Metropolitan Open-Space Protection with Uncertain Site Availability

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Abstract: *Urban planners acquire open space to protect natural areas and provide public access to recreation opportunities. Because of limited budgets and dynamic land markets, acquisitions take place sequentially depending on available funds and sites. To address these planning features, we formulated a two-period site selection model with two objectives: maximize the expected number of species represented in protected sites and maximize the expected number of people with access to protected sites. These objectives were both maximized subject to an upper bound on area protected over two periods. The trade-off between species representation and public access was generated by the weighting method of multiobjective programming. Uncertainty was represented with a set of probabilistic scenarios of site availability in a linear-integer formulation. We used data for 27 rare species in 31 candidate sites in western Lake County, near the city of Chicago, to illustrate the model. Each trade-off curve had a concave shape in which species representation dropped at an increasing rate as public accessibility increased, with the trade-off being smaller at higher levels of the area budget. Several sites were included in optimal solutions regardless of objective function weights, and these core sites had high species richness and public access per unit area. The area protected in period one depended on current site availability and on the probabilities of sites being undeveloped and available in the second period. Although the numerical results are specific for our study, the methodology is general and applicable elsewhere.*

Key Words: Chicago, optimization, public access, site selection model, species representation

Protección de Espacios Abiertos Metropolitanos con Disponibilidad de Sitios Incierta

Resumen: *Planificadores urbanos adquieren espacios abiertos para proteger áreas naturales y proporcionar acceso público a oportunidades de recreación. Debido a presupuestos limitados y a la dinámica de los mercados de terrenos, las adquisiciones se llevan a cabo secuencialmente en función de la disponibilidad de fondos y sitios. Para atender estas características de la planificación, formulamos un modelo de selección de sitios de dos períodos con dos objetivos: maximizar el número esperado de especies representado en sitios protegidos y maximizar el número esperado de personas con acceso a sitios protegidos. Ambos objetivos fueron maximizados con un límite superior en la superficie protegida en los dos períodos. El balance entre la representación de especies y el acceso público fue generado por el método de ponderación de programación de multiobjetivos. La incertidumbre fue representada con un conjunto de escenarios probabilísticos de la disponibilidad de sitios en una formulación lineal-integral. Para demostrar el modelo, utilizamos datos para 27 especies raras en 31 sitios potenciales en el oeste del Condado Lake, cerca de la ciudad de Chicago. Cada curva tenía forma cóncava y la representación de especies descendió a medida que incrementó la accesibilidad pública, con un menor equilibrio en niveles altos del presupuesto para el área. Varios sitios fueron incluidos en soluciones óptimas independientemente de las funciones de ponderación de los objetivos, y estos sitios tuvieron alta riqueza de especies y acceso público por unidad de área. La superficie protegida en el período uno dependió de la disponibilidad de sitios y de las probabilidades de que los sitios no fueran desarrollados y de su disponibilidad en el*

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segundo período. Aunque los resultados numéricos son específicos a nuestro estudio, la metodología es general y aplicable en otros sitios.

Palabras Clave: acceso público, Chicago, modelo de selección de sitio, optimización, representación de especies

Introduction

Open-space protection in metropolitan areas of the United States has grown in popularity in recent years with the passage of numerous state and local referenda raising billions of dollars for public acquisition of open space (Hollis & Fulton 2002). Open-space reserves, broadly defined as lands protected from urban development, are important not only for the protection they afford rare species and ecosystems but also for the education and recreation opportunities they provide to urban residents (Miller & Hobbs 2002).

Metropolitan land acquisition programs are typically run by city or county governments and have a number of features. First, planners have a variety of objectives for land acquisition including habitat protection for rare species, public accessibility, and economic efficiency (Ruliffson et al. 2002). Second, planners often face intense competition for open space from land developers. As a result, open space is expensive and resources are usually insufficient to acquire a large number of parcels at once. Third, land availability is dynamic: open-space sites currently on the market may be developed if protection is delayed, and sites not immediately available may be on the market later. As a result, acquisition decisions take place sequentially depending on funding and site availability.

We describe a site selection model that addresses these features of metropolitan open-space protection: multiple objectives, limited budgets, and uncertain site availability. In previous work, we developed a two-period model to select the set of sites that maximized expected species representation subject to uncertainty about future site development and upper bounds on the number of sites protected (Snyder et al. 2004*a*). Development uncertainty was characterized by scenarios, each of which was a second-period development outcome with a probability of occurrence. Here, we expand the scenario optimization model to enhance its applicability in urban settings. The model includes twin objectives of maximizing public access and species representation. Public access was first introduced as an objective in a single-period site selection model by Ruliffson et al. (2003), and we adapted their logic to the scenario optimization model introduced here. The model also includes an upper bound on the total area of sites protected over two periods, which allows for the allocation of an area budget over time. Finally, the model recognizes that some sites are not immediately available for protection but have a probability of being undeveloped and available in the next time period. Although we developed the site selection model to address problems of metropolitan open-space protection, the characteristics of the project—multiple objectives, limited budgets, and uncertain site availability—are common to many area-protection situations.

We present the optimization model and then describe its application to a problem of acquiring open space for protection in the Lake County portion of the Fox River Watershed northwest of Chicago (Fig. 1). The Chicago area is the third largest metropolitan region in the United States, and many local governments in the area have land-protection programs. For example, since 1958 the forest preserve district of Lake County protected more than 10,000 ha of open land, including more than 1,200 ha in 1999–2001, when voters approved $90 million in bond referenda. We used the optimization model with data from 31 open-space sites containing 27 rare species and embedded in 34 towns in western Lake County. We used the model to quantify the trade-offs between maximizing species representation and maximizing public access and to identify priority sites for protection with limited budgets and uncertainty about future site development.

Literature Review

Site selection models are based on information on the distribution of species or other conservation features among potential reserve sites and representation targets for these features (see Cabeza & Moilanen [2001], ReVelle et al. [2002], and Rodrigues & Gaston [2002] for summaries of published studies). The pioneering applications selected the minimum number of sites that represented all species (Kirkpatrick 1983; Margules et al. 1988; Sætersdal et al. 1993). Later applications maximized the number of species that could be represented within a given number of sites (e.g., Camm et al. 1996; Church et al. 1996). Site selection models typically assume that decisions are made all at once and protection takes place rapidly before site degradation or loss. Only recently have researchers begun to develop methods to address sequential site selection problems with budget restrictions and uncertainties about site degradation and loss.

One approach to scheduling conservation actions over time involves prioritizing sites according to their irreplaceability and vulnerability (Pressey 1999; Margules &

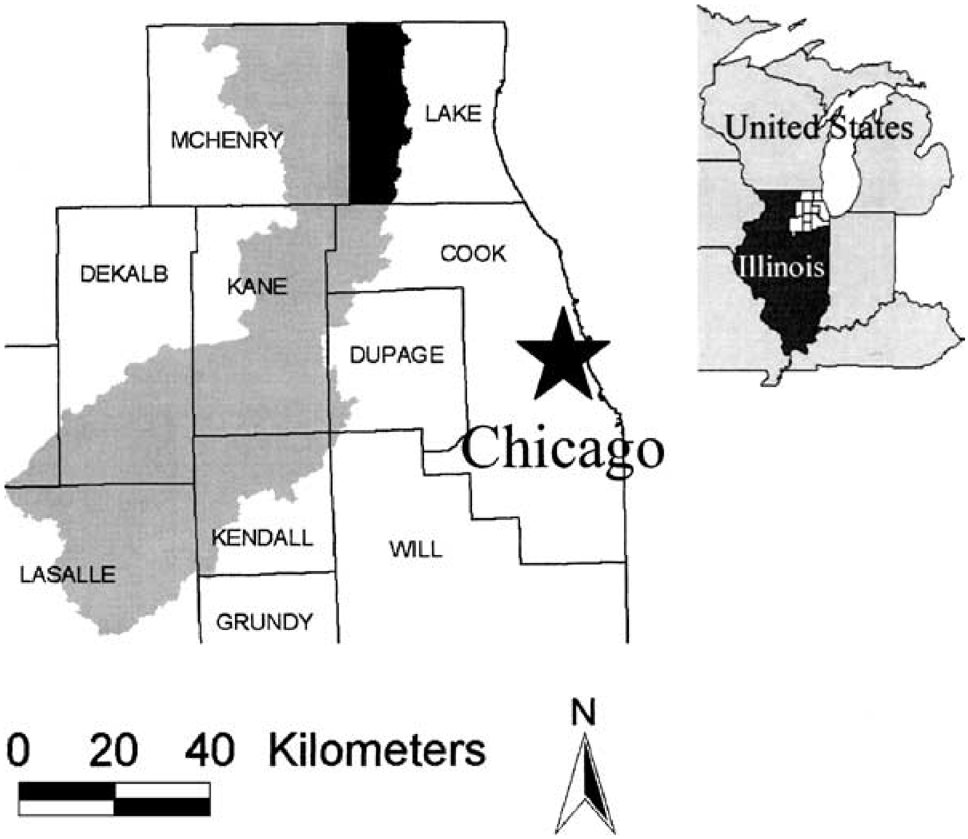

Figure 1. Fox River watershed (shaded gray) in counties of northeastern Illinois (USA). The study area (shaded black) is the northeastern portion of the watershed located in Lake County.

Pressey 2000). Irreplaceability measures the importance of the sites to achieving the conservation target (Ferrier et al. 2000), and vulnerability measures the likelihood that important features will be lost because of development or degradation. Sites with high irreplaceability and vulnerability should be protected first because the loss of an irreplaceable site will compromise the achievement of the conservation target. Variations of this methodology have been successfully applied to complex problems involving public and private lands with ongoing site degradation and loss (Pressey & Taffs 2001; Noss et al. 2002; Lawler et al. 2003).

Another approach to sequential site selection is building a stochastic dynamic programming model that includes periodic budget constraints and uncertainty about future site availability. The optimal solution includes the set of sites to protect now along with a policy or rule that describes the sites to protect in the future depending on sites already protected and sites currently available. Possingham et al. (1993) developed a model to maximize expected species representation at the end of the planning horizon and determined how increasing the probability of site development influenced the optimal site-protection rule. Costello and Polasky (2004) demonstrated a similar dynamic programming model and emphasized that current methods prevent solution of problems with more than about 10 sites, which is far less than can be handled with heuristic algorithms. They found some simple heuristics that performed reasonably well in comparison with optimal policies obtained from dynamic programming, suggesting that some heuristics may perform well on larger problems.

Snyder et al. (2004*a*) developed a two-period linear-integer model for sequential site selection in which uncertainty about future site availability was represented with a set of probabilistic scenarios. The decision variables included the set of sites to protect now and sites to protect later, depending on availability. The linear-integer formulation allows solution of realistic-sized problems with commercial software on personal computers. Furthermore, the formulation can be expanded to model multiple objectives and constraints that allow for budget allocation between periods, as we demonstrate in the discussion that follows.

Multiobjective site selection models are useful tools for investigating the opportunities for simultaneously meeting multiple conservation objectives (Rothley 1999; Church et al. 2000; Ruliffson et al. 2003). Analyses typically determine the trade-off between objectives—the pareto-optimal curve that displays the best value of one objective given a required achievement of the other. In addition, important information can be obtained by analyzing site selection decisions for alternative solutions along the trade-off curve, including identification of sites that should be selected no matter what the decision maker's position on the relative importance of the two objectives

(Schilling et al. 1982; ReVelle 1987). We show how to display model solutions in terms of both the objectives and decisions in our multiobjective analysis.

Methods

Dynamic Site Selection Model

We formulated a two-period linear-integer optimization model with two objectives: maximize the expected number of species represented in open-space reserves and maximize the expected number of people with access to reserves. A weighted sum of the objectives was maximized subject to an upper bound on the total area available for protection. The weights were ramped from small to large to generate the trade-off curve between the objectives.

The model employed a list of sites, some of which were available for protection in the first period and others that were not. Each site not protected in the first period had a probability of remaining undeveloped and being available for protection in the second period. To handle this uncertainty about the development of unprotected sites, we created a set of development scenarios. Each scenario was one possible development outcome identifying which sites were undeveloped and available for protection in the second period. Associated with each scenario was a probability of occurrence. Scenario construction is described in the application that follows.

The model employed information about the location of species and people. Each site was described by a list of species present. A species was represented if it was present in at least one site selected for protection. Each site was also described by a list of towns that were within 3.2 km (2 mi). The residents of a town had access to protected sites if at least one site within this distance was protected.

The model had two sets of 0–1 site selection decision variables. The first set included the yes-no protection choices for sites in the first period. The model assumed that protection decisions in the second period were made after the decisions in the first period were implemented and the site development scenario was revealed. Thus, the second set of decision variables included the yes-no protection choices for sites in the second period under each development scenario. The model was formulated with the following notation:

i, I = index and set of species;
j, J = index and set of towns;
k, K = index and set of sites eligible for protection;
s, S = index and set of site development scenarios;
Q_1 = expected number of species represented in the selected sites;
Q_2 = expected number of people with access to the selected sites;
p_s = probability that scenario s occurs;
r_j = number of residents in town j;
u_{ks} = 0–1 parameter: 1 if site k is undeveloped and available in period-two scenario s, 0 otherwise;
a_k = area of site k;
b = upper bound on total area of sites selected in periods one and two;
L = set of sites k that are not available for protection in period one;
M_i = set of sites k that contain species I;
D = a distance standard;
d_{jk} = distance between town j and site k;
N_j = set of sites k within distance D of town j, that is, $N_j = \{k \mid d_{jk} \le D\}$;
x_{k1} = 0–1 variable: 1 if site k is selected for protection in period one, 0 otherwise;
x_{k2s} = 0–1 variable: 1 if site k is selected for protection in period two scenario s, 0 otherwise;
y_{is} = 0–1 variable: 1 if species i is represented in at least one protected site in scenario s, 0 otherwise; and
z_{js} = 0–1 variable: 1 if town j has at least one protected site within distance D in scenario s, 0 otherwise.

The model was formulated as follows:

maximize

$$Q_1 = \sum_{s \in S} p_s \sum_{i \in I} y_{is} \quad \text{and} \tag{1}$$

$$Q_2 = \sum_{s \in S} p_s \sum_{j \in J} r_j z_{js} \tag{2}$$

subject to

$$x_{k1} + x_{k2s} \le 1 \quad \text{for all } k \in K \text{ and } s \in S, \tag{3}$$

$$x_{k2s} \le u_{ks} \quad \text{for all } k \in K \text{ and } s \in S, \tag{4}$$

$$\sum_{k \in K} a_k x_{k1} + \sum_{k \in K} a_k x_{k2s} \le b \quad \text{for all } s \in S, \tag{5}$$

$$x_{k1} = 0 \quad \text{for all } k \in L, \tag{6}$$

$$y_{is} \le \sum_{k \in M_i} (x_{k1} + x_{k2s}) \quad \text{for all } i \in I \text{ and } s \in S, \tag{7}$$

$$z_{js} \le \sum_{k \in N_j} (x_{k1} + x_{k2s}) \quad \text{for all } j \in J \text{ and } s \in S, \text{ and} \tag{8}$$

$$x_{k1}, x_{k2s}, y_{is}, z_{js} \in \{0, 1\}. \tag{9}$$

The first objective (the expected number of species represented in protected sites [Eq. 1]) was to determine the number of species represented under each scenario weighted by the probability of that scenario's occurrence. The second objective (the expected number of people with access to protected sites [Eq. 2]) was to determine the number of people with access under each scenario

Table 1. Attributes of open-space sites in western Lake County, Illinois.

Site	Area (ha)	Risk class*	Number of species	People with access (1000s)	Species per ha	Rank	People with access per ha (1000s)	Rank
1	37	1	1	0.0	0.03	26	0.00	30
2	40	2	2	8.0	0.05	19	0.20	18
3	65	2	2	2.7	0.03	25	0.04	24
4	24	2	2	9.3	0.08	13	0.39	13
5	9	2	1	2.9	0.11	10	0.31	15
6	47	3	3	3.3	0.06	16	0.07	23
7	1	3	5	1.8	5.00	1	1.80	1
8	16	2	1	17.6	0.06	17	1.09	5
9	39	1	4	36.1	0.10	11	0.93	6
10	121	3	5	9.3	0.04	23	0.08	22
11	141	3	2	3.3	0.01	28	0.02	27
12	29	3	2	0.0	0.07	14	0.00	31
13	22	3	1	33.8	0.05	21	1.55	3
14	9	3	5	2.7	0.56	3	0.30	16
15	84	3	7	21.4	0.08	12	0.26	17
16	23	2	1	9.1	0.04	22	0.39	12
17	5	2	4	3.1	0.82	2	0.64	8
18	14	2	3	32.9	0.21	6	2.33	2
19	13	2	2	6.0	0.16	8	0.48	10
20	30	3	2	26.7	0.07	15	0.88	7
21	7	2	1	10.5	0.14	9	1.44	4
22	189	3	9	2.7	0.05	20	0.01	28
23	313	2	2	32.5	0.01	31	0.10	20
24	80	3	1	2.4	0.01	29	0.03	26
25	10	2	2	5.8	0.20	7	0.57	9
26	142	2	1	5.8	0.01	30	0.04	25
27	92	3	2	35.2	0.02	27	0.38	14
28	17	2	4	0.2	0.23	5	0.01	29
29	24	3	1	2.7	0.04	24	0.11	19
30	7	1	2	2.9	0.29	4	0.42	11
31	37	3	2	3.1	0.05	18	0.08	21

**Risk classes are based on an assessment of future land conversion conducted by the Openlands Project of Chicago (Openlands Project 1999). Sites in class 1 were expected to be developed in 10 years. Class-2 sites were expected to be developed in 30 years. Class-3 sites were not under pressure of development and included lakes and wetlands with development restrictions.*

weighted by the scenario probability. Public access under each scenario was the number of towns with access weighted by population size. Equation 3 specifies that site k can be selected for protection in either period one or period two, but not both, over all scenarios. Equation 4 specifies that site k can only be selected for protection in period two in scenario s if site k is undeveloped and available for protection in that scenario. Equation 5 places an upper bound b on the total area of sites selected for protection in periods one and two under each scenario.

If all sites are available in period one, the area budget should be optimally allocated to the first period to avoid the possibility of site development and loss. If some sites are not immediately available, however, Eq. 5 allows the determination of how much of the area budget should be held until the second period. Equation 6 defines the sites that are not available for protection in period one. Equation 7 defines the condition under which species i is represented in protected sites under scenario s: at least one site that contains species i must be selected for protection in the first or second period. Equation 8 defines the condition under which town j has access to protected sites under scenario s: at least one site that is within distance D from town j must be selected for protection in the first or second period. Equation 9 defines the integer restrictions on the decision variables. The optimal solution is a set of sites for protection in period one and a set of sites for protection in period two under each scenario that maximizes the weighted sum of expected number of species represented in protected sites and expected number of people with access to protected sites.

Data

We applied the model to data for 31 open-space sites in the Lake County portion of the Fox River watershed (Fig. 1). The data were part of the Fox River Watershed Biodiversity Inventory completed in the 1990s. Some sites contained high-quality natural communities or habitat for rare animal or plant species. Other sites were large open spaces that contained potentially restorable natural communities, special geological or archaeological features, rare species, or large grasslands. The sites varied in size from 1 to 313 ha, with median of 29 ha (Table 1).

At the time of our study, all 31 sites were privately owned and at varying risk of development. We assigned each site to one of three risk classes (Table 1). The assignments were based on an assessment of future land conversion conducted by the Openlands Project of Chicago (Openlands Project 1999). Sites in class 1 were expected to be developed in 10 years. Class-2 sites were expected to be developed in 30 years. Class-3 sites were not under pressure of development, and included lakes and wetlands with development restrictions. We assigned development probabilities of 0.9, 0.6, and 0.3 to classes 1, 2, and 3, respectively, based on our perception of the relative risk of development implicit in the risk classes. The absolute levels of the probabilities were arbitrary, and for the purpose of this study, represented probabilities of development in the next 5 years. Thus, we assumed that 5 years separates the site protection decisions in the first and second periods.

Each site was described by a list of rare plants and animals present. Collectively, 27 rare species occurred in the 31 sites, and species richness of individual sites varied from 1 to 9 species (Table 1). Because the budget constraint placed an upper bound on total area of sites selected, we expected that smaller sites with more species may be preferable, and we listed the number of species per unit area in Table 1. As an index of desirability, species per unit area was approximate because it did not account for unique or complementary species.

There are 34 towns in western Lake County. Based on the 2000 U.S. Census, the towns collectively held 222,000 people, and individual towns were home to 1,000 to 30,000 people. In a previous analysis, we calculated the distance between each town and site as an average of the Euclidean distances between points in the town and edges of the site (Ruliffson et al. 2003). We used that distance matrix to list towns that were within 3.2 km (2.0 mi) of each site. Using these town lists and the census information, we computed the number of people within 3.2 km of each site (Table 1). Almost all sites had at least 2,000 people within 3.2 km, and five sites had more than 30,000 people within 3.2 km. We also computed the number of people with access per unit area as an approximate index of site desirability (Table 1).

Analysis

Our analysis focused on the trade-off between species representation and public access. We determined how period-one site selection decisions varied as we traded off species representation against public access while varying the number of sites immediately available and the total area available for protection. We computed optimal site selections for problems in which the objective function weight was decreased from 1.0 (maximize species representation) to 0.0 (maximize public access) in increments of 0.05 subject to area constraints of 81 ha (200 acres) and 324 ha (800 acres). First, we assumed that three randomly selected sites were not available for protection in period one. Then, we repeated the analysis assuming that 15 randomly selected sites were not available in period one.

Development Scenarios

A development scenario was a list of sites that were undeveloped and available for protection in period two. Because the number of possible development scenarios increased exponentially with the number of sites (there were 2^{31} possible scenarios in our application), we could not include all possible scenarios in the optimization model. Therefore, we randomly selected a subset of 50 development scenarios. Each scenario u_{ks} $k = 1, \ldots, 31$ was a vector of 0–1 parameters, where $u_{ks} = 1$ meant that site k was undeveloped under scenario s. The value of each parameter u_{ks} was determined by comparing a uniform 0–1 random number with the probability of development of site k. Because the scenarios were selected at random, we assumed that each scenario had the same probability of occurrence, 0.02. Because 50 scenarios was a small sample of the possible development outcomes for 31 sites, we investigated the impacts of changing the set of scenarios in the model. We repeated the analysis of the trade-offs between species representation and public access with three different sets of 50 randomly generated scenarios.

Solution Method

The model specified in Eqs. 1–9 was solved on a Dell Pentium 4 laptop computer (CPU 2.4 GHz) with the integrated solution package GAMS/Cplex 9.0 (GAMS Development Corporation 1990), which is designed for large and complex linear and mixed-integer programming problems. Input files were created in GAMS (General Algebraic Modeling System), a program designed to generate data files in a format that standard optimization packages can read and process. Cplex solves a mixed-integer programming problem with a branch and cut algorithm, which solves a series of linear programming subproblems. Even a small mixed-integer problem can require significant computer memory and execution time.

Results

The curves showing trade-offs between species representation and public access had concave shapes in which species representation dropped at an increasing rate as public accessibility increased (Fig. 2). The points on each curve in Fig. 2 represent nondominated sets of sites and their relative performance with respect to the two objectives. For each nondominated set of sites, improvement in one objective cannot be achieved without simultaneously

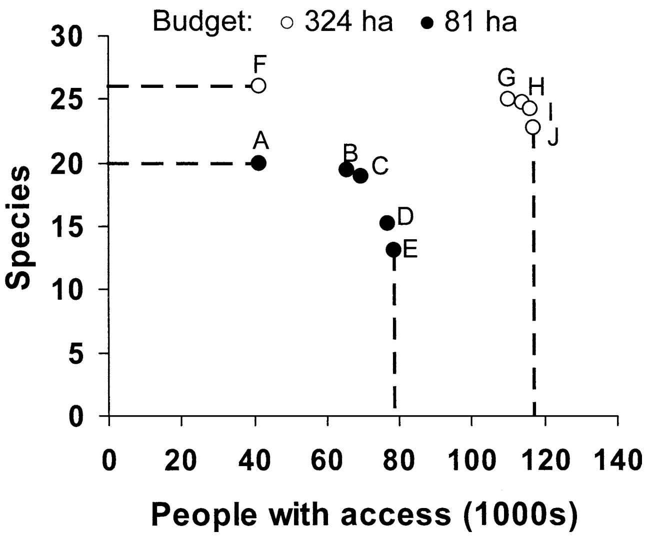

Figure 2. Trade-offs between open-space protection objectives of maximizing expected species representation and maximizing expected public access under different budgets. The points (A–J) represent nondominated configurations of sites and their relative performance with respect to the two objectives. The points are for the case where three randomly selected sites of the set of 31 sites were not available in period one.

causing degradation in the value of the other objective. As a result, the points on each trade-off curve represent a frontier beyond which there were no better solutions. The points on each curve were determined by optimizing the weighted objective function $wQ_1 + (1 - w)Q_2$ and ranging the weight between 1 and 0 in increments of 0.05. The solution points on each curve were only those on the outer hull of the bicriterion space; other solutions may exist in the physical gaps between these hull points. Those "gap points" can be found using the constraint method: optimizing one objective subject to a constraint on the achievement of the second objective and varying the level of the constraint (Cohon 1978). We did not solve for the gap points because the solutions found with the weighting method gave a good picture of the trade-offs between objectives and the constraint method was less computationally efficient (Snyder et al. 2004*b*).

Among the nondominated solutions for a given budget, the best depended on the decision maker's preference for the two objectives. If species representation was most important and the budget was 81 ha, the choice was alternative A, in which expected species representation was 20 (74% of the maximum representation without a budget constraint) and expected public access was 41,600 people (19% of the maximum accessibility). The dashed horizontal line between the y-axis and point A indicates that we found a number of solutions that had the same species representation as alternative A but with less public access. A move from alternative A to alternative B or C increased public access more than 60% and reduced species representation only 5%. Higher levels of public access in alternatives D or E were obtained at the expense of much larger reductions in species representation. The dashed vertical line from point E to the x-axis indicates that we found a number of solutions that had the same level of public access as alternative E but with less species representation.

Increasing the budget from 81 to 324 ha shifted the trade-off curve up and to the right and reduced the trade-off between the site protection objectives (Fig. 2). When species representation was most important, the optimal solution was alternative F, in which expected species representation was 26 and expected public access was 41,600 people. Little in the way of species representation was lost with substantial increases in public access (Fig. 2). Switching from alternative F to alternative J almost tripled public access from 41,600 to 117,300 people and reduced species representation only 12% from 26.0 to 22.8 species.

To complement the trade-off curves, it is important to look at the results in decision space and identify core sites, which are sites selected for protection in period one throughout the range of objectives. With a budget of 81 ha, four core sites (7, 8, 17, and 21) were protected in period one (Table 2) in all five solutions (Fig. 2). With a budget of 324 ha, there was one additional core site (30). The core sites were small ($<$16 ha) and had relatively large numbers of species or people with access (Table 1). As a result, the core sites ranked relatively high in terms of species per hectare and people with access per hectare, two indices of site desirability listed in Table 1.

There was a lot of overlap in the sets of period-one sites selected for protection in the five alternative solutions under each budget (Table 2). As a result of the overlap in composition, the choice between alternative solutions on a trade-off curve involved shifting a portion of the area budget between a few sites. For example, with a budget of 81 ha, moving from alternative A to alternative C shifted about 25% of the budget from protecting site 28 to protecting site 13. Moving from alternative C to alternative E shifted about 35% of the budget from protecting sites 14, 19, and 30 in period one and using that portion of the budget in period two. Because adjacent solutions on the trade-off curve differed in only a few sites, decisions about which alternative to select can focus on the strengths and weaknesses of those few sites.

In addition to period-one site selections, each solution included selections in period two. The allocation of the area budget to period-two selections depended on the objective weights and the characteristics of the sites that were not available in period one. We randomly selected three sites and removed them from consideration for protection in period one. Those three sites (18, 20, and 25) were relatively small (10–30 ha; Table 1). Two sites (18

Table 2. Objective function values and sites selected for protection in period one for nondominated solutions with area budgets of 81 ha (solutions A, B, C, D, E) and 324 ha (solutions F, G, H, I, J) for the case in which three randomly selected sites of the set of 31 sites are not available for protection in period one.

	Objective value		*Sites protected in period one*																*Area protected (ha)*
Solution	*species*	*people (1000s)*	*3*	*7*	*8*	*9*	*13*	*14*	*15*	*16*	*17*	*19*	*21*	*22*	*24*	*28*	*30*	*31*	
A	20.0	41.6		X	X			X			X	X	X			X	X		74
B	19.5	65.7		X	X			X			X	X	X				X		57
C	19.0	69.7		X	X		X	X			X	X	X				X		79
D	15.2	77.0		X	X						X		X						29
E	13.1	78.6		X	X		X				X		X						51
F	26.0	41.6	X	X	X						X	X	X	X		X	X		320
G	25.0	110.2	X	X	X	X			X	X	X		X				X	X	283
H	24.8	114.0	X	X	X		X		X	X	X	X	X			X	X		260
I	24.3	116.4	X	X	X		X	X	X	X	X	X	X				X		242
J	22.8	117.3		X	X		X	X	X	X	X	X	X		X	X	X		284

and 25) ranked in the top 30% in both species representation and accessibility per unit area but had relatively high probabilities of being developed in period two (60%). Site 20 had a relatively low probability of development (30%) and ranked in the top 30% in accessibility per unit area. When species representation was most important (alternatives A and F), almost all the budget was spent in period one (Table 2) and no sites were selected in period two. In these cases, the value of waiting to see if sites 18, 20, and 25 were available in period two was relatively low because either the probability of development was high (sites 18 and 25) or the number of species per unit area was low (site 20). When public access was most important (alternatives E and J), however, a portion of the area budget was withheld in period one (Table 2) for use in period two. For example, in alternative J, 40 ha of the area budget was allocated to period two, and site 20 was protected when it was available in 35 of 50 scenarios. When site 20 was not available, the period-two area budget was used to protect site 31 (11 scenarios) or site 18 (4 scenarios).

We tested the robustness of the budget allocations between periods by reducing the probability of development of sites 18 and 25 from 60% to 30% and finding optimal solutions to problems with either species representation or public access objectives. With a budget of 324 ha, the results were unchanged; however, with a budget of 81 ha, the budget allocation was sensitive to reductions in probabilities of development. When species representation received the most weight, about 20% of the area budget was withheld in period one to protect site 18 when it was available in period two. When public access received the most weight, more than half the area budget was withheld in period one to protect sites 18, 20, and 25 when they were available in period two.

We tested the robustness of budget allocations by increasing the number of sites that were not available for protection in period one from 3 to 15 and finding optimal solutions to problems with budgets of 81 and 324 ha. Ranging the objective function weight from 1 to 0, we found four nondominated solutions with a budget of 81 ha and five solutions with a budget of 324 ha (Table 3). With fewer sites available in period one, there were fewer options for site protection, and the available sites were larger and had fewer species and people with access. As a result, fewer sites were protected in period one and the trade-off curve for a given budget shifted inward toward the origin (as shown in Fig. 3 with a budget

Table 3. Objective function values and sites selected for protection in period one for nondominated solutions with budgets of 81 ha (solutions A, B, C, D) and 324 ha (solutions E, F, G, H, I) for the case where 15 randomly selected sites of the set of 31 sites are not available for protection in period one.

	Objective value		*Sites protected in period one*									*Area protected (ha)*
Solution	*species*	*people (1000s)*	*1*	*3*	*5*	*8*	*9*	*14*	*15*	*28*	*31*	
A	15.4	53.9				X		X		X		43
B	15.2	63.0			X	X	X	X				73
C	14.3	71.5				X		X				25
D	10.7	73.5			X	X						26
E	22.0	82.4	X	X		X	X		X	X	X	295
F	20.7	99.3		X	X	X	X		X	X		230
G	20.6	104.0		X	X	X	X		X			213
H	19.8	104.8	X		X	X	X	X	X			194
I	19.1	105.3			X	X	X	X	X	X		175

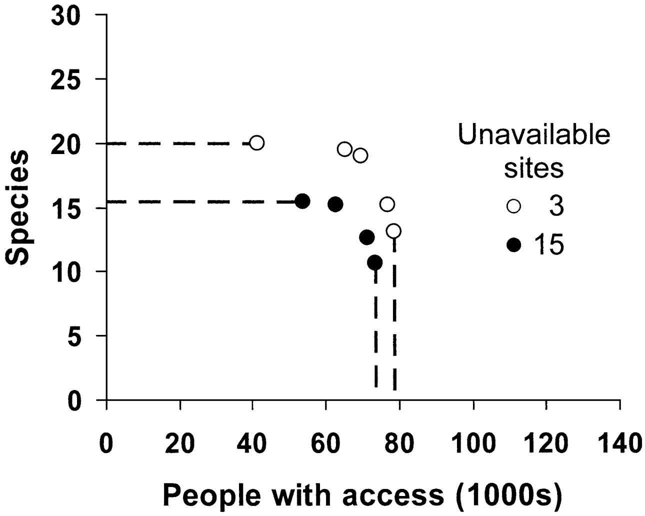

Figure 3. Trade-offs between open-space protection objectives of maximizing expected species representation and maximizing expected public access when the number of sites not available in period one increases from 3 to 15 and the budget is 81 ha. The points represent nondominated configurations of sites and their relative performance with respect to the two objectives.

of 81 ha), indicating that maximum levels of expected species representation and public access were reduced. Further, smaller portions of the area budget were spent in period one, leaving more of the budget available in period two when more sites may be available. For example, with a budget of 81 ha and priority given to the public access objective (solution D in Table 3), 68% of the budget was withheld in period one to protect additional sites in period two if they were available.

We tested the robustness of the results to changes in the development scenarios representing uncertainty about site development. We repeated the analysis of the trade-offs between species representation and public access with three different sets of 50 randomly generated scenarios. Although a few of the period-one site selection decisions varied across the sets of scenarios, the core sites (those selected regardless of the objective weights) did not vary at all from one set of scenarios to another. Furthermore, the maximum value of each objective varied <6% across the sets of scenarios. The computation time required to solve a problem with 31 sites and 50 scenarios using GAMS/Cplex 9.0 was <1 minute.

Discussion

Our site selection model addresses three features of open-space protection that few models address: multiple objectives, limited budgets, and uncertain site availability. These features are especially important in urban settings, where limited budgets and dynamic land markets make planners acquire open space sequentially depending on available funds and sites. The model accounts for uncertain site availability by separating decisions into two periods, defining a set of probabilistic scenarios for the availability of undeveloped sites in the second period and conditioning period-two decisions on sites available in each scenario. The model can be expressed in a linear-integer formulation solvable with off-the-shelf commercial software. Other site selection models with sequential decisions and uncertain site availability rely on dynamic programming solution methods (Possingham et al. 1993; Costello & Polasky 2004), which require custom software. Heuristics algorithms based on site irreplaceability and vulnerability have been developed to address sequential site selection problems and software is available for general use (e.g., Ferrier et al. 2000).

In our application in Chicago, the open-space protection objectives of maximizing expected species representation and maximizing expected number of people with access to protected sites did not align closely except when the area budget allowed protection of a large number of sites. Even though there was a significant trade-off between the two objectives, we found several core sites that were selected in period one regardless of the point on the trade-off curve. These core sites were small and had high species richness and public access per unit area and could be included in a recommendation no matter what the decision maker's position on the relative importance of the two objectives (Schilling et al. 1982; ReVelle 1987).

With a period-two formulation, we were able to analyze the allocation of an area budget over time. For example, under what conditions should the planner withhold some of the budget for use in period two when site availability is better known? The model results were intuitively satisfying: the amount to withhold depended on the number and quality of sites that were not immediately available and their probabilities of development. If high-quality sites were not immediately available but could be on the market in the next period, it was better to withhold some of the budget for selection decisions in period two when more would be known about site availability. If the probabilities of development were high, however, it was best to use the budget primarily in period one. The implication is that portions of a limited budget should not be reserved in the hope of protecting high-quality sites that are not available immediately and are vulnerable to development. The results illustrate the importance of carefully assessing the vulnerability of sites to development and using this information in planning for protected areas (Pressey & Taffs 2001).

The linear-integer formulation can be modified to address other resource constraints and objectives. For example, in the current formulation with a species representation objective, we did not address population persistence within the sites. We found that model solutions usually included many small sites, which may not support long-term species persistence. Species persistence can be modeled using surrogate constraints such as minimum levels of habitat area, quality, and contiguity (Williams & ReVelle 1996; Church et al. 2000; Önal & Briers 2002; Fischer & Church 2003). Our linear-integer formulation can be expanded to incorporate these types of constraints, which offers the opportunity to examine their impacts in the context of sequential site selection. The current model also assumes that accessibility is defined only by distance to open space, regardless of the species present. It would be interesting to maximize the number of people with access to rare species and investigate the trade-off with a species representation objective.

It would also be interesting to apply scenario optimization to reserve selection problems in which the occurrence of species in sites is uncertain. This uncertainty could arise from the limitations of survey methods or changes in species presence since the previous survey. Some reserve selection models explicitly account for incidence uncertainty (Haight et al. 2000; Camm et al. 2002; Arthur et al. 2004); however, those models take a static approach to conservation planning. A two-period scenario model could be formulated with decision variables for sites to survey in period one and sites to protect in period two contingent on survey results.

An important limitation of the scenario-optimization model is computational. It is well known that scenario-optimization models with integer decision variables are more difficult to solve with commercial software as the number of scenarios increases (Ahmed & Shapiro 2002). The difficulty is compounded in our model because the budget constraint defined for each scenario included cost coefficients that were not 0–1 (Eq. 5). Specialized solution algorithms have been developed to solve scenario models with integer decision variables (Ahmed & Shapiro 2002), and they may perform well on the two-period reserve selection problem.

Another important limitation of the model is structural: the linear formulation requires that scenario probabilities be independent of actions taken in the first period. As a result, the model assumes that open-space protection decisions do not affect the likelihood of future site availability. Relaxing this assumption would result in a nonlinear formulation, which could be addressed with dynamic programming or heuristic solution methods.

Land protection organizations in the Chicago region and urban areas throughout the United States pursue a variety of objectives in addition to biodiversity protection. Two important objectives are to provide an equitable distribution of outdoor recreation opportunities among local residents and to get the biggest bang for the buck from available funding (Ruliffson et al. 2002). Planners recognize that their protection objectives may conflict, and they seek sets of sites that are valuable from the standpoint of more than one objective. For example, it is much easier for a planner to justify protection decisions that meet biodiversity objectives if at the same time those sites are accessible to a large portion of the local residents. Multiobjective site selection models, like the one we describe, can help planners define trade-off curves that identify the limits of what can be achieved with respect to each objective under a given budget. And the models can help identify sets of sites that should be selected regardless of the weights given to various objectives. Planners can use this information to construct a small number of promising alternatives for further evaluation with criteria that are not included in the optimization model.

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Literature Cited

Ahmed, S., and A. Shapiro. 2002. The sample average approximation method for stochastic programs with integer recourse. Technical report. School of Industrial & Systems Engineering, Georgia Institute of Technology. Available from www.optimization-online.org (accessed July 2004).

Arthur, J. L., J. D. Camm, R. G. Haight, C. A. Montgomery, and S. Polasky. 2004. Weighing conservation objectives: maximum expected coverage versus endangered species protection. Ecological Applications **14:**1936–1945.

Cabeza, M., and A. Moilanen. 2001. Design of reserve networks and the persistence of biodiversity. Trends in Ecology & Evolution **16:**242–248.

Camm, J. D., S.K. Norman, S. Polasky, and A. Solow. 2002. Nature reserve selection to maximize expected species covered. Operations Research **50:**946–955.

Camm, J. D., S. Polasky, A. Solow, and B. Csuti. 1996. A note on optimal algorithms for reserve site selection. Biological Conservation **79:**353–355.

Church, R. L., D. M. Stoms, and F. W. Davis. 1996. Reserve selection as a maximal coverage location problem. Biological Conservation **76:**105–112.

Church, R. L., R. A. Gerrard, A. D. Hollander, and D. M. Stoms. 2000. Understanding the tradeoffs between site quality and species presence in reserve site selection. Forest Science **46:**157–167.

Cohon, J. L. 1978. Multiobjective programming and planning. Academic Press, New York.

Costello, C., and S. Polasky. 2004. Dynamic reserve site selection. Resource and Energy Economics **26:**157–174.

Ferrier, S., R. L. Pressey, and T. W. Barrett. 2000. A new predictor of the irreplaceability of areas for achieving a conservation goal, its applicability to real-world planning, and a research agenda for further refinement. Biological Conservation **93:**303–325.

Fischer, D. T., and R. L. Church. 2003. Clustering and compactness in reserve site selection: an extension of the biodiversity management area selection model. Forest Science **49:**555–565.

GAMS Development Corporation. 1990. General algebraic modeling system. Version 2.25.090. GAMS Development Corporation, Washington, D.C.

Haight, R. G., C. S. ReVelle, and S. A. Snyder. 2000. An integer optimization approach to the probabilistic reserve site selection problem. Operations Research **48:**697–708.

Hollis, L. E., and W. Fulton. 2002. Open space protection: conservation meets growth management. The Brookings Institution Center on Urban and Metropolitan Policy, Washington, D.C.

Kirkpatrick, J. B. 1983. An iterative method for establishing priorities for the selection of nature reserves: an example from Tasmania. Biological Conservation **25:**127–134.

Lawler, J. J., D. White, and L. L. Master. 2003. Integrating representation and vulnerability: two approaches for prioritizing areas for conservation. Ecological Applications **13:**1762–1772.

Margules, C. R., and R. L. Pressey. 2000. Systematic conservation planning. Nature **405:**243–253.

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

Miller, J. R., and R. J. Hobbs. 2002. Conservation where people live and work. Conservation Biology **16:**330–337.

Noss, R. F., C. Carroll, K. Vance-Borland, and G. Wuerthner. 2002. A multicriteria assessment of the irreplaceability and vulnerability of sites in the greater Yellowstone ecosystem. Conservation Biology **16:**895–908.

Önal, H., and R. A. Briers. 2002. Incorporating spatial criteria in optimum reserve network selection. Proceedings of the Royal Society of London B **269:**2437–2441.

Openlands Project. 1999. Under pressure: land consumption in the Chicago region 1998–2028. Openlands Project, Chicago.

Possingham, H., J. Day, M. Goldfinch, and F. Salzborn. 1993. The mathematics of designing a network of protected areas for conservation. Pages 536–545 in D. J. Sutton, C. E. M. Pearce, and E. A. Cousins, editors. Decision sciences: tools for today, proceedings of the 12th National Australian Society for Operations Research Conference. Australian Society for Operations Research, Adelaide.

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

Pressey, R. L., and K. H. Taffs. 2001. Scheduling conservation action in production landscapes: priority areas in western New South Wales defined by irreplaceability and vulnerability to vegetation loss. Biological Conservation **100:**355–376.

ReVelle, C. S. 1987. Urban public facility location. Pages 1053–1096 in E.S. Mills, editor. Handbook of regional and urban economics. Volume II. Elsevier Science, Amsterdam.

ReVelle, C. S., J. C. Williams, and J. J. Boland. 2002. Counterpart models in facility location science and reserve selection science. Environmental Modeling and Assessment **7:**71–80.

Rodrigues, A. S. L., and K. J. Gaston. 2002. Optimisation in reserve selection procedures—why not? Biological Conservation **107:**123–129.

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

Ruliffson, J. A., P. H. Gobster, R. G. Haight, and F. R. Homans. 2002. Niches in the urban forest: organizations and their role in acquiring metropolitan open space. Journal of Forestry **9:**16–23.

Ruliffson, J. A., R. G. Haight, P. H. Gobster, and F. R. Homans. 2003. Metropolitan natural area protection to maximize public access and species representation. Environmental Science and Policy **6:**291–299.

Sætersdal, M., J. M. Line, and H. B. Birks. 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.

Schilling, D. A., A. McGarity, and C. S. ReVelle. 1982. Hidden attributes and the display of information in multiobjective analysis. Management Science **9:**236–242.

Snyder, S. A., R. G. Haight, and C. S. ReVelle. 2004*a*. A scenario optimization model for dynamic reserve site selection. Environmental Modeling and Assessment **9:**179–187.

Snyder, S., C. ReVelle, and R. Haight. 2004*b*. One and two objective approaches to an area-constrained habitat reserve site selection problem. Biological Conservation **119:**565–574.

Williams, J. C., and C. S. ReVelle. 1996. A 0–1 programming approach to delineating protected reserves. Environmental and Planning B **23:**607–624.