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Metropolitan natural area protection to maximize public access and species representation

Jane A. Ruliffson [a], Robert G. Haight [b,*], Paul H. Gobster [c], Frances R. Homans [a]

[a] *Department of Applied Economics, 1994 Buford Avenue, University of Minnesota, St. Paul, MN 55108, USA*

[b] *USDA Forest Service, North Central Research Station, 1992 Folwell Avenue, St. Paul, MN 55108, USA*

[c] *USDA Forest Service, North Central Research Station, 1033 University Place, Suite 360, Evanston, IL 60201, USA*

Abstract

In response to widespread urban development, local governments in metropolitan areas in the United States acquire and protect privately-owned open space. We addressed the planner's problem of allocating a fixed budget for open space protection among eligible natural areas with the twin objectives of maximizing public access and species representation. Both objectives were incorporated into a discrete, 0–1 integer optimization model and applied to a problem with 68 sites, 61 species, and 34 towns in the Chicago metropolitan area. Increasing required species representation reduced the maximum number of towns with access to reserves, and the tradeoff between species representation and site accessibility increased as the budget was reduced. The definition of site accessibility affected optimal reserve design. A town had access if a specified number of reserves was located within a specified distance from the town. Increasing the distance standard resulted in more, smaller sites protected in a uniform spatial pattern. Increasing the minimum number of sites required to be within a distance standard caused the selection of clusters of sites near a few towns. The study adds a new dimension to reserve site selection models by including site accessibility as a goal.

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Keywords: Biodiversity protection; Chicago; Facility location; Metropolitan open space protection; Reserve site selection

1. Introduction

The establishment and enhancement of biological reserves is a cornerstone of biodiversity conservation (Noss and Cooperrider, 1994; Pimm and Lawton, 1998). Recognizing that resources are limited and land use pressures from population and economic expansion compete with reserve protection, biologists, operations researchers, and economists have in recent years explored ways to rationalize the choice and assembly of reserves (Kingsland, 2002). An outcome was the development of reserve site selection models, which maximize the diversity of species or other features that can be preserved with a limited amount of resources (e.g. Ando et al., 1998; Snyder et al., 1999). Such models provide case-specific policy guidance including sets of reserves that efficiently achieve desired conservation goals and efficient tradeoffs between conservation goals and reserve costs. Following the pioneering applications in Australia (Margules et al., 1988; Cocks and Baird, 1989), site selection models have been used in countries around the world where biodiversity is threatened and in need of protection (see Rodrigues and Gaston, 2002 for a summary of published studies). Excellent reviews of reserve design principles and modeling techniques are also available (Pressey et al., 1993; Margules and Pressey, 2000; Kingsland, 2002; ReVelle et al., 2002). While site selection models are mostly applied in rural areas where biodiversity protection is a primary objective, none address problems in metropolitan areas, where competition for open space is intense and planners have a variety of goals for land protection in addition to biodiversity protection. This paper describes the development and application of a site selection model in an urban setting.

Population growth on the edges of metropolitan areas in the United States exceeded 10% in 1990–2000 (Heimlich and Anderson, 2001), and rates of land conversion from open space to developed uses far exceeded rates of population growth (Fulton et al., 2001). At the same time, government programs to protect open space grew in popularity with the passage of numerous state and local referenda, which raised billions of dollars for the acquisition of privately-owned open space (Hollis and Fulton, 2002). Local governments play a major role in metropolitan open space protection in the United States, and they have a variety of goals, including the protection and restoration of natural areas and habitat for

* Corresponding author. Tel.: +1-612-649-5178; fax: +1-612-649-5285.
E-mail address: rhaight@fs.fed.us (R.G. Haight).

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rare and endangered species. In addition to biodiversity protection, a top protection goal is, arguably, site accessibility: the provision of public access to opportunities for recreation and education (Ruliffson et al., 2002). Metropolitan planners cite public access as a primary goal because constituents can see the direct benefits of their financial contributions through their ability to use and enjoy protected sites.

Faced with multiple goals, limited budgets, and persistent development, metropolitan planners need to measure tradeoffs and make difficult choices about which privately-owned sites to acquire and protect. We developed a site selection model that incorporated two important goals for metropolitan open space protection: maximizing public access and maximizing species representation. We use the term open space in the broad sense of land that is not devoted to urban development. Open space can have many uses including provision of recreation or education opportunities and protection of biodiversity. While conflicts between species protection and recreation may exist in a site, we assume that those conflicts can be effectively mitigated so that a single site can provide multiple uses. We also assume that open space can be protected by government purchase of property rights and do not consider tax incentive or regulation as alternative mechanisms for protecting privately-owned open space.

The approach to maximizing public access was based on the maximal covering location problem (Church and ReVelle, 1974), which locates service facilities to maximize the number of demand regions that have access to service. Our model maximized the number of cities with access to open space reserves. A city had access if a specified minimum number of reserves was located within a specified distance from the city. The approach to maximizing species representation was based on the maximal covering species problem (Camm et al., 1996; Church et al., 1996; ReVelle et al., 2002). Sites were selected to maximize the number of species represented, where a species was represented if it was present in at least one of the selected sites. The model addresses the basic question of how to allocate a fixed budget among a large number of potential reserves, and it is used here to investigate the tradeoffs between the goals of site accessibility and species representation.

We first present the optimization model and then describe its application to a problem of acquiring open space for protection in a portion of the Fox River watershed in the Chicago metropolitan area. The Chicago area is one of the largest metropolitan regions in the United States, and it experienced rapid population growth and land conversion in the 1990s (Johnson, 2002). If current trends persist, the size of the metropolitan area could double in the next 30 years (Openlands Project, 1999). In response, county forest preserve districts evaluate and acquire privately-owned open space for protection (Ruliffson et al., 2002). Our application focuses on the tradeoffs between the goals of maximizing public access and maximizing species representation in one county in the Fox River watershed.

2. Methods

2.1. Site selection model

To address the metropolitan planner's problem, we formulated a discrete, 0–1 integer optimization model to select the set of sites that maximizes the number of cities with access to protected sites subject to budget and species coverage constraints. The model assumes that we have a list of sites, each of which is either already protected or eligible for protection. The model also assumes that we have a list of cities along with a distance between each city and site. A city is assumed to have access to reserves if a specified minimum number of sites is protected within a specified distance from the city. The need for the protected status of sites is seen in the need to count the number of sites within the specified distance of the city. For simplicity, when counting the number of cities with access, we treated cities equally and did not weight them according to population size. Further, we defined accessibility only in terms of distances between cities and sites and not sizes of sites. Extensions of the model to relax these assumptions are presented in the discussion. Finally, the model assumes that we have a list of species present in each site and that a species is represented if at least one site that contains the species is protected. The model includes logic from maximal covering problems in facility location and reserve selection science (ReVelle et al., 2002) and is expressed with the following notation:

i, I: index and set of species
j, J: index and set of cities
k, K: index and set of sites that are either already protected or eligible for protection
L: set of sites k that are already protected
M_i: set of sites k that contain species i
B: an upper bound on the budget available for site protection
c_k: cost of protecting site k, where $c_k = 0$ all $k \in L$
d_{jk}: distance between city j and site k
D: a distance standard
N_j: set of sites k within distance standard D of city j, that is, $N_j = \{k | d_{jk} \leq D\}$
n: minimum number of sites required to be within distance standard D for a city to have access
S: a lower bound on the number of species represented in protected sites
x_k: a 0–1 variable; 1 if site k is protected, 0 otherwise
y_i: a 0–1 variable; 1 if species i is represented in protected sites, 0 otherwise
z_j: a 0–1 variable; 1 if city j has at least n protected sites within distance standard D, 0 otherwise.

The model is formulated as follows:

$$\text{Maximize} \sum_{j \in J} z_j, \tag{1}$$

Subject to:

$$z_j \leq \frac{1}{n} \sum_{k \in N_j} x_k, \quad \text{all } j \in J, \tag{2}$$

$$y_i \leq \sum_{k \in M_i} x_k, \quad \text{all } i \in I, \tag{3}$$

$$\sum_{i \in I} y_i \geq S, \tag{4}$$

$$\sum_{k \in K} c_k x_k \leq B, \tag{5}$$

$$x_k = 1, \quad \text{all } k \in L, \tag{6}$$

$$x_k, y_i, z_j \in \{0, 1\}. \tag{7}$$

The objective (1) maximizes the number of cities that have access to protected sites. Constraints (2) stipulate that each city j has access to protected sites only if at least n of the sites that are within distance standard D of the city are protected. Constraints (3) stipulate that each species i is represented only if at least one of the sites that contain the species is protected. Constraint (4) sets the lower bound on the number of species that must be represented in the protected sites. Constraint (5) requires that the total cost of protecting sites does not exceed the budget. Constraints (6) define the sites that are already protected. The last set of constraints (7) defines the integer restrictions for the variables.

We used the model to develop cost curves for different definitions of site accessibility. The model used two parameters to define whether or not a city had access to protected sites: a distance standard D and the minimum number of sites n required to be within the distance standard. For a given set of accessibility parameters and budget, the optimization model was used to determine the set of reserves that maximized the number of cities with access. Then, by resolving the model with incrementally higher budgets, a relationship showing the cost of incremental increases in the number of cities with access was determined.

We also used the model to analyze the tradeoffs between the planner's goals of site accessibility and species representation. For a given definition of site accessibility, we developed curves showing the costs of incremental increases in access under different lower bounds for number of species covered. Those cost curves were the basis of the tradeoff analysis.

2.2. Study area

The study area was the Fox River watershed in northeastern Illinois, USA (Fig. 1). The Fox River starts in southeastern Wisconsin and flows south to join the Illinois River and eventually the Mississippi River. The Fox River watershed covers more than 4000 km^2 in parts of 10 counties in northeastern Illinois. The topography is flat with elevations of 150–300 m. The climate is continental with hot, humid summers, cold winters, and precipitation throughout the year. The watershed covers prairie, savanna, and woodland ecosystems and includes 1389 plant and animal species, 44% of the species in Illinois. More than 100 of those species are listed as threatened or endangered in the state.

Another feature of the watershed is its proximity to the city of Chicago, which is located in Cook County on the shore of Lake Michigan (Fig. 1). The Chicago metropolitan area includes Cook County and nine surrounding counties. In the 2000 census, the region had more than 8 million people making it the third largest metropolitan region in the United States (Johnson, 2002). About 64% of the people lived in Cook County, and 36% lived in the nine surrounding suburban counties. While the regional population increased 11.6% (>850,000 people) in the period 1990–2000, population growth in the nine suburban counties (598,000 people, 25%) was more than twice the population growth in Cook County (281,000 people, 5.5%).

In response to population growth and conversion of open space to housing and commercial development, county governments in the Chicago metropolitan area have acquired and protected open space for a variety of public goals (Ruliffson et al., 2002). In 1995–2000, voters in six counties approved bond referenda, backed by property tax increases, to finance more than $400 million of open space acquisition. Acquisition decisions were made at the county level largely independently across counties.

We focused our analysis on the western portion of Lake County that overlaps the Fox River watershed (Fig. 1). Lake County has a large and active land protection program administered by Lake County Forest Preserves, a county-level government taxing body. Since 1958, the forest preserve district protected more than 10,000 ha of open land, including more than 1200 ha in 1999–2001 when voters approved $90 million in bond referenda. The goals for open space protection included protecting habitat of rare animals and plants, protecting native wetlands, woodlands, and prairies, and providing equitable public access to recreation and educational opportunities.

2.3. Data

Our analysis was conducted using data from 68 natural areas in the Lake County portion of the Fox River watershed. The data were obtained from the Fox River Watershed Biodiversity Inventory, a collection of historic information about the natural areas in the watershed. The inventory was completed in the 1990s under the direction of Chicago Wilderness, a coalition of over 85 organizations dedicated to the survival of the natural ecosystems of the Chicago area. The Nature Conservancy made the dataset available to us. Some sites contained high quality natural communities or habitat for rare animal or plant species. Other sites were significant open spaces that contained potentially restorable natural communities, special geological or archaeological features, rare species, or large grasslands. The natural areas

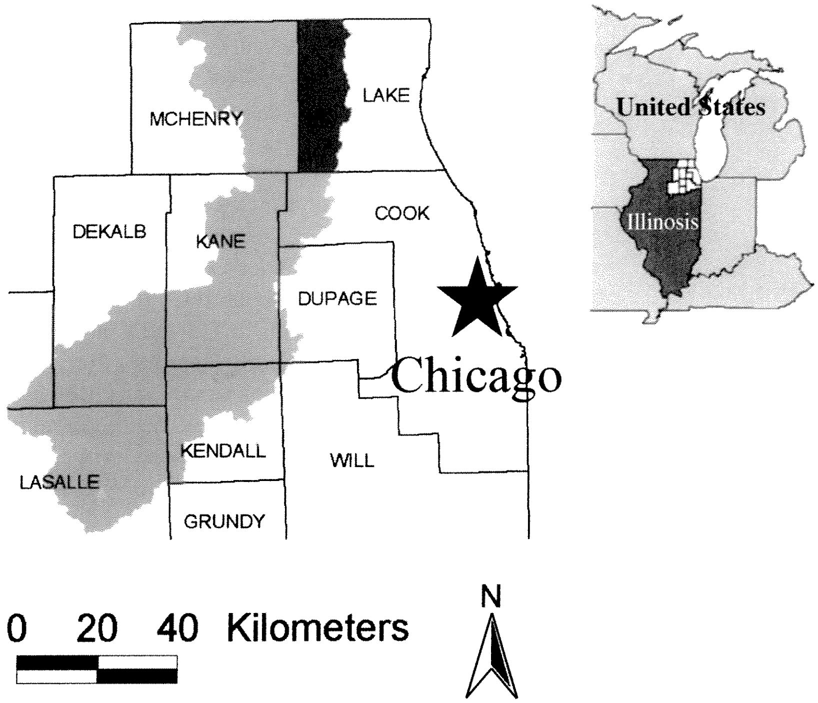

Fig. 1. Fox River watershed in counties of northeastern Illinois, USA. The analysis focused on the western portion of Lake County, north of the city of Chicago.

were 1–2400 ha in size, with median 25 ha. Collectively, the natural areas covered 7890 ha. Each site was described by a list of rare plants and animals living in the site. Collectively, 61 rare species were found in one or more of the sites. While a majority of sites contained at least one rare species, 23 of the sites contained none. At the time of our study, 17 of the 68 sites were protected public land covering 5757 ha.

Our analysis was conducted using 34 population centers in western Lake County. Each population center was an incorporated area or census designated place according to the 2000 US census. Incorporated areas were reported to the US Census Bureau as legally in existence on 1 January 2000 as cities, boroughs, towns, and villages. Census designated places represented settled concentrations of people that were identifiable by name but not legally incorporated under the laws of the state. Boundaries and census information of the population centers were obtained from the US Census Bureau's Cartographic Boundary Files web site. Collectively, the population centers held more than 200,000 people in the year 2000, with each center having 1000–30,000 people. Ignoring differences in legal definition, we refer to the 34 population centers as towns.

We wanted the distance between each town and natural area to represent the average distance a resident would travel to reach the site. A road map of the study area suggested that many towns were composed of housing subdivisions connected by major roads. While there are ways to estimate road distances between points on the plane based on the coordinates of the endpoints and the settlement pattern (Love et al., 1988; Brimberg and Love, 1995), for simplicity we used Euclidean distances to estimate travel distances. First, we projected a raster map of the study area in a geographic information system. Cells were 18 m × 18 m. Next, the Euclidean distance between each cell in the raster map and the closest cell in a given natural area was measured. Then, the distance between each town and the natural area was computed as the mean of the distance measures of all cells in the town. This procedure was repeated for each natural area. The distances between towns and natural areas ranged from 0.1 to 37.2 km with a mean of 13.9 km.

2.4. Solution method

The model specified in Eqs. (1)–(7) was solved on an IBM Pentium III laptop computer using the integrated solution package GAMS/OSL 2.25 (GAMS Development Corporation, 1990), which was designed for large and complex linear and mixed integer programming problems. Input files were created using general algebraic modeling system (GAMS), a program designed to generate data files in a format that standard optimization packages can read and process. The model was solved using a revised simplex algorithm in conjunction with a branch and bound algorithm for integer-variable problems. Both of these algorithms were part of IBMs optimization subroutine library, a FORTRAN-based subroutine library designed to solve optimization problems. Solutions to the relatively small problems were obtained in less than 5 s.

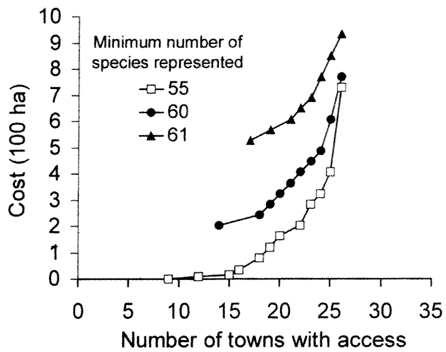

Fig. 2. Cost (expressed in ha protected) of increasing the number of towns with access to protected sites under different requirements for the number of species represented. A town had access if it had at least two protected sites within 3 km.

3. Results

In the base case, we maximized the number of towns with access to protected sites assuming that 17 of the 68 sites were already protected. A town had access if at least two sites were protected within an average travel distance of 3 km of the town. For simplicity, we assumed that the cost per unit area was the same in each site and therefore the cost of protecting a site was equal to its area. To estimate a cost curve, we solved the optimization model using upper bounds on the budget from 0 to 1000 ha. The lower bound on the number of species was 55, which was the number of species represented in the 17 already-protected sites. Under these base-case assumptions, the slope of the cost curve was flat initially and then increased rapidly (Fig. 2), indicating that incremental increases in the number of towns with access required purchasing larger numbers of sites and amounts of land. When the budget was zero, nine towns had at least two already-protected sites within the 3 km distance standard. While increasing the number of towns with access from 9 to 18 required the protection of 80 ha, increasing the number of towns with access from 18 to 26 required protecting an additional 650 ha.

To investigate the tradeoff between site accessibility and species representation, we computed cost curves with representation constraints of 60 and 61 species. Increasing the representation constraint from 55 to 61 species did not affect the shapes of the cost curves but moved them up (Fig. 2). The horizontal distance between points on the cost curves shows the tradeoff for a given budget. For example, with a budget of 200 ha, increasing the representation requirement from 55 to 60 species means that eight fewer towns have access to protected sites. In our Lake County data, six species are not represented in the 17 already-protected sites, and they are present in a small number of unprotected sites. As a result, requiring representation of more than 55 species restricts the number of sites that can be picked and reduces the number of towns that can have access to protected sites under a given budget. The maps in Fig. 3 demonstrate this tradeoff. With a representation requirement of 55 species, 12 new sites covering 200 ha are protected so that 22 towns have access to reserves. With a representation requirement of 60 species, four new sites covering 199 ha are protected so that 14 towns have access to reserves.

The vertical distance between points on the cost curves shows the additional area required to protect increasing numbers of species (Fig. 2). For example, if 24 towns are required to have access to reserves, increasing the species coverage requirement from 55 to 60 requires approximately 160 ha of additional site protection. Increasing the species coverage requirement from 60 to 61 requires approximately 280 ha of additional protection.

We were interested in the effectiveness of the 17 already-protected sites in terms of accessibility and species representation. Could we take the budget needed to purchase the 17 sites and choose a different set of sites that increased accessibility beyond the nine towns covered in the

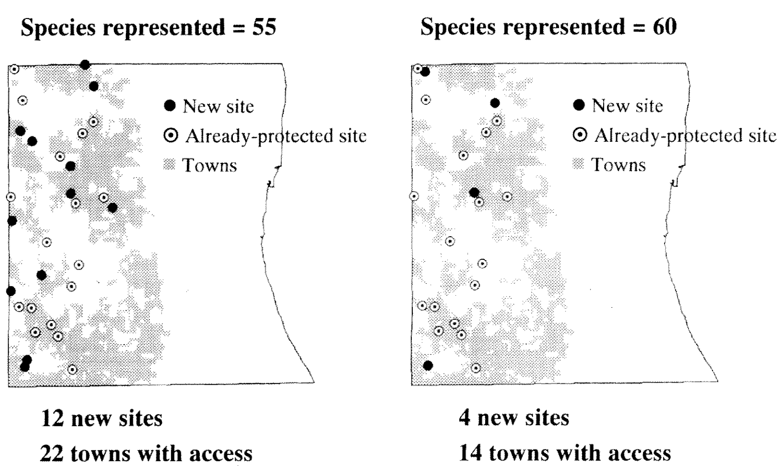

Fig. 3. Impacts of changing the species representation requirement. A town had access if it had at least two protected sites within 3 km. The budget was 200 ha.

base case while maintaining the level of species representation? The cost of the 17 protected sites in terms of area was 5757 ha. After adjusting the budget to 5757 ha, designating the protected sites as unprotected, and requiring the same level of species representation (55), we found a set of 27 sites that provided access to 26 towns, an improvement in accessibility of 17 towns compared with the base case. The 27 sites were smaller and more uniformly distributed over the study area. To see what could be accomplished in terms of species representation, we increased the representation requirement to 61 species and found a set of 24 sites that provided access to 24 towns. As a result, if we assumed that none of the 68 natural areas were protected and we had a budget to protect 5757 ha, we could acquire a set of 24 sites that provided more access and represented more species than the set of 17 currently protected sites.

To investigate the impacts of changing the definition of accessibility, we computed cost curves with different distance standards for comparison with the base case. The distance standard affected the location and slope of the cost curve (Fig. 4). When the distance standard was reduced from 3 to 1 km, the cost curve shifted to the left. In this case, each existing and potential reserve was accessible to fewer towns, and as a result, fewer towns could have access to reserves under a given budget. When the distance standard was increased from 3 to 5 km, the cost curve shifted to the right and was flatter. In this case, each site was accessible to more towns, which allowed more towns to have access under a given budget. Further, more towns could have access through the protection of smaller sites, which made the cost curve flatter. Changing the distance standard also affected the location of reserves. With a budget of 200 ha, decreasing the distance standard from 3 to 1 km resulted in the purchase of fewer sites that were less uniformly distributed in the study area (Fig. 5).

We continued the sensitivity analysis by computing cost curves with different requirements for the minimum number of sites that must be within the distance standard for a town to have access. Increasing the minimum number of sites within 3 km of a town from two (base case) to three shifted the cost curve to the left (Fig. 6). Because more sites were required for accessibility, fewer towns could have access under a given budget. Reducing the minimum number of sites from two to one shifted the cost curve to the right because more towns could have access under a given budget. Changing the minimum number of sites strongly affected the location of reserves. With a budget of 120 ha, increasing the required number of sites from one to three reduced the number of towns with access from 29 to 15 and clustered the newly protected sites around particular towns (Fig. 7).

The results were obtained with minimal computational effort. The problems described above, which involved 68 sites, 61 species, and 34 towns, were each solved in less than 5 s, and most solutions required no branch and bound nodes. When branch and bound was required, the number of nodes was less than 50.

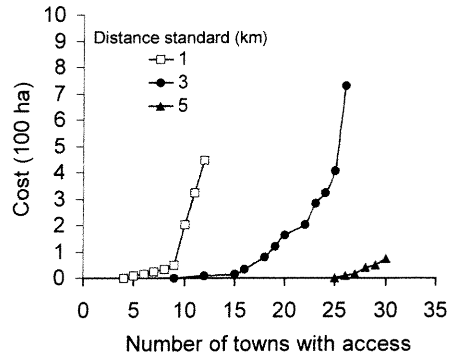

Fig. 4. Cost (expressed in ha protected) of increasing the number of towns with access to protected sites under different distance standards for defining access. A town had access if it had at least two protected sites within the distance standard. The minimum number of species represented was 55.

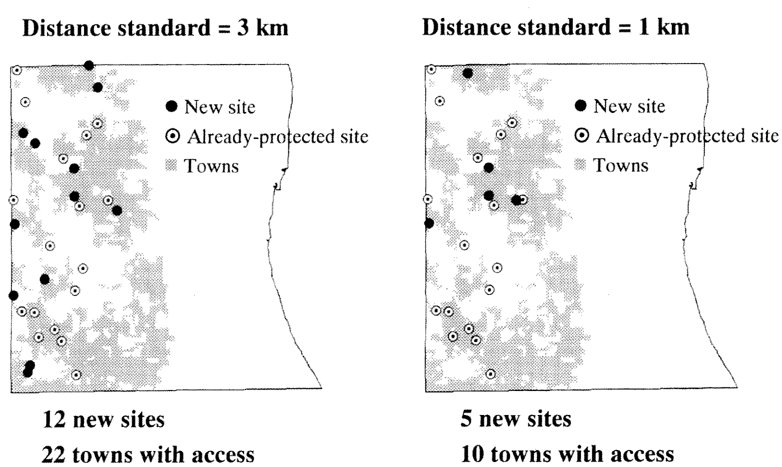

Fig. 5. Impacts of changing the distance standard in the definition of site accessibility. The number of sites required to be within the distance standard was 2 and the budget was 200 ha.

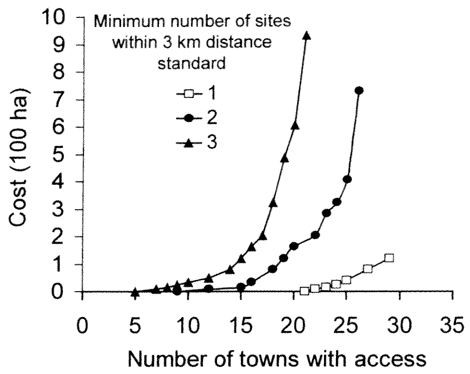

Fig. 6. Cost (expressed in ha protected) of increasing the number of towns with access to protected sites under different requirements for the minimum number of sites that must be within a 3 km distance standard. The minimum number of species represented was 55.

4. Discussion

We addressed the problem of allocating a fixed budget for open space protection among eligible natural areas with the twin objectives of maximizing public access and species representation, which are primary concerns of planners involved in metropolitan open space protection (Ruliffson et al., 2002). We demonstrated that both objectives can be incorporated in a discrete, 0–1 integer optimization model using logic from maximal covering problems in the facility location and reserve selection literature (ReVelle et al., 2002). This is important because the model can be solved using commercial software to determine the best places to allocate funds to maximize site accessibility and species representation under a given budget. Further, the model can be used to determine efficient tradeoffs between site accessibility and species representation.

We found a sharp tradeoff between site accessibility and species representation, but this tradeoff resulted from the species presence and site accessibility data used in our problem and need not always be the case. In our application, most of the species were represented in already-protected sites. Because the remaining species were present in a small number of unprotected sites, there was little flexibility in choosing sites to represent all of the species. In addition, those sites were located far from towns that did not have access to already-protected sites. As a result, when the budget was limiting, a requirement for complete species representation caused large reductions in the number of towns with access.

We found that the definition of site accessibility affected optimal reserve design. Our definition was based on average distances between towns and reserves: a town had access if a specified minimum number of reserves were protected within a specified distance from the town. In our application, increasing the distance standard increased the number of reserves that were accessible to towns, which allowed more flexibility in the selection of sites. As a result, more, smaller sites were protected with a more uniform distribution in the study area. Increasing the minimum number of sites required to be within a distance standard caused the selection of clusters of sites in the vicinity of a few towns.

Alternative measures of accessibility can easily be modeled. For example, access could be defined as a minimum area of reserves within a specified distance from a town. Then, area coefficients would weight the site selection variables x_k in constraint (2), and the parameter n in constraint (2) would represent the minimum area of reserves. Our measure of accessibility treated towns equally regardless of population size. If providing access to the greatest number of people was the objective, coefficients could be added to the objective function (1) that weighted each town by its population size. Alternatively, the parameter n for the number of sites needed for access could be dependent on town size; that is, $n_j = f(a_j)$, where a_j is the current or expected population of town j. A larger town would require more sites to be within the distance standard. Each of these changes in the measure of accessibility would likely change the optimal reserve design and cost curve. Further, additional research

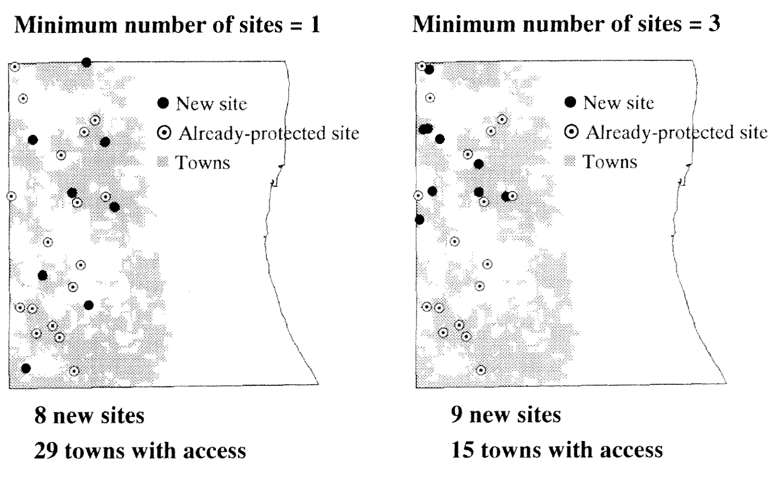

Fig. 7. Impacts of changing the minimum number of sites required to be within 3 km of a town. The budget was 120 ha and the species representation requirement was 55.

is required to investigate how these model extensions and increases in model size affect computational requirements.

We found that the set of already-protected sites was not as effective in terms of accessibility and species representation as efficient sets of sites found by the model. While this analysis showed how the model could be used to evaluate alternative sets of sites, it also helped identify practical considerations used in site selection that were not incorporated in the model. For example, a limitation of our model was the assumption that site selection and purchase is completed all at once. In practice, building a system of reserves is an incremental process that can take years to complete because owners vary in their willingness to sell property. During interviews with planners, we learned that ease of transfer of property rights strongly depends on an owner's willingness to sell (Ruliffson et al., 2002). Many times a willing seller can be found when the price is right, and some owners accept slightly lower-than-market-value prices knowing that the site will remain in its natural state in perpetuity. When owners are unwilling to sell, government agencies can in some cases use eminent domain, or a taking, to force the transfer of the property, but planners avoid this practice because of unfavorable public response.

Recognizing that there is no guarantee that a site can be successfully transferred into protected status once it is targeted, planners can still use a static site selection model to help decide which sites to pursue based on site accessibility and species representation. When a desired site cannot be purchased, sensitivity analysis can be used to determine how the objective function value will change when the unavailable site is eliminated from the set of available sites. By excluding a particular site or set of sites from the pool of eligible sites, a planner can place a value on the eliminated sites in terms of foregone site accessibility and species representation or in terms of replacement cost.

Another approach to handling the dynamic nature of planning decisions is to create a dynamic site selection model that maximizes site accessibility and species representation while accounting for uncertainty in parcel availability. Dynamic programming has been used to address this problem (Costello and Polasky, 2002), but formulations and solution algorithms are needed to make large problems tractable.

Another limitation of our model was the assumption that a species is represented if it is present in at least one protected site regardless of habitat features. For example, because the model does not quantify the biological benefits of protecting larger sites, the model will be biased toward protecting smaller, cheaper sites, which may not be very good for species conservation purposes. In practice, site selection may be based not only on species presence but also on population viability, which may depend on the amount, quality, and spatial arrangement of habitat in protected sites (Beissinger and Westphal, 1998; Kingsland, 2002). While site selection models that account for species dynamics and survival probabilities have been developed (Bevers et al., 1997; Rothley, 2002; Haight et al., 2002), more work is needed to integrate the results from those single-species conservation models into multi-objective site selection models like the one presented here.

While site selection decisions are often made within political boundaries such as a county, species and ecosystem conservation goals are often expressed within ecological boundaries such as a watershed. Because the Fox River watershed covers several counties, we are now designing a watershed-level site selection model to investigate how sharing land acquisition funds among counties affects the attainment of species representation and site accessibility goals.

Protecting open space, natural areas, and opportunities to experience them are concerns of people in metropolitan areas in the United States as demonstrated by the passage of open space protection measures and increases in government land acquisition budgets. While there is heightened demand for open space protection, planners face multiple goals and limited budgets and must make difficult choices about which sites to protect. Site selection models that include multiple objectives, such as maximizing site accessibility and species representation, can help planners clarify the impacts of their choices.

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Jane A. Ruliffson is a PhD candidate in the Department of Applied Economics at the University of Minnesota. She holds a BA in mathematics and economics from Macalester College and an MS in applied economics from the University of Minnesota. Her research interests include using mathematical models to examine the balance between wildlife conservation and recreation and open space goals in urbanizing areas.

Robert G. Haight is a Research Forester with the US Forest Service North Central Research Station and co-director of the Station's research program on Midwestern landscape change. He holds a BS in forestry from the University of California, Berkeley and a PhD in forest economics from Oregon State University. His research focuses on the evaluation of public policies for forest and wildlife conservation and the development of appropriate modeling tools.

Paul H. Gobster is a Research Social Scientist with the US Forest Service North Central Research Station in Chicago and co-director of the Station's research program on Midwestern landscape change. He holds a BS in regional analysis and leisure sciences, an MS in landscape architecture, and PhD in land resources from the University of Wisconsin. In addition to his work in landscape change, his research interests include landscape aesthetics, the social aspects of ecological restoration, and access and equity issues in urban parks.

Frances R. Homans is an Associate Professor in the Department of Applied Economics at the University of Minnesota. She holds a BA in religion from Pomona College and an MS and PhD in agricultural economics from the University of California, Davis. Her research focuses on the management of natural resource systems, including wildlife areas within urban landscapes and regulated open access resources.