Providing Equitable Spatial Distribution of Protected Natural Areas in a Metropolitan Setting: An Application of the Location Set-Covering Problem

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An emerging literature--the site selection literature--has focused on the problem of how to select natural areas to protect from development (see, e.g., Haight *et al.*2000, Polasky *et al.* 2000, Williams and Revelle 1998). This literature has endeavored to show how smart choices can be made about how to spend limited budgets while pursuing goals such as maximizing the number of animal and plant species preserved.

Much of the recent action in land preservation has taken place in metropolitan settings, however, where additional goals are likely to be just as important. Many major metropolitan areas in the United States have been experiencing very rapid growth, which has resulted in high rates of conversion of natural areas and open space in and around urban centers. Remaining undeveloped areas at the urban fringe, whether they have significant natural attributes or not, are prime candidates for development. In the Chicago region, as in other places nationwide, this rapid rate of land conversion has coincided with the passage of numerous county-level bond referenda in which funds have been raised to acquire and protect open space and natural areas. Private non-profit groups have also been active in this effort. With limited land acquisition budgets and persistent development pressure, staff must measure priorities against each other and make difficult choices about which sites to protect.

We have sought to understand the variety of goals pursued by government and private groups in the land preservation arena, with a view to formalizing their problem with a programming model. We interviewed a number of people representing a wide variety of public and private organizations that work to protect open space and natural areas in the Chicago region (Table 1). A variety of goals surfaced. Besides the fundamental goal of preserving natural areas and the biodiversity that they support, the most important objective of many land preservation planners is, arguably, site accessibility: the provision of public access for passive recreation. Groups in this region with the largest amounts of money to spend on land protection tend to be government agencies, which must argue their case to the public when persuading them to approve bond referenda. Public access is then seen to be a powerful public relations tool by the planners, because constituents can see the direct benefits of their financial contributions through their ability to use and enjoy a site. For both government and non-government groups, educational programs that teach the value of open space and natural areas also tend to be important. Therefore, providing access to areas with on-site educational opportunities serves to support their end goals as well.

Recognition of the importance of site accessibility introduces a new dimension into the programming approaches that have been used to date. In fact, the goal of acquiring land with the greatest amount of biodiversity while constrained by a limited budget would tend to be best served by choosing sites far away from cities, since land prices near urban areas are likely to be high. Also, larger sites tend to be further away from developed areas. Therefore, we choose to use what is known as the location set covering problem (Toregas and ReVelle 1973, Toregas *et al*.1971) as a basis to define our site selection problem. This framework allows us to explicitly consider the equity of site distribution to constituents by stipulating that each population center has access to a passive recreational space within a specified distance. So, while we maximize the number of species protected within a preserved network of sites purchased under a given a limited budget, we also ensure that residents have easy access to recreation sites.

Trade-offs among different levels of goal achievement are measured by looking at the difference in the number of species that can be preserved when constraint levels for access and budget are varied. We use data from the Chicago region that consists of information on the remaining natural areas as well as population centers in a part of the Fox River watershed, one that covers portions of many of the counties in a six-county region that includes and surrounds Chicago (Figures 1.1 and 1.2).

This study contributes to the natural area site selection literature by addressing trade-offs associated with the goals of preserving land in populated and growing metropolitan settings. Preservation of natural areas in these places has repeatedly been shown to be important through the passing of bond referenda and other "sprawl" initiatives in the last decade.

Model

The model we use to analyze this problem is a linear-integer programming model that is an adaptation of the Maximal Covering Problem (MCP), which maximizes the number of species protected without exceeding a land acquisition budget. It also incorporates the idea behind the Location Set Covering Problem where each city has a protected site within a certain distance. Our model, which we call the species/location covering problem (SLCP), maximizes the number of species protected while insuring that a certain number of population centers, or cities, have access to a natural area.

The objective in the model is to maximize the number of species that are protected within the chosen network of protected sites. The binary decision variable, x(j), represents the decision whether to protect site j. The budget constraint is expressed in terms of acres. We assume that every acre has the same cost; the number of acres in the site is used as a

Species/Location Covering Problem

I: set of species;
J: set of sites;
M: set of cities;
y(i): binary variable; 1 if species i is protected, 0 otherwise;
x(j): binary variable; 1 if site j is protected, 0 otherwise;
w(m): binary variable; 1 if city m has at least one protected site that is adjacent or contained site within its borders, 0 otherwise;
c(j):cost of site j in acres;
r(m, j) = 1 if site j is adjacent or at least partly contained within city m's borders, 0 otherwise;
q(i, j) = 1 if species i is present at site j, 0 otherwise;
B: land acquisition budget in acres
N: fewest number of cities to have direct access to a site;

$$\underset{x(j)}{\text{Maximize}} \quad \sum_{i \in I} y(i) \qquad \text{(Biodiversity)}$$

subject to:

$$\sum_{j \in J} c(j) \cdot x(j) \leq B \qquad \text{(Budget Constraint)}$$

$$\sum_{j \in J} r(m, j)x(j) \geq w(m) \quad \forall\, m \in M \qquad \text{(City Coverage)}$$

$$\sum_{j \in J} q(i, j)x(j) \geq y(i) \quad \forall\, i \in I \qquad \text{(Species Coverage)}$$

$$\sum_{m \in M} w(m) \geq N \qquad \text{(Accessibility Constraint)}$$

proxy for price. The sum of the acres of the protected sites must be less than or equal to a specified maximum, B. The model accounts for species coverage by summing the number of species present within the set of protected sites. If at least one of the protected sites contains a particular species, then the species is considered protected. The accessibility constraint is defined as a minimum number of cities that have direct access to a site. A site is considered to be adjacent to a city if it either shares a border with the city or is at least partially contained within the city's boundaries. A city has access if at least one of the sites adjacent to it is protected. The number of cities with access to at least one site must meet a minimum threshold, N

Data

The data consist of sets of sites and cities within the study area, and also a set of all of the species that are present within at least one site within our set of sites. The data display the presence and absence of each species at each site, as well as the adjacency information for all of the sites and cities.

The data that we used for this project come from two sources. The first is the Fox River Watershed Biodiversity Inventory (FRWBI)[1], which was a two-phase project sponsored by the Chicago Region Biodiversity Council, a collaboration of more than 100 organizations dedicated to the protection, restoration and stewardship of the natural communities of the Chicago region. According to the documentation for the FRWBI, the database is a collection of information on sites in the watershed that meet at least one of

[1] The Fox River Watershed Biodiversity Inventory was made possible through a grant from Chicago Wilderness, along with the cooperation of the following agencies: Conservation Research Institute, Forest Preserve Districts of Cook, DuPage, Lake and Kane Counties, Illinois Dept. of Natural Resources, Illinois Nature Preserves Commission, McHenry County Conservation District, St. Charles Park District, The Nature Conservancy and the U.S. Fish and Wildlife Service.

the following criteria based on the 1998 edition of the McHenry County Natural Areas Inventory:

1. All natural areas containing a minimum or better standard for quality of natural area or community, with no minimum size limits placed on area;
2. Any site containing at least one state endangered or threatened species;
3. All ecologically significant public open space areas actively or potentially restorable to natural communities;
4. Ecologically "special" areas, as determined by individual participants—examples include outstanding geological features; outstanding archaeological sites; large grasslands, even Eurasian, supporting declining prairie bird communities; heron rookeries; reptile hibernacula; areas with Federal Category 2 species not listed as E/T/W in Illinois (e.g. Blanding's turtle); Illinois watch list species locations;
5. Biological corridors linking other features entered;
6. Buffer land for protection or expansion of known natural features.

Information provided for each site included:

1. Location by township, range, and section;
2. Size (in acres);
3. Natural resources, including communities, rare plants, rare animals, and other features deemed significant;
4. Protection status;
5. Management concerns;
6. A copy of a USGS 7.5' topographic map showing the boundaries of the site. Contributors were asked to draw the boundaries of sites liberally and include all land and water deemed necessary to: a) guarantee protection of the natural feature(s) illustrated, or b) design an ecologically viable restored area. The concept of preserve design was considered an essential element of this project.

For the first phase of the project, groups in the region that had access to and specific knowledge about the sites compiled the data. The second phase entailed converting the data into a form that was usable within a geographic information system (GIS). These data then were put together on a CD-ROM for members of Chicago Wilderness, a consortium of land preservation groups, to use. The data set consists of information on all of the natural areas in the watershed that met the criteria listed above. (FRWBI)

The information about the cities and population concentrations was downloaded from the U.S. Government's Census web site. The Census categories that we used are the Incorporated Places and the Census Designated Places (CDPs). Incorporated places recognized in the 2000 Census data products are those reported to the U.S. Census Bureau as legally in existence on January 1, 2000, under the laws of their respective states, as cities, boroughs, towns, and villages, with some exceptions. CDPs are delineated to provide data for settled concentrations of population that are identifiable by name but are not legally incorporated under the laws of the state in which they are located. The boundaries usually are defined in cooperation with local officials. These boundaries, which usually coincide with visible features or the boundary of an adjacent incorporated place or other legal entity boundary, have no legal status, nor do these places have officials elected to serve traditional municipal functions. The information on the cities was obtained from the U.S. Census Bureau's Cartographic Boundary Files web site (citation). The cities' boundaries map was downloaded from the Bureau's TIGER geographic database designed for use in a Geographic Information System (GIS). We used Arc/View GIS program to project the two data sets (places and sites) to gain a spatial perspective of the problem, as well as, use the two databases together as a whole.

For our study area, we used the sites that are located within both Lake County and the Fox River Watershed (Figure 1.2) as well as the cities that are located in western Lake County (Figure 3). This area contained 68 natural area sites, 61 species and a total of 27 cities that are adjacent to at least one of the sites within the set. The natural area sites identified in the region ranged from 0.1 acres to 6063, where the largest site is already a preserved state park that contains many natural communities, rare plants and animals. The smallest site is unprotected and contains one identified high quality plant community and a handful of rare plant species. The average size natural area is 286 acres, but the median size is 65 acres. The total number of natural area acres within the study area is 19,480 acres. Seventeen of the 68 sights were already classified as protected.

Results

The model was solved on an IBM Pentium III laptop using the integrated solution package GAMS/OSL version 2.25 (GAMS Development Corporation 1990), which was designed for large and complex linear and mixed integer programming problems. The program solved the problem very quickly, (in most cases the problem was solved in well under one second) using the branch-and-bound algorithm for integer variable problems. One of the first results was that when the seventeen protected sites were already accounted for[2], 55 of the 61 species already had coverage, and that only an additional four sites would provide complete coverage for all 61 sites. To demonstrate a better range of tradeoffs, we assumed that all of the sites were unprotected. Plans for future research are to expand the study are to a much larger area in the Fox River Watershed which will allow for the reinstatement of the protected status information on the sites.

After making the assumption that none of the sites were previously protected, the model was run numerous times, first varying the budget parameter, B, in the cost constraint with no restrictions on the number of cities that required access (N = 0). The cost curve in Figure 4 shows how the number of species covered increased as the land acquisition budget was expanded. The marginal cost of covering less than 40 species is relatively low, while it increases rapidly for covering more than 40. To compare the costs of imposing the accessibility constraint, we imposed a city coverage (accessibility)

[2] This required additional constraints within the model that are not presented here.

level where sites were required to be adjacent to at least 25 cities (N = 25). Just as before, we then varied the land acquisition budget, B. Starting at 2000 acres, we increased it incrementally up to 10,000 acres. Just as with the previous problem, the cost curve started out relatively flat and increased sharply as marginal costs increased rapidly.

The horizontal distance between the two curves in Figure 4 represents the cost, in terms of reduced species coverage, of requiring 25 cities to have access to protected sites. For example, when funding allows purchase of 2,000 acres, the distance between points a and b means that 15 fewer species are covered when 25 cities are required to have access to protected sites. The impact of imposing the municipality constraint is less as the funding level increases.

Maps of the solutions represented by points b and a are presented in Figures 5 and 6, respectively. The differences in the results between solutions at a and b are that when the accessibility constraint is imposed, 1998 acres are preserved, as opposed to only 1763.3 acres when there is no constraint on the number of cities that require an adjacent site. In addition, only two sites were dropped, while thirteen new ones were gained. In essence, there is another trade-off here in that there is a loss of species protection, but a gain in the number of acres protected as well as an increase in the number of locations where protected sites occur.

Conclusions

As shown in the above example, requiring that cities have direct access to open spaces and natural areas will impose some costs in terms of species protection. There are real trade-offs between objectives and constraints, which translate into setting priorities for the network of preserved sites within a region. One purpose of our model is to provide a tool for planners to weigh the costs of pitting these goals against each other. We saw the costs in terms of species gone unprotected when accessibility became more of a priority. We could easily see the impact that increasing the budget has on the ability of planners to protect species. We could see at what level the marginal cost to protect a species begins to increase dramatically. This model could help planners set their budgets, or at least give them a tool by which they could press their case for a minimum amount.

To preserve the sensitive nature of the data, we refrained from comparing which species were not being protected or losing their protection when we provided people with easier access to a site. But a planner could easily add such weights to the different species to more clearly outline the costs of imposing such an accessibility requirement. In turn, if more importance is placed on providing better access to more people, weights representing population density could be imposed just as readily.

Further research can be naturally extended from this work. First, our interviews revealed a number of other objectives to consider and hopefully achieve, at least to some degree. Besides the human-oriented goal of accessibility to natural places, other goals relating to biodiversity have surfaced as important. Some examples of these goals are as follows: protection of examples of all of the native terrestrial communities in the area, protection of a specific site because it is a rare habitat for an endangered species or because it is an upstream site that will help preserve downstream water quality, and the requirement of large sites that provide improved habitat in that they offer seclusion from development. These goals can be included as constraints in modeling efforts.

The second extension of this research is to expand the adjacency constraint so that the minimum distance from a city to a site is greater than zero. This assumes that it is acceptable that a user from a particular city can be expected to travel a maximum distance outside city limits to reach the nearest site. This extension will allow sites in relatively undeveloped areas to be considered for acquisition within the framework of an accessibility constraint where they might not be otherwise. This may have an especially noticeable impact on acquisition choices if a different measure of cost is included in the model, primarily because lands further from developed areas tend to be cheaper in price per acre.

There are many important questions left to be examined that are particular to the problem of protecting natural areas that are in close proximity to metropolitan regions. Protecting open space, natural areas, species that live in these places, and the opportunity to use and experience them all are concerns that are on people's minds; this is being shown around the United States through heightened activity by land preservation groups, as well as increases in land acquisition budgets and the placing of open space protection measures on ballots. Site selection models like the one above can help planners make choices that are being considered in this arena. If nothing else, they can at least clarify some of their impacts.

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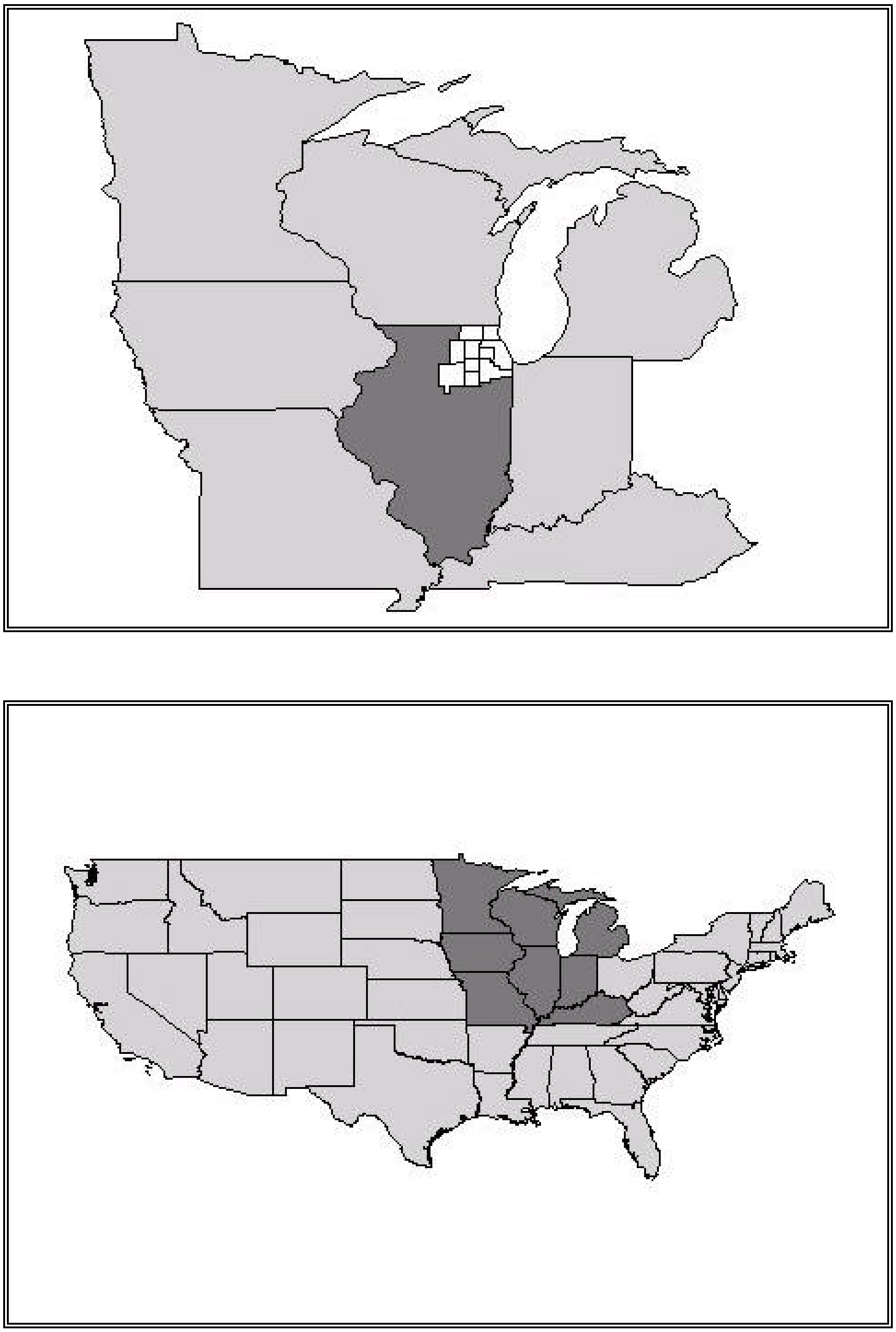

Figure 1.1. The Fox River watershed is located in the northeast corner in Illinois. It covers parts of 9 counties in Illinois.

Fox River Watershed
Northeastern Illinois

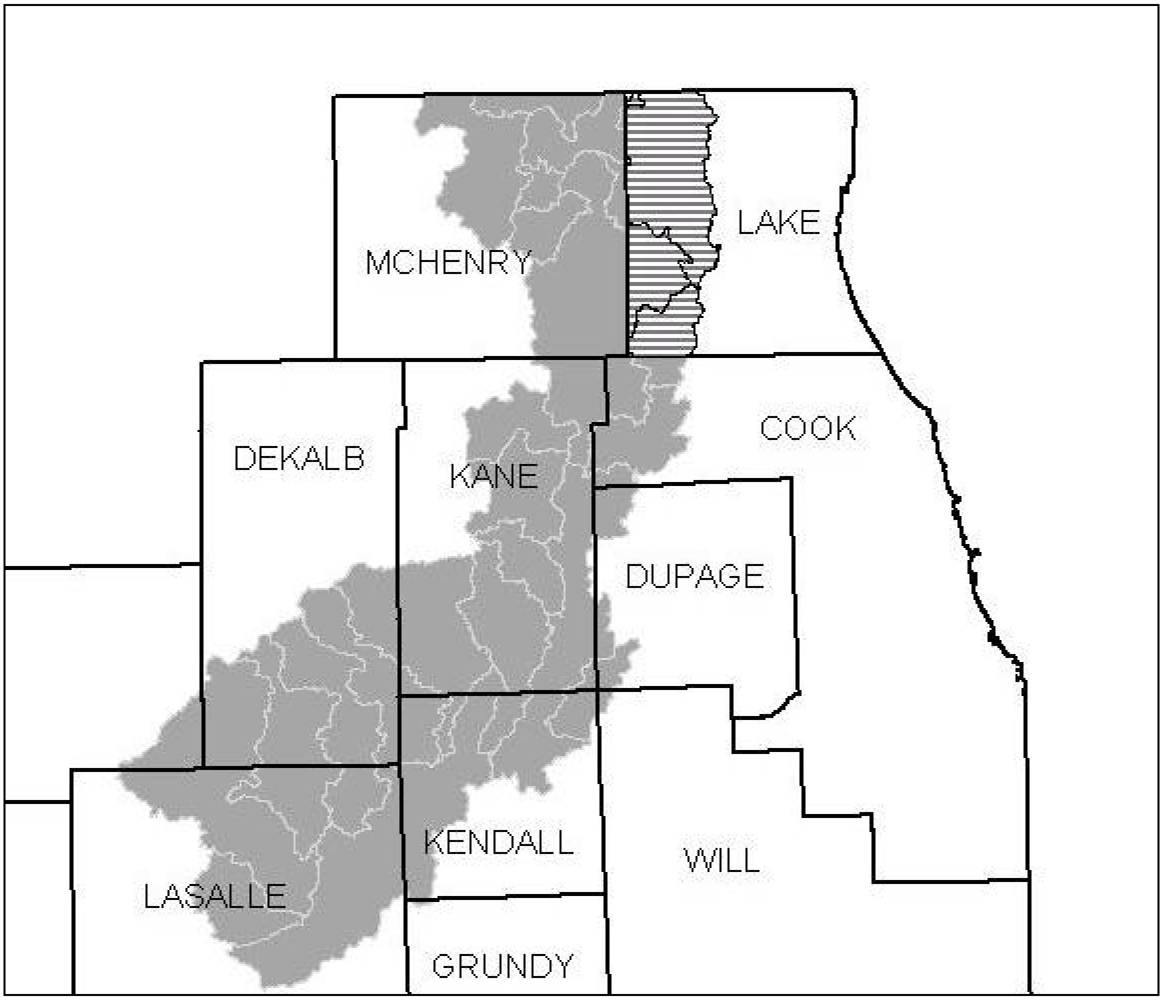

Figure 1.2 The Fox River watershed is shaded in gray. The study area for this paper is also included in the watershed but is denoted by horizontal lines in the western portion of Lake County.

Organization	Scope	Functions
Governmental Organizations		
Lake Co. Forest Preserve District	County	Planning, acquisition, management, education
Kane Co. Forest Preserve District	County	Planning, acquisition, management, education
DuPage Co. Forest Preserve District	County	Planning, acquisition, management, education
McHenry Co. Conservation District	County	Planning, acquisition, management, education
Will Co. Forest Preserve District	County	Planning, acquisition, management, education
IL Department of Natural Resources	State	Funding, planning, acquisition, management
NE IL Planning Commission	Region	Planning, coordination
Chicago Park District	City	Planning, acquisition, management
Chicago Dept. Planning & Development	City	Planning, acquisition
Non-governmental organizations		
The Nature Conservancy	Global	Planning, acquisition, management
Conservation Fund	National	Acquisition, holding, transfer
Conservation Foundation	Regional	Acquisition, holding, transfer
CorLands	Regional	Acquisition, holding, transfer
Lake Forest Open Lands Association	Township	Acquisition, management, education
Citizens for Conservation	Sub-county	Acquisition, management, education

Table 1. Structure and function of organizations involved in land protection in the Chicago region.

Natural Areas and City Boundaries
In Western Lake County, Illinois

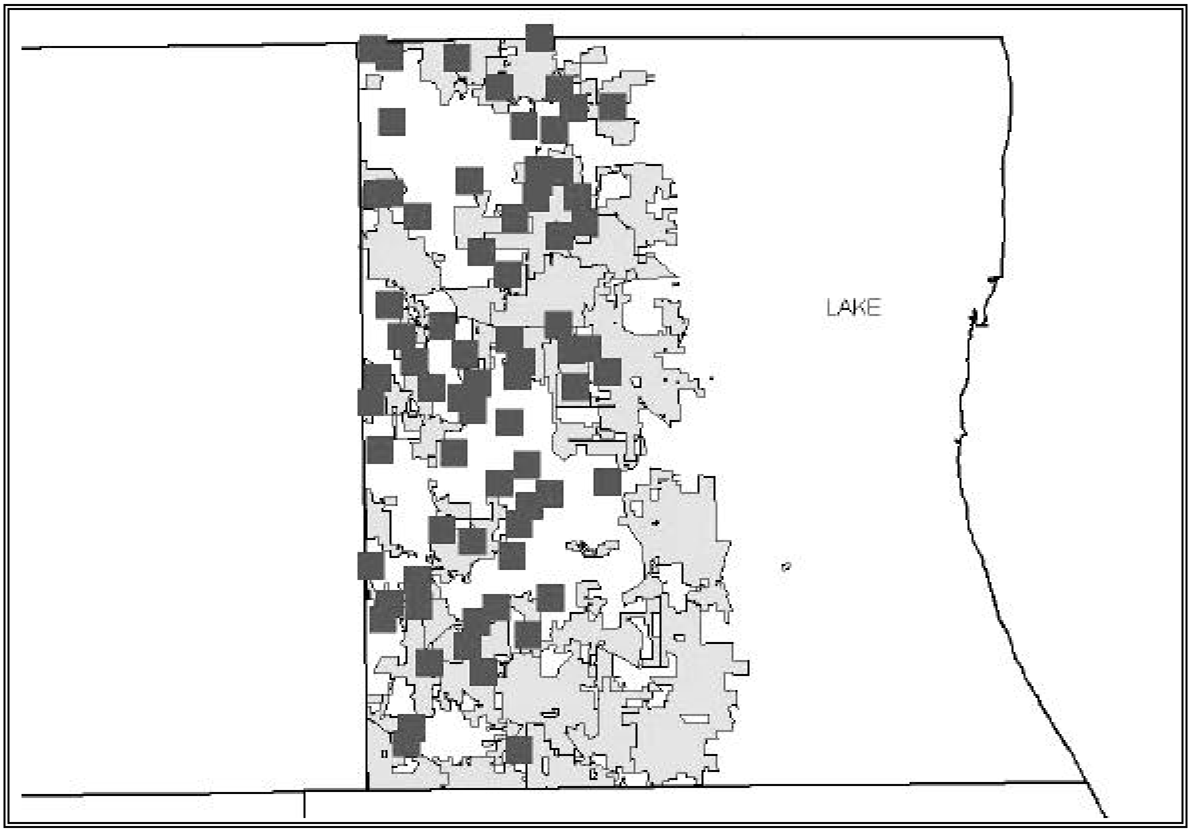

Figure 3. The sites are denoted by black squares laid over the cities, which are represented by the gray figures. The sites are presented in this manner so as to obscure the true size and exact location of each site.

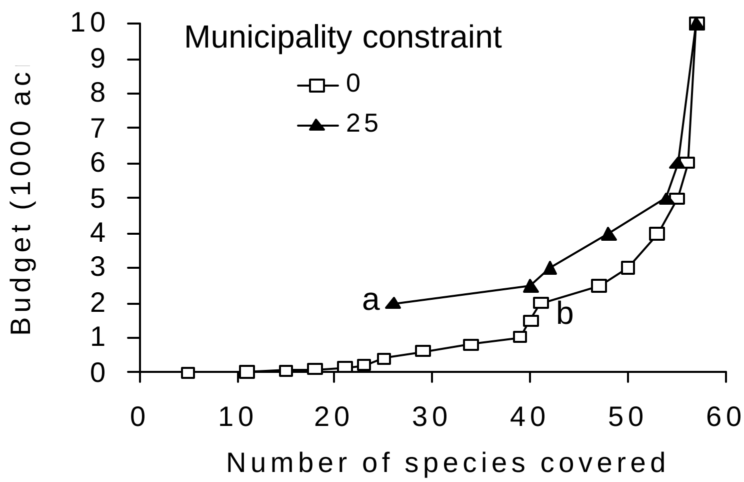

Figure 4. Cost curves showing gain in expected number of species covered for increasing funding (expressed in acres protected) under different constraints for the minimum number of municipalities with access to protected sites. The marginal cost of covering <40 species is relatively low. Marginal cost increases rapidly for covering >40 species.

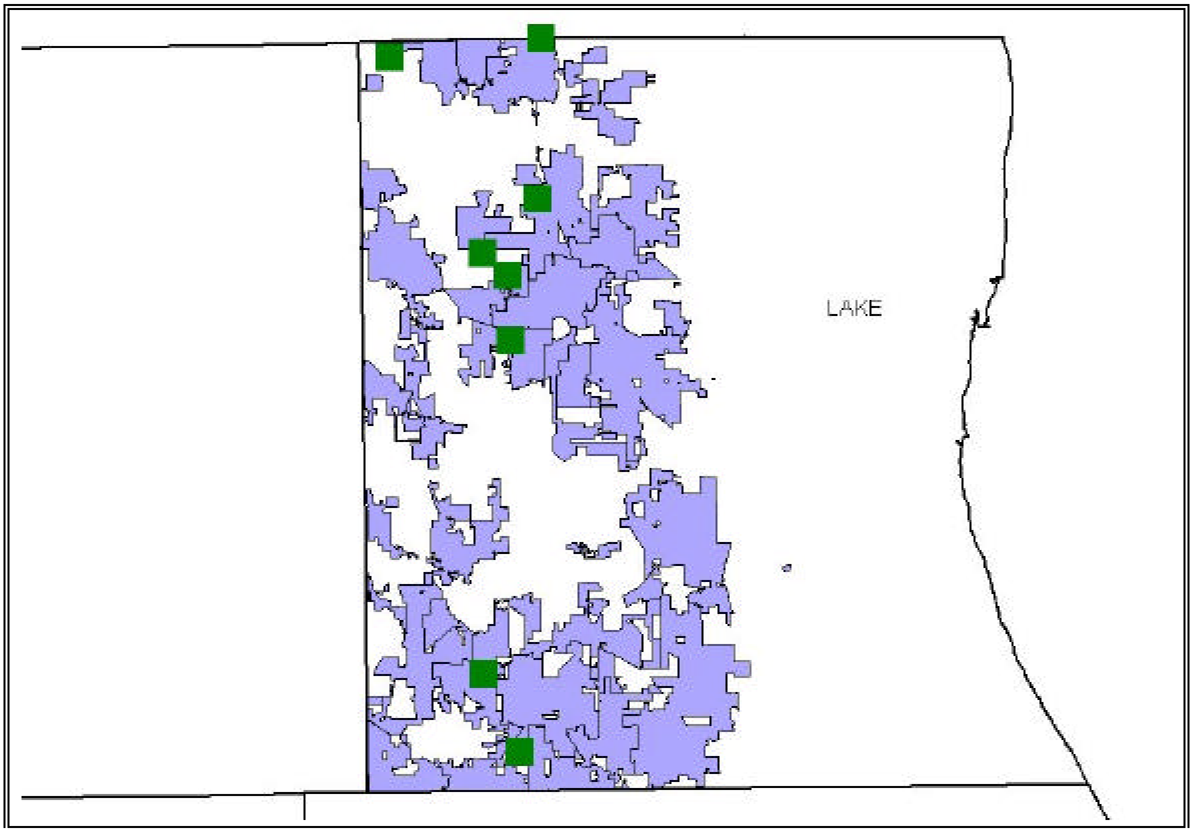

Figure 5. The dark squares represent the set of sites that were selected by the model that correspond to point b in Figure 4. There are 8 sites that protect 41 species. They are not required to be adjacent to any number of cities. Together they total 1763.3 acres.

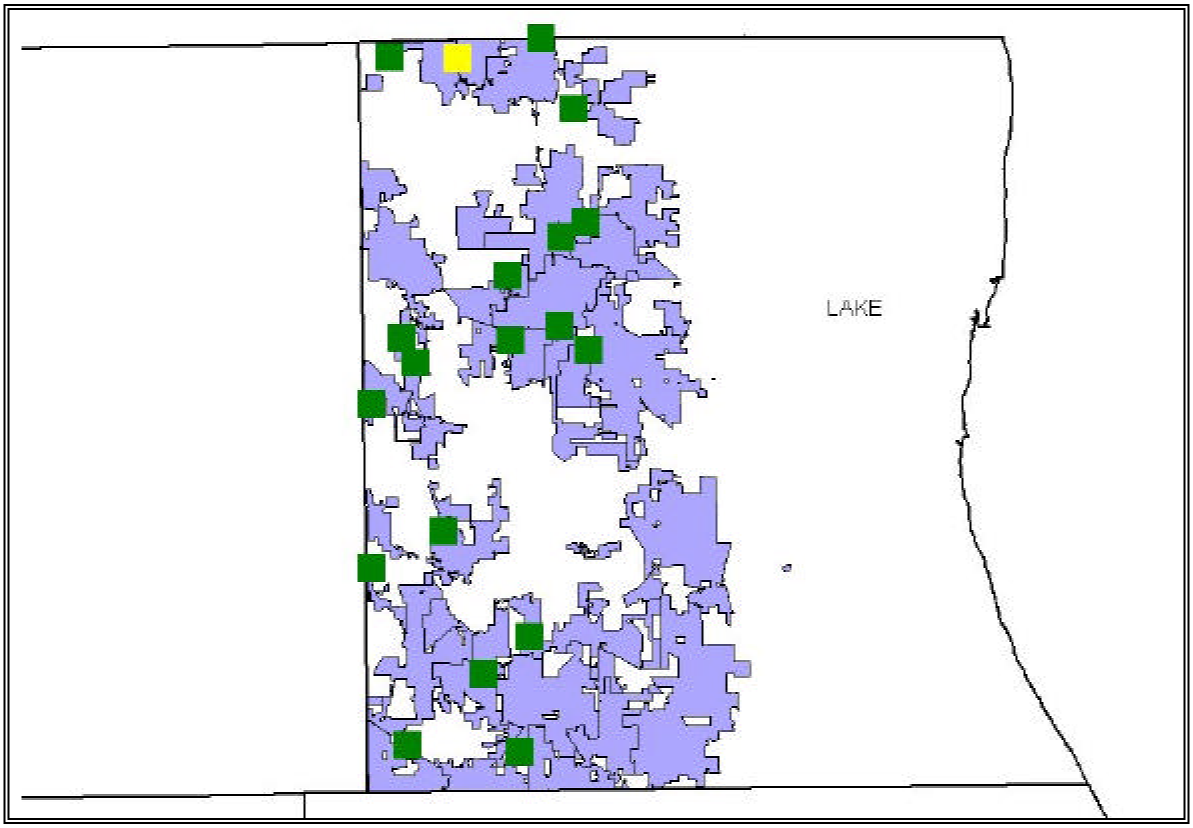

Figure 6. The green squares represent the set of sites that were selected by the model that correspond to point a in Figure 4. There are 19 sites that protect 26 species. They are required to be adjacent to 25 of cities. Together they total 1998 acres.