location problem (Toregas et al. 1971; Church and ReVelle 1974). They aim at delineating nature reserves for protecting either all species or as many species as possible. The objective of these models is to inform the conservation of biological diversity by identifying land to set aside for the creation or enlargement of nature reserves that protect the key habitats and species.

Correspondence: Bertrand Hamaide, Faculté des Sciences Economiques, Sociales et Politiques, Facultés Universitaires Saint-Louis, 1000 Brussels, Belgium
e-mail: hamaide@fusl.ac.be

Submitted: April 27, 2006. Revised version accepted: January 15, 2008.

More specifically, the SSCP model selects the minimum number of land sites so that each species is covered, that is, each species is present in at least one chosen site, which ensures its representation. The MCSP model, in contrast, aims at protecting as many species as possible for a given number of land sites selected or for a given budget. The SSCP was first developed by Possingham et al. (1993) and Underhill (1994); the MCSP was formulated by Church, Stoms, and Davis (1996) and Camm et al. (1996), while Ando et al. (1998) and Polasky, Camm, and Garber-Yonts (2001), recognizing that scarce resources ought to be allocated efficiently, formulated budget-constrained versions of the MCSP.

Other reserve site selection models have been formulated in recent years. For example, some authors developed probabilistic models (e.g., Haight, ReVelle, and Snyder 2000; Polasky et al. 2000) while others introduced a dynamic component (e.g., Costello and Polasky 2004). Researchers have also added spatial optimization characteristics to their formulation, that is, they have tried to prevent selection of scattered sites of land by incorporating spatial criteria such as connectivity or compactness. Williams, ReVelle, and Levin (2005) review the literature of nature reserve design with spatial criteria.

In most prior reserve site selection models, all species were treated equally, regardless of their level of rarity or vulnerability. The need to protect rare and vulnerable species has long been recognized (see, e.g., Gaston 1994) but has unfortunately received little attention in reserve selection models. Recently, Arthur et al. (2004), in a probabilistic formulation model, took endangered species into account by adding a constraint ensuring that these recognized species meet a minimum coverage probability threshold; and Hamaide, ReVelle, and Malcolm (2006) maximized site appearances of rare species[1] in a covering model. Besides, various researchers have recently been addressing specific habitat needs for individual species: Bassett and Edwards (2003) used species-specific home range estimates as a measure of habitat required for individual species, Pykälä and Heikkinen (2005) considered habitat quality and species rarity and Marianov, ReVelle, and Snyder (2008) required species-specific selection of minimum contiguous area for covering a species.

The purpose of this article is to explicitly model the protection of critical species (which may be defined as rare, vulnerable, threatened, or endangered species[2]) in the SSCP framework by imposing a spatial requirement on sites that have been selected to protect critical species. In particular, such sites will need to be "core" sites that are surrounded by a buffering ring. These models are demonstrated below with both a random data set and a real data set.

The remainder of the article is organized as follows. The next section defines the notion of critical species used in this study and reviews the importance of spatial requirements when selecting land sites as a means of biological conservation. The following section presents new set covering models with spatial requirements for rare species. Related set covering models with physical and economic constraints, differentiating critical and common species, and requiring spatial attributes for the former are detailed in the next section. The next section discusses a simulation example while the penultimate sectionapplies these models using a data set from the state of Oregon and evaluates the solutions. Finally, the last section concludes.

Rare species and spatial characteristics

One method for enhancing the protection of critical species is to add requirements for spatial coherence when selecting sites inhabited by critical species. Williams, ReVelle, and Levin (2005) review various spatial attributes such as connectivity and compactness that may be used in the optimal selection of reserve sites. In this study, the spatial characteristic involves core areas and buffer zones.

We make the requirement that, for a critical species to be protected (represented), it must appear within a selected core site, which is a site that is completely surrounded by other selected (buffer) sites. We apply this requirement to critical species only and not to common species. That is, the selection of a single (possibly isolated) site containing a common species is assumed to be sufficient to protect that species—selection of the surrounding buffer sites is not required.

It is important to stress that buffered cores are not intended to ensure persistence—indeed, they cannot—they just promote it. This spatial characteristic has a biological motivation. One of the functions of the buffer zone is to surround the core cell and shield it from negative external impacts (Dearden 1988; Laurance and Yensen 1991), therefore promoting the long-term viability of critical species. Obviously, buffer zones (as boundaries defined by humans) do not necessarily coincide with edge habitat. Natural edges may occur both within and between cores and buffer zones. Thus, both interior species and edge species can benefit from the existence of a buffer zone. The appropriate width of a buffer zone can vary, depending on the intensity of external impacts and the ability of the buffering ring to mitigate those impacts (Schonewald-Cox and Bayless 1986). The optimization of reserve core areas and buffer zones has been modeled in several previous articles (Williams and ReVelle 1996, 1998; Clemens, ReVelle, and Williams 1999).

Of course, common species could also benefit from buffer zones, but our assumption is that the additional costs of a buffer ring for a common species in any particular site is not justified because common species are more ubiquitous in the landscape.

The two following sections describe the integer programming models which will be run with Xpress MP (2006) on the Oregon data set and on random data, respectively.

Set covering models for protecting critical species

Let there be n sites of land indexed j and k and represented by the set of sites J ($J = \{1, 2, \ldots, n\}$) and m species indexed i and represented by the set of species I

($I = \{1, 2, \ldots, m\}$). The critical species form the subset R of I, while noncritical or common species form the complement subset C of I. Hence, $I = C \cup R$.

The first set covering model addresses the problem of minimizing the total cost of protecting all critical species within core sites. This problem is formulated as the following integer program.

$$\text{Model 1}: \text{ Min } B = \sum_{j=1}^{n} c_j x_j \tag{1}$$

$$\text{s.t.} \quad \sum_{j \in N_i} v_j \geq 1 \quad \forall i \in R \tag{2}$$

$$v_j \leq x_k \quad \forall j \in J, \; \forall k \in H_j \tag{3}$$

$$x_j \in \{0, 1\}; v_j \in \{0, 1\} \quad \forall j \in J \tag{4}$$

where

$$x_j = \begin{cases} 1 \text{ if site } j \text{ is selected for the reserve system, as either a core site or a buffer site} \\ 0 \text{ otherwise} \end{cases}$$

$$v_j = \begin{cases} 1 \text{ if site } j \text{ is selected as a core site} \\ 0 \text{ otherwise} \end{cases}$$

H_j is the set of sites that includes j itself plus all of the sites adjacent to j which are needed to buffer j. The sites in H_j are the sites that need to be selected to ensure that j is a core site. N_i is the set of sites j containing critical species i, c_j is the cost of acquiring site j for the reserve system.

Objective (1) seeks to minimize the total land acquisition cost of the reserve. We note that if $c_j = 1$ for all sites j, then the objective is one of minimizing the total number of sites selected. Constraint (2) requires that each critical species $i \in R$ be represented in at least one core site. Constraint (3) enforces the definition of core sites by stipulating that, for site j to be selected as a core site ($v_j = 1$), j plus all of sites k adjacent to j must be selected ($x_k = 1 \; \forall k \in H_j$). This constraint ensures that a buffer zone will surround site j if j is selected.

The objective function value (B) in an optimal solution to Model 1 is the minimum cost (or number of sites) necessary to protect all critical species within core sites. Below we refer to this optimum for Model 1 as $B = B_1$.

Model 1 has no requirement to protect common species and is likely to perform poorly in this respect to the extent that critical species do not occur in species-rich areas (see Prendergast et al. 1993).

This limitation can be addressed by formulating a new model (Model 2) in which a covering constraint (5), that requires all common species $i \in C$ to be protected (represented) in at least one site (any site—not necessarily a core site), is added to Model 1

$$\sum_{j \in N_i} x_j \geq 1 \quad \forall i \in C \tag{5}$$

The solution to the Model 2 problem likely entails a higher cost or the selection of more sites because more expensive land and/or additional land is likely to be needed to protect the common species in addition to the critical species. That is, $B_2 > B_1$, where $B = B_2$ is the optimal objective value for Model 2 (terms (1) through (5)).

Related set covering models for protecting critical species

Because limited resources (such as a fixed budget) may make it impossible to set aside enough land to protect all species, related set covering models were developed.

Maximal covering problem formulations are avoided here for two reasons. First, one problem with maximal covering models, which simply maximize the total *number* of species represented in the reserve system, is that species that occur only in species-poor sites (often the case for rare species) are less likely to be protected than other species for the reason that the model is less likely to select species-poor sites than species-rich sites. Second, maximal covering models often incorporate a budget constraint, and these various user-selected budgets may bring about non-Pareto optimal solutions. That is, it might be possible to protect the same number of species for any budget within a particular budget range, although only the low endpoint of the range would represent an efficient solution. Hence, a related set covering model is preferred to a standard maximal covering problem. Model 3 is formulated as such:

$$\text{Model 3}: \text{ Min } B_3 = \sum_{j \in J} c_j x_j \tag{6}$$

$$\text{s.t. } y_i \leq \sum_{j \in N_i} x_j \quad \forall i \in C \tag{7}$$

$$\sum_{j \in N_i} v_j \geq 1 \quad \forall i \in R \tag{8}$$

$$v_j \leq x_k \quad \forall j \in J, \forall k \in H_j \tag{9}$$

$$\sum_{i \in C} y_i \geq S \tag{10}$$

$$x_j \in \{0,1\}; v_j \in \{0,1\} \quad \forall j \in J \tag{11}$$

$$y_i \in \{0,1\}, \quad \forall i \in I \tag{12}$$

where

$$y_i = \begin{cases} 1 \text{ if common species } i \text{ is covered} \\ 0 \text{ otherwise} \end{cases}$$

Objective (6) aims at minimizing the cost of the reserve network. Constraint (7) enforces the definition of y_i by ensuring that a common species is covered ($y_i = 1$, $\forall i \in C$) only if it is present in at least one of the sites selected to be part of the nature reserve (i.e., if $\sum_{j \in N_i} x_j \geq 1$). Constraints (8) and (9) ensure the presence of all critical species in buffered core areas (as in Models 1 and 2), and (10) requires that at least S noncritical species be protected in either core or buffer sites, where $0 \leq S \leq |C|$. Because a budget constraint is not used, we avoid the problem of selecting an inappropriate budget increment if the model is run for various budget data; the noncritical species constraint (10) is on the contrary changed by increments of 1 as S is an integer-valued parameter.

Hence, this formulation enables us to determine the impacts of various requirements on the number of noncritical species to be protected in order to identify the pareto-optimal trade-offs between cost and number of species protected. In the model demonstration below, the value of S is incrementally varied by one unit from $S = 1$ to $S = |C|$, and the results are compared with those of models 1 and 2 described above. Note that a budget of at least B_1 is needed for Model 3 to be feasible and that the budget need not exceed B_2 for all species to be represented. These models are referred to below as ''cost-minimizing models.''

If the site costs are unknown—or if all sites effectively have the same cost—objective (6) becomes that of minimizing the number of sites that are selected. This model is referred to below as the ''site-minimizing model.''

Classroom examples

The purpose of this section is to exercise the models described in the previous two chapters with a classroom example in order to demonstrate the models before applying them to real data.

Suppose that we are considering establishing a nature reserve on an island with 20 terrestrial species of interest ($|I| = 20$), three of which are listed as critical ($|R| = 3$ and $|C| = 17$). Suppose also that the island can be divided into 36 equivalent square sites ($|J| = 36$). Finally, suppose that the cost for purchasing land sites to be set aside as reserve is known and highest for the four center sites (dark cells), that is, unit cost is equal to 10 and lower when moving away from the center—it goes down to 8 (grey cells) and then to 5 around the border (light grey cells) as shown in Fig. 1.

Presence and absence data of the 20 species in the 36 sites are generated randomly. Species appearing in fewer than 20% of all sites have been defined as critical species. The random data show that there are three such species appearing in 7 or fewer sites.[3]

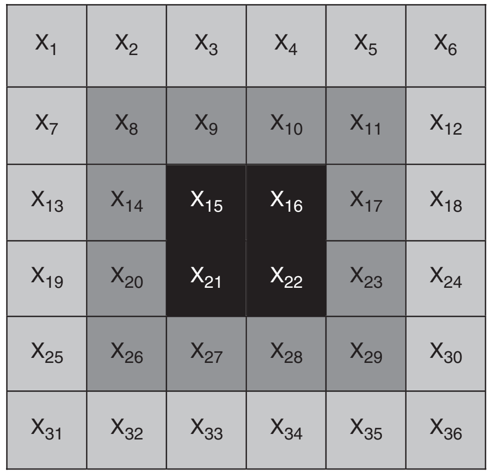

Figure 1. Land sites and costs.

The models in this section and in the next section were coded with Mosel language and run with Xpress-MP[4] (Xpress MP 2006).

SSCP classroom example

First we applied Model 1, which aims at buffering the three critical species (equations 1–4). One optimal scenario among the various alternate optima is illustrated in Fig. 2a.

Model 1 tends to select sites as far away as possible from the center because cost is lower and because the number of cells needed in buffering the chosen (core) site is smaller; eight sites are selected for a cost of 49 and 17 species, among which the critical species are said to be covered. Hence, this creates a tight cluster favoring the spatial characteristics of compactness and contiguity.

Model 2 (equations 1–5) requires that all 20 species are protected, with the critical species protected within core sites. In the solution to Model 2, starting from the optimal scenario depicted in Fig. 2a, two additional sites were selected—as two

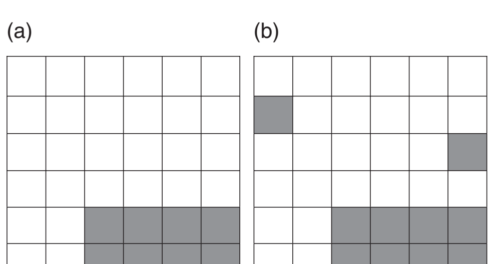

Figure 2. Nature reserve selection buffering rare species with (a) and without (b) set covering constraints.

sites were sufficient to cover the three (noncritical) species left unprotected in the solution to Model 1 (Fig. 2b). Because there was no spatial requirements on common species, the resulting reserve network was not as compact as before.[5]

Related SSCP classroom example

The solution to the third model (equations 6–12), aimed at minimizing the cost of protecting at least 14 common species while requiring that all 3 rare species be buffered is equivalent to that of the minimization problem of model 1 ($B_3 = B_1 = 49$) if the right-hand-side of equation 10 is equal to 14. Indeed, we are back in Fig. 2a because, with that budget, eight sites are selected for a cost of 49 and 17 species—among which 14 common species—are protected $\left(\sum_{i \in I} y_i = 17\right)$.

Increasing S by one unit in constraint (10) ($S = 15$) would increase budget from 49 to 54 with the selection of one additional land site ($x_7 = 1$). A further increment of 1 in ($S = 16$) in the same constraint gives the same cost solution (as site x_7 contains more than one common species). Hence, protection of the last common species ($S = 17 = |C|$) would require an additional budget and the selection of one more land site; in this case, $B_3 = B_2 = 59$. This solution is equivalent to Model 2's output and Fig. 2b.

If the models seem to function well, one important remark should nevertheless be stated and taken into consideration. As shown in Fig. 2, sites are essentially selected in the border zones. This is not mainly due to the fact that cost is lower there[6] but it is mostly because buffering a border or a corner square cell would respectively require selection of only five or three additional sites compared with eight sites that are necessary to buffer an interior cell. This is a crucial point to consider when implementing the model on the Oregon data set. As a matter of fact, it would not make sense that border cells be considered buffered without taking into account the adjacent states of California, Washington, Idaho, or Nevada. Hence, in the next section, sites that contain part of Oregon's boundary are removed from consideration as core sites.

Demonstration with Oregon data

Since 1989, biodiversity data have been compiled and refined for the U.S. Environmental Protection Agency (EPA). Various states have been divided into 648 km^2 hexagons, and presence/absence occurrence data for vertebrate species have been estimated for each of the hexagons. Presence/absence assessments were made based on known records of occurrences and on known habitat preferences, as well as on known or suspected habitat occurrences within an hexagon, provided that their presence in a site is confident (verified sightings in the past two decades) or probable (suitable habitat and verified sightings in adjacent hexagons).

Data have been developed for the Pacific Northwest States—Oregon, Washington—and middle Atlantic States—Pennsylvania, West Virginia, Virginia, Maryland, Delaware—(Master 1996; White et al. 1999) and various versions of the Oregon data set have been widely used for implementing site selection models (e.g., Csuti et al. 1997; Haight, ReVelle, and Snyder 2000; Polasky, Camm, and Garber-Yonts 2001; Arthur et al. 2004; Hamaide, ReVelle, and Malcolm 2006; and others). The three models described above were applied to a part of the Oregon data set. Our data set concentrates on the 113 terrestrial mammals of the original 426 species and on 404 of the original 441 hexagonal sites. The sites excluded in the White et al. (1999) analysis are those sites that mostly overlap the borders of Idaho, California, Washington, Nevada, and the Pacific Ocean.

Of the 113 terrestrial mammals, 4 are listed by the State of Oregon as threatened or endangered (Oregon Department of Fish and Wildlife 2005). These four—the wolverine, the gray wolf, the kit fox, and the Washington ground squirrel—are most in need of protection and are defined as critical in our study. The remaining 109 species are defined as noncritical or common.

We note that some species defined as common in this study appear in fewer sites than some of the threatened or endangered species; however, the former may not be at risk. For example, the Brazilian free-tailed bat is present in Southern Oregon in only 2 sites out of 404, although it is widely distributed in the Western Hemisphere, including Southern Oregon where it is found in abundance. In contrast, the wolverine, the gray wolf, the kit fox, and the Washington ground squirrel respectively appear in 29, 37, 7, and 40 sites, but their natural reproductive potentials are in danger of failure due to small population sizes, diseases, predation, and human causes such as habitat loss and current regulations may be inadequate to protect these species (Oregon Department of Fish and Wildlife 1997).

SSCP—Oregon data

The set covering models are exercised, both with the site-minimizing objective (imposing $c_j = 1$ for all j in equations 1 and 6) and the cost-minimizing objective. Requiring that the four critical species are part of a nature reserve and that their selected site is surrounded by 6 hexagonal sites[7] necessitates a selection of 15 sites altogether. As shown in Fig. 3, the reserve is very compact and contiguous. The model is constructed to select buffer cells as close as possible to each other. In this particular case, even though not a single site contains more than one rare species, the model was able to find—and hence selected—contiguous cells containing threatened or endangered species, enabling the buffer zones to partially overlap. As far as the management of the reserve is concerned, this selection seems to be a good method for preserving rare species as the boundary length of the reserve—and hence management costs—is minimal (McDonnell et al. 2002) and sites are tightly clustered.

Another point to consider is the monetary cost of creating such a reserve. This study makes a very simple approximation—or proxy—for site costs and uses the estimated market value of land and buildings for farms published, for each county of Oregon, by the Census of Agriculture (CA) (2001). To sites fully located in a single county, we have assigned the per-acre cost reported in the CA, while sites overlapping two or more counties have been given an area-weighted average of the

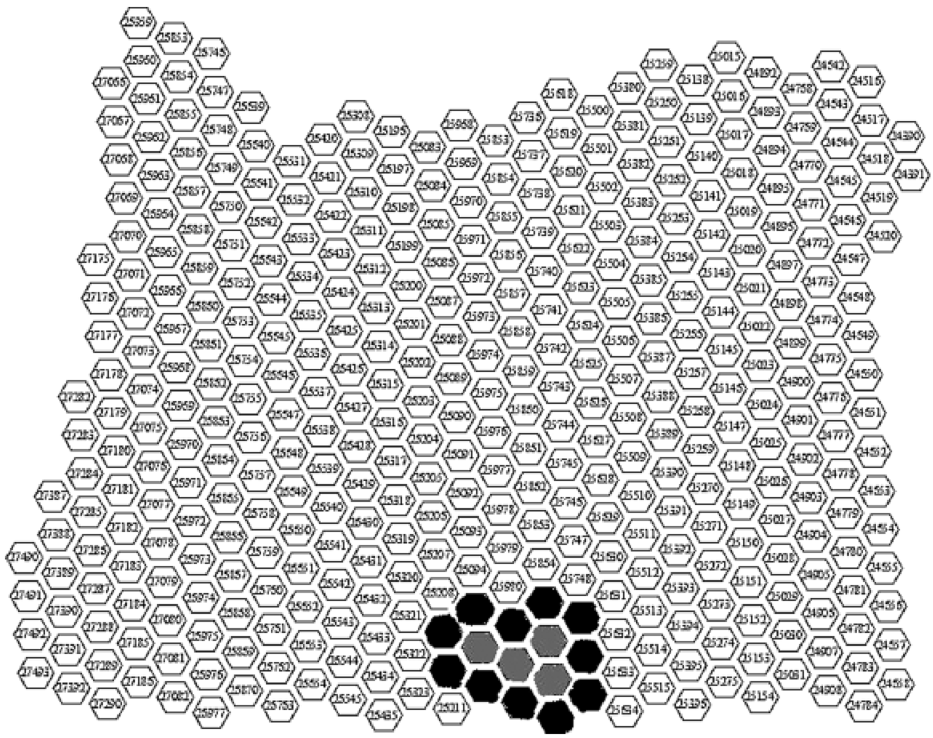

Figure 3. Output of the site-minimizing model 1 (selected land sites with critical species are in light color).

per-acre costs. These cost data should be interpreted with great caution for various reasons. First, agricultural land values are used as surrogates for the costs of all land, including nonagricultural land. Second, this computation presumes that the entire hexagon is rural land and that its entire surface is protected if set aside as a reserve. Moreover, there is little heterogeneity in land costs within counties, the value of nonmarket urban land is not taken into account, and vulnerability of land conversion is not incorporated. Also, there is no distinction between private and public land, there is no consideration about economic activities and market value of land, and buildings may not measure the real opportunity cost of creating a reserve.

But the purpose of this exercise is not to determine precise cost or precise economic analysis; its purpose is to compare various alternatives and determine which ones are likely to be relatively cheaper or more expensive (in dollar terms or in terms of the number of sites selected) based on the same data. An immediate budget cannot be inferred from this exercise but we believe it is nevertheless interesting as it enables critical comparisons. Based on such data, the cost of the reserve is 1299.[8]

The purpose of minimizing the total number of sites for buffering all rare species may not coincide with that of minimizing the total cost of the reserve. Indeed, solving the same model but using the cost objective shows that the four rare species can be buffered at a cost of 935.[9] This cheapest alternative selects more land sites (20 instead of 15—because these are not minimized anymore) but spatially speaking, as illustrated in Fig. 4, even though the reserve remains compact, it is now divided in two clusters and the boundary length is larger—which is expected because more sites are selected.

The second model again aims at buffering rare species but now requires that all species are protected. Running the site-minimizing model ($c_j = 1$ for all j in equation 1) and cost-minimizing model yields the following results. At optimality, the models are selecting 20 land sites (site-minimizing model 2) instead of 15 (site-minimizing model 1) or reach a cost of 2107 (cost-minimizing model 2) instead of 935 (cost-minimizing model 1) because in both cases, more sites need to be selected so that all 113 species are protected. The resulting reserve networks are displayed in Figs. 5 and 6. The site-minimizing model results in five additional scattered sites because no spatial requirements were imposed for common species (Fig. 5); this brings about an additional cost of 1440, which more than doubles total costs (2739 compared with 1299). The cost-minimizing model selects more

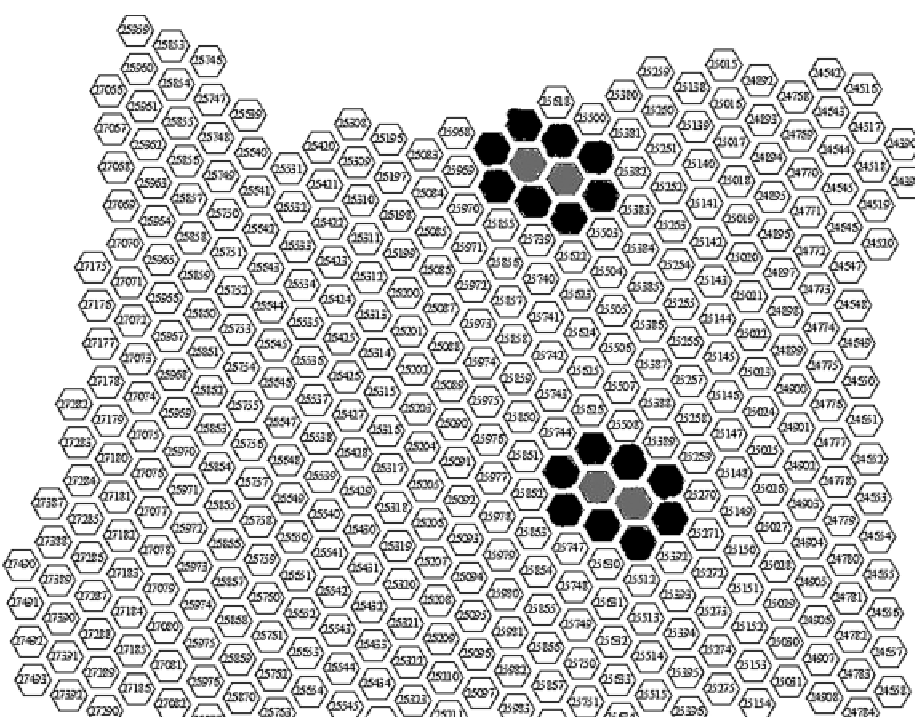

Figure 4. Output of the cost-minimizing model 1 (selected land sites with critical species are in light color).

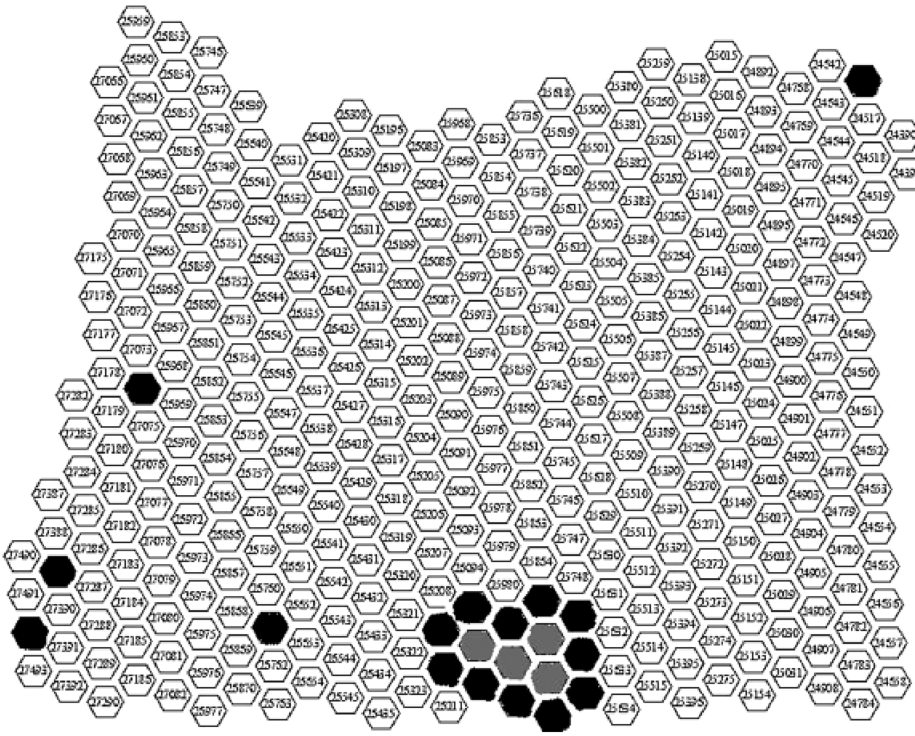

Figure 5. Reserve selection for the site-minimizing model 2.

additional sparse isolated sites—8 instead of 5—and gets a cost minimizing value of 2107 for 28 sites (Fig. 6); this nevertheless more than doubles total costs as well.

It may be interesting to compare these results with the well-known SSCP so as to determine the cost attributed to buffering rare species when all species are protected. Running the SSCP on the Oregon data set results in the selection of eight sites for the site-minimizing objective and in a reserve cost of 1306 for the cost-minimizing objective.

Three conclusions can be drawn from the above results. First, as expected, selecting the smallest number of sites is not necessarily cost-efficient. In all cases, it was possible to reach the same protection level for a smaller cost with the cost-minimizing rather than the site-minimizing objective, as demonstrated previously by Ando et al. (1998) and Polasky, Camm, and Garber-Yonts (2001) using other data. Second, the buffering of rare species also enables the simultaneous protection of many common species (that appear in the buffer sites), but protecting all species is nevertheless relatively expensive, both in terms of number of sites (Fig. 5 counts five additional sites compared with Fig. 3, that is a 25% increase from model 1 to model 2) and in economic terms (the minimum budget needed more than doubles as additional sites are selected in Fig. 6 compared with Fig. 4). Finally, a much larger budget is mobilized when buffer zone requirements are added. Compared

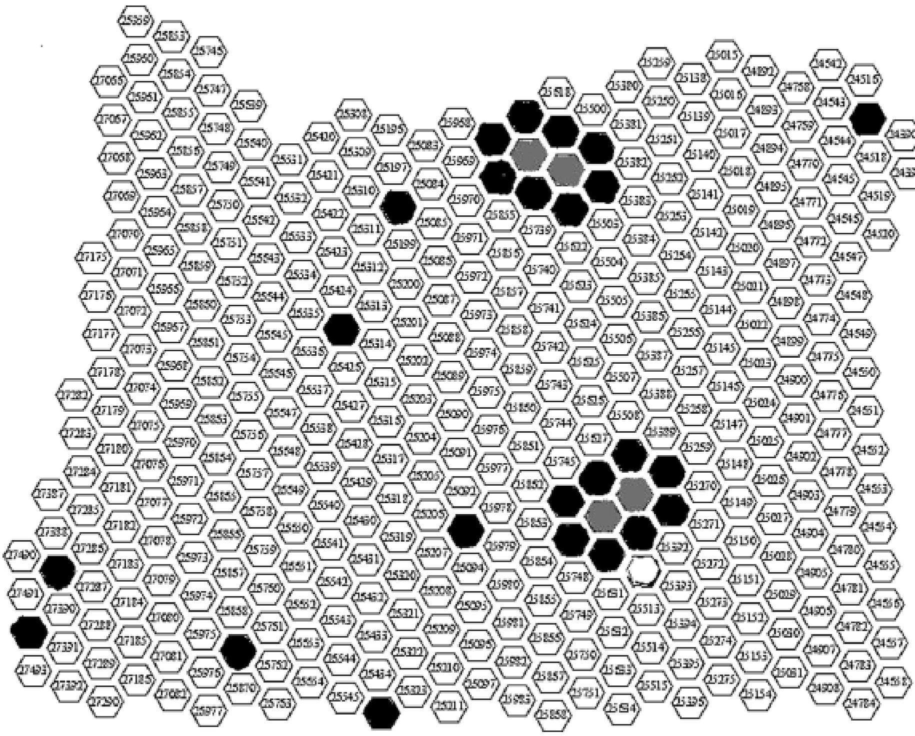

Figure 6. Reserve selection for the cost-minimizing model 2.

with the SSCP, buffering critical species costs 12 sites (the minimum number of sites needed jumps from 8 to 20) for the site-minimizing objective and increases total budget by more than 60% for an economically efficient selection of sites (the budget goes from 1306 to 2107).

Related SSCP—Oregon data

The problem (model 3) is now to determine the lowest cost (cost-minimizing model 3)—or the smallest number of parcels (site-minimizing model 3)—of preserving a certain number of noncritical species, knowing that all critical species need to be protected and surrounded by a buffer zone.

The site-minimizing and cost-minimizing models are run various times with a common-species constraint (10) increment stating that, for each run, $\sum_{i \in C} y_i \geq S + \alpha \quad \forall \alpha = 1, 2, \ldots, |C| - S$.

In other words, the site-minimizing model first computes the minimum number of sites needed when S noncritical species are selected and all critical species are buffered ($B_3 = B_1$). Then, one additional noncritical species is required to be protected at each run until all of them are preserved, which corresponds to the SSCP with rare species buffered ($B_3 = B_2$).

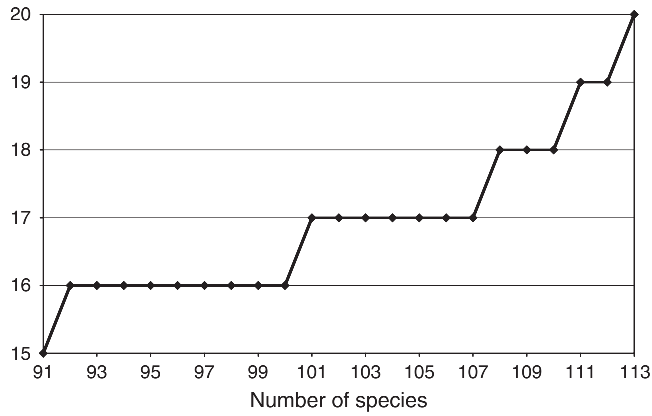

Figure 7. Number of sites needed for protecting a predetermined number of species.

As shown in Fig. 7, the site-minimizing model requires 15 sites to protect 91 species (i.e., 87 common species—$S = 87$—and the 4 critical species). It also shows that each additional species covered is costlier in terms of sites; that is, the marginal cost of species protection increases with the number of sites.

The conclusion is obviously the same for the cost-minimizing problem. Fig. 8 shows that 86 species ($S = 82$ in equation (10)) can be protected for an amount (935) corresponding to the budget necessary for buffering all rare species. In other words, at least for the Oregon data set and as already mentioned above, many common species appear in sites close to sites inhabited by critical species. As more common species are protected, more sites are selected and the cost is higher.

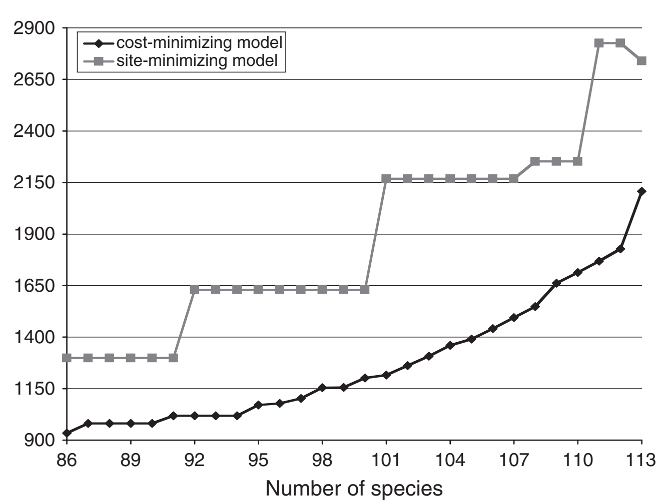

Figure 8. Budgetary impact of species coverage for the cost- and site-minimizing models 3.

Hence, total costs and marginal costs do increase when moving toward full protection, as shown by the shape of the cost-minimizing curve; marginal costs of the last two species are 60 and 279, respectively. In other words, protecting the last species costs more than four times as much as the previous species and around 30% of the budget used for protecting the first 86 species.

The related set covering model with buffered protection for rare species supports Polasky, Camm, and Garber-Yonts's (2001) finding that total costs for protecting a certain number of species are always smaller relative to the site-minimizing solution if resources are used cost efficiently. Indeed, Fig. 8 clearly shows that the cost of creating a reserve is cheaper with the cost-minimizing model than the site-minimizing model, no matter the number of species protected.[10] In addition, the cost-minimizing reserve typically has a larger total area than the site-minimizing reserve (assuming, as is the case here, that all sites have the same area). This is likely a good thing, as a larger area may provide additional conservation benefits not accounted for in the model (''large reserves are better than small reserves''—see, e.g., Diamond 1975).

Conclusion and caveats

One of the reasons to create nature reserves is to preserve and protect species. This study gives added focus to critical species which may be defined as, for example, terrestrial mammals officially listed as threatened or endangered. For enhancing their probability of survival, each critical species is required to be present in at least one selected site (a core site) and all sites around this core must be selected for the reserve as well to provide a buffer zone. We utilize this core area–buffer zone concept in three models: the first model requires the protection of only critical species within core sites, the second model requires the protection of all species—critical species within core sites and noncritical species within either core sites or buffer sites, and the third model requires protection of all critical species and a certain number of noncritical species.

Applying these decision models to the Oregon data set demonstrates how the user can determine (a) the cost of the spatial requirements—that is, how many additional sites or what additional budget would be required to protect critical species with buffer zones (SSCP and model 2 comparison); (b) the cost of common species protection—that is, once all critical species are buffered, how much extra it would cost to protect all the common species (model 1 versus model 2); and (c) the marginal cost of species protection—that is, starting with the budget needed to buffer all critical species, which also protects many common species, how much the additional cost would be for protecting one more species until all of them are preserved.

Some caveats and limitations do appear in the analysis and require caution in interpreting the results. First, the area of each site in the Oregon data is very large for systematically considering the creation of an identical buffer zone around the location of critical species; in reality, a buffer zone smaller than the Oregon hexagons would likely be sufficient to protect at least some of the species from adverse conditions. However, if a change in buffer zone width can easily be realized with a classroom example, such as the one illustrated above, it is not easily transposed in a real-world problem such as that described in the ''Related set covering models for protecting critical species'' section above. Indeed, species occurrence data are available per hexagon only. Site selection for core areas and buffer zones using smaller cells would require data about the sizes and locations of species populations within subsections of each hexagons; currently such data are unavailable.

A corollary concern is the hexagonal shape of the cells, which obviously does not match the size and shape of individual land parcels. Thus, in interpreting the above results, a selected hexagon can be thought of not as a site to acquire or a reserve, but as a general locale in which specific (smaller) parcels for acquisition could be identified by local planners and decision makers (see Williams, ReVelle, and Bain 2003). Similarly, the ''course-scale'' analysis in our context suggests that buffer zones identified are general areas in which buffers may be needed (e.g., if the habitat of a critical species is near the boundary of a core hexagon—but data do not tell us where the species is located within an hexagon).

Second, all critical species are treated equally in terms of habitat needs, which is obviously unrealistic. Among the critical species, it may be advisable to buffer the gray wolf and the wolverine as they are both wide ranging: their annual home range amounts to a few hundred square kilometers. However, the kit fox and the Washington ground squirrel might not need a buffering ring. Solving the cost-minimizing model 2 (equations 1–5) with the rare species set including the gray wolf and the wolverine only, results in the selection of 17 land sites for a cost of 1674. This corresponds to a cost saving of 20% (1674 instead of 2107) with a selection of a much smaller number of sites (17 instead of 28), relative to the scenario which buffers all four critical species. Also, biologically speaking, it may be interesting to require that *some* wide-ranging common species also receive buffering rings. A few tests have also been undertaken and some do indeed bring about cost savings compared with the original model.

Finally, as mentioned above, cost data are a crude proxy based on average agricultural land values with little heterogeneity in land cost within counties. If absolute cost values are thus of limited use, relative cost comparison for various alternatives have much more meaning. That being said, even if more realistic cost data can be used, the economic analysis of habitat protection increasingly requires the concurrence of spatial economic data with spatial biological data; this is analogous to the concurrence of spatial units for economic data and human census data. These data unfortunately do not exist.

Notwithstanding these caveats, as critical species are the most in need of protection but as preserving them is obviously not cost neutral, we nevertheless believe that these theoretical models may be helpful as part of the cost-efficient management and creation of nature reserves.

Acknowledgments

We are very grateful to Elizabeth S. Jeffers for help provided with the Oregon data set and maps. We would also like to thank the precise and constructive comments of three anonymous referees and one of the editors of this special issue as well as the participants of the 2006 World Conference of Environmental and Resource Economics in Tokyo. Justin Williams and Charles ReVelle were partially supported by a grant from the David and Lucile Packard Foundation, Interdisciplinary Science Program, and gratefully acknowledge this support. Bertand Hamaide and Justin Williams dedicate this article to the late Charles ReVelle, who developed many of the ideas for the models herein and made substantial contributions to the original draft.

Notes

1 In that paper, rare species were defined as species appearing in less than 10% of the surface of Oregon.
2 ''Critical'' species will be defined as rare and threatened species when the models will be exercised with Oregon data set (see ''Related set covering models for protecting critical species'').
3 The random data set is available by request. The three critical species are species number 11, 12, and 19 and they all appear in 7 sites (i.e., $|N_i| = 7$) while all the other species appear in at least 9 sites and at the most 27 sites (i.e., $9 \leq |N_{il}| \leq 27$).
4 Computation times for all models in ''Classroom examples'' was <1 second whereas maximum computation time in models of ''Related set covering models for protecting critical species'' reached 9 s on a Pentium M personal computer.
5 Contiguity is not ensured anymore but note that a buffer constraint does not ensure contiguity even though, in this example, the reserve network was contiguous (by chance) in Fig. 2a.
6 Indeed, solving the same models with $c_j = 1$, that is, solving site-minimizing models gives (nearly) the same results of parcel selections at the border cells.
7 Sites are hexagons and not squares; hence, 6 of them are needed to buffer a core parcel. In other words, we take the strong hypothesis that all critical species need to be surrounded by a buffering ring the size of an hexagon. This simplifying assumption does not consider the range of edge effects mentioned by Laurance and Yensen (1991) because of unavailable data for sites smaller than an hexagon.
8 All cost data are expressed in Million 1997 U.S. Dollars.
9 This is the solution with the lowest possible cost for that number of sites.
10 Total cost goes down for the last species protected in the cost-minimizing problem because the selection of the last parcel where the last rare species breeds in brings about a change in other sites selection due to spatial constraints. As the newly selected sites have (in general) a lower unitary cost than the previous ones, total budget is somewhat lower.

References

Ando, A., J. Camm, S. Polasky, and A. Solow. (1998). ''Species Distributions, Land Values, and Efficient Conservation.'' *Science* 279, 2126–28.

Arthur, J., J. Camm, R. Haight, C. Montgomery, and S. Polasky. (2004). ''Weighing Conservation Objectives: Maximum Expected Coverage Versus Endangered Species Protection.'' *Ecological Applications* 14, 1936–45.

Bassett, S., and T. Edwards. (2003). ''Effect of Different Sampling Schemes on the Spatial Placement of Conservation Reserves in Utah, USA.'' *Biological Conservation* 113, 141–51.

Camm, J., S. Polasky, A. Solow, and B. Csuti. (1996). ''A Note on Optimal Algorithms for Reserve Site Selection.'' *Biological Conservation* 78, 353–55.

Census of Agriculture. (2001). ''USDA, National Agricultural Statistics Service – Census of Agriculture, County Data, Table 6: Farms, Land in Farms, Value of Land and Buildings, and Land Use.'' 1997, 198–207.

Church, R., and C. S. ReVelle. (1974). ''The Maximal Covering Location Problem.'' *Papers of the Regional Science Association* 32, 101–18.

Church, R., D. Stoms, and F. Davis. (1996). ''Reserve Selection as Maximal Covering Location Problem.'' *Biological Conservation* 76, 105–12.

Clemens, M., C. ReVelle, and J. C. Williams. (1999). ''Reserve Design for Species Preservation.'' *European Journal of Operational Research* 112, 273–78.

Costello, C., and S. Polasky. (2004). ''Dynamic Reserve Site Selection.'' *Resource and Energy Economics* 26, 157–74.

Csuti, B., S. Polasky, P. Williams, R. Pressey, J. Camm, M. Kershaw, A. Keisler, and B. Downs. (1997). ''A Comparison of Reserve Selection Algorithms Using Data on Terrestrial Vertebrates in Oregon.'' *Biological Conservation* 80, 83–97.

Dearden, P. (1988). ''Protected Areas and the Boundary Model: Meares Island and Pacific Rim National Park.'' *Canadian Geographer* 32, 256–65.

Diamond, J. M. (1975). ''The Island Dilemma: Lessons of Modern Biogeographic Studies for the Design of Nature Reserves.'' *Biological Conservation* 7, 129–46.

Gaston, K. (1994). *Rarity*. New York: Chapman and Hall.

Haight, R., C. S. ReVelle, and S. Snyder. (2000). ''An Integer Optimization Approach to a Probabilistic Reserve Site Selection Problem.'' *Operations Research* 48, 697–708.

Hamaide, B., C. S. ReVelle, and S. Malcolm. (2006). ''Biological Reserves, Rare Species and the Trade-off between Species Abundance and Species Diversity.'' *Ecological Economics* 56, 570–83.

Laurance, W., and E. Yensen. (1991). ''Predicting the Impact of Edge Effects in Fragmented Habitats.'' *Biological Conservation* 55(1), 77–92.

Marianov, V., C. S. ReVelle, and S. Snyder. (2008). ''Selecting Compact Habitat Reserves for Species with Differential Habitat Size Needs.'' *Computers and Operations Research* 35, 475–87.

Master, L. (1996). ''Predicting Distribution of Vertebrate Species: Some Observations.'' In *Gap Analysis: A Landscape Approach to Biodiversity Planning*, 171–76, edited by J. Scott, T. Tear, and F. Davis. Bethesda, MD: American Society for Photogrammetry and Remote Sensing.

McDonnell, M., H. Possingham, I. Ball, and M. Cousins. (2002). ''Mathematical Methods for Spatially Cohesive Reserve Design.'' *Environmental Modeling and Assessment* 7, 107–14.

Oregon Department of Fish and Wildlife. (1997). *Questions and Answers About the Oregon Threatened and Endangered Species Act*, http://www.dfw.state.or.us/wildlife/diversity/backgrounder_esa.pdf

Oregon Department of Fish and Wildlife. (2005). *Oregon List of Threatened and Endangered Fish and Wildlife Species,* http://www.dfw.state.or.us/threatened_endangered/t_e.html

Polasky, S., J. Camm, and B. Garber-Yonts. (2001). ''Selecting Biological Reserves Cost-Effectively: An Application to Terrestrial Vertebrate Conservation in Oregon.'' *Land Economics* 77, 68–78.

Polasky, S., J. Camm, A. Solow, B. Csuti, D. White, and R. Ding. (2000). ''Choosing Reserve Networks with Incomplete Species Information.'' *Biological Conservation* 94, 1–10.

Possingham, H., J. Day, M. Goldfinch, and F. Salzborn. (1993). ''The Mathematics of Designing a Network of Protected Areas for Conservation.'' In *Decision Sciences, Tools for Today, Proceedings of the ASOR Conference, Adelaide, Australia*, edited by D. Sutton, E. Cousins, and C. Pierce. Adelaide, Australia: University of Adelaide Publications.

Prendergast, J., R. Quinn, J. Lawton, B. Eversham, and D. Gibbons. (1993). ''Rare Species, the Coincidence of Diversity Hotspots and Conservation Strategies.'' *Nature* 365, 335–37.

Pykälä, J., and R. Heikkinen. (2005). ''Complementarity-Based Algorithms for Selecting Sites to Preserve Grassland Plant Species.'' *Agriculture, Ecosystems and Environment* 106, 41–48.

ReVelle, C., J. C. Williams, and J. Boland. (2002). ''Counterpart Models in Facility Location Science and Reserve Selection Science.'' *Environmental Modeling and Assessment* 7, 71–80.

Schonewald-Cox, C., and J. Bayless. (1986). ''A Geographical Analysis of Design and Conservation of Nature Reserves.'' *Biological Conservation* 38, 305–22.

Toregas, C., R. Swain, C. ReVelle, and L. Bergman. (1971). ''The Location of Emergency Service Facilities.'' *Operations Research* 19, 1363–67.

Underhill, L. (1994). ''Optimal and Suboptimal Reserve Selection Algorithms.'' *Biological Conservation* 35, 85–87.

White, D., E. Preston, K. Freemark, and A. Kiester. (1999). ''A Hierarchical Framework for Conserving Biodiversity.'' In *Landscape Ecological Analysis: Issues and Applications*, 127–53, edited by J. Klopatek and R. Gardner. New York: Springer-Verlag.

Williams, J. C., and C. S. ReVelle. (1996). ''A 0–1 Programming Approach to Delineating Protected Reserves.'' *Environment and Planning B* 23, 607–24.

Williams, J. C., and C. S. ReVelle. (1998). ''Reserve Assemblage of Critical Areas: A Zero-One Programming Approach.'' *European Journal of Operational Research* 104, 497–509.

Williams, J. C., C. S. ReVelle, and D. Bain. (2003). ''A Decision Model for Selecting Protected Habitat Areas within Migratory Flyways.'' *Socio-Economic Planning Sciences* 37, 239–68.

Williams, J. C., C. S. ReVelle, and S. A. Levin. (2005). ''Spatial Attributes and Reserve Design Models: A Review.'' *Environmental Modeling and Assessment* 10(3), 163–81.

Xpress M. P. (2006). *Xpress MP Software Development, Dash optimization, Release 2006.* Englewood Cliffs, NJ: Author.