Reserve Selection with Minimum Contiguous Area Restrictions: An Application to Open Space Protection Planning in Suburban Chicago

Sándor F. TÓTH[1], Robert G. HAIGHT[2], Stephanie A. SNYDER[2], Sonney GEORGE[3], James R. MILLER[4], Mark S. GREGORY[5], Adam M. SKIBBE[6]

[1]Corresponding Author: College of Forest Resources, University of Washington, Box 352100, Seattle, Washington 98195 USA, E-mail: toths@u.washington.edu, Tel.: 1.206.616.2738, Fax:1.206.685.3091

[2]USDA Forest Service, Northern Research Station, 1992 Folwell Ave., St. Paul, Minnesota 55108 USA. E-mail: rhaight@fs.fed.us, stephaniesnyder@fs.fed.us

[3]School of Forest Resources, Penn State University, 203 Forest Resources Bldg.,University Park, Pennsylvania16802, USA. E-mail: sgp113@psu.edu

[4] Department of Natural Resources and Environmental Sciences, University of Illinois at Urbana-Campaign, N-407 Turner Hall, M-C 047, Urbana, Illinois 61801, USA..E-mail: jrmillr@illinois.edu

[5]Department of Natural Resource Ecology and Management, Oklahoma State University, 008C Ag Hall, Stillwater, Oklahoma 74078, USA. E-mail: mark.gregory@okstate.edu

[6]Division of Biology, Kansas State University, 116 Ackert Hall, Manhattan, Kansas 66506, USA. E-mail: askibbe@ksu.edu

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Abstract: Conservation efforts often require site or parcel selection strategies that lead to spatially cohesive reserves. Although habitat contiguity is thought to be conducive to the persistence of many sensitive species, availability of funding and suitable land may restrict the extent to which this spatial attribute can be pursued in land management or conservation. Using optimization modeling, we explore the economic and spatial tradeoffs of retaining or restoring grassland habitat in contiguous patches of various sizes near the Chicago metropolitan area. The underlying mathematical construct is the first exact, generalized formulation that directly models spatial contiguity in optimal reserve selection. The construct allows conservation planners to analyze and weigh different minimum contiguous habitat size requirements that are to be used in specific land acquisition or retention projects.

Keywords: reserve design, contiguity, urban sprawl, spatial optimization, 0-1 programming

Introduction:

Land acquisitions, conservation easements and market-based incentives are the primary tools available to community planners who want to preserve open space, critical habitat or key ecosystem functions. These options, the first two in particular, generally require a strategy to identify high-priority sites to be targeted for acquisition or retention. Finding cost-effective reserve selection strategies can be difficult, however, due to the often competing conservation goals or the complexity of ecological, operational and budgetary constraints. While it is widely recognized that the spatial features of a reserve, contiguity in particular, can be critical to a conservation effort (e.g., Williams et al., 2005 or Pressey et al., 2007), prior models that attempted to incorporate contiguity were either indirect approaches that did not warrant reserves with minimum contiguous habitat sizes, or were built on assumptions that tied them to very specific spatial configurations, such as grids, of the candidate sites. We propose a model that relaxes these assumptions and explicitly accounts for spatial contiguity in a generalized fashion. The novel mathematical construct allows decision makers to analyze the tradeoffs and costs of different contiguous habitat size requirements in conservation planning.

Why preserve urban open space? The last few decades saw a growing and increasingly wealthy population in the United States demanding larger homes on larger lots. Cheap transportation costs allowed these homes to be built further away from services and jobs. The resulting process, known as urban sprawl, not only compromises the ecological function of environmental systems but also adds pressure to a declining land-base to provide an increasing amount of timber, water, food, outdoor recreation, carbon sequestration and other competing services. According to Alig et al. (2003), 2 million hectares of nonfederal forestland, predominantly private land, were converted permanently to urban development between 1992 and 1997. The total forest loss in the United States, mostly due to urban sprawl, is projected to be about 9.3 million ha by 2050 (Alig et al., 2003). The trends affecting grasslands in North America are similar (Grassland Conservation Council of British Columbia, 2008).

Beyond the obvious but politically and culturally sensitive human population control measures or a dramatic and lasting increase in energy prices, few options are available to society to preserve urban open space and key ecosystem functions. Regulatory or market-based mechanisms to compensate landowners who choose not to develop their land but to keep producing ecosystem services are not yet widely available. The remaining alternatives, namely land acquisition or retention initiatives, often require cost-effective strategies to select sites whose characteristics or restoration potential would best serve agreed conservation goals. Selecting a set of sites from a candidate pool, however, almost always leads to a tremendous number of choices. This has given rise to the development of analytical models that have the capacity to implicitly but rigorously evaluate these choices and find optimal site selection strategies. Site selection models, most often formulated as mathematical programs, not only provide case-specific policy guidance on protection strategies, but also can be used to quantify the tradeoffs between conservation goals and reserve costs. This tradeoff information has significant value for conservation planners because it shows how much of one particular conservation goal would have to be forgone to achieve a certain improvement in another goal.

Site selection models have been used in countries around the world where biodiversity and open space 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 broadly available: e.g., Pressey et al. (1993), Margules and Pressey (2000), Kingsland (2002), and ReVelle et al. (2002). Many of the early site selection models focused on selecting sites in order to maximize species representation. One shortcoming of these models, however, is that they did not consider or account for the resulting spatial design or distribution of the protected sites. The recognition that reserves with specific spatial attributes, such as connectivity or compactness, can be conducive to the survival and well-being of many species has lead to a variety of streamlined, spatially-explicit reserve design models. The diversity of models reflects the varying spatial needs of different species that are targeted for conservation. Williams et al. (2005) provide a comprehensive survey of spatial site selection models.

Developing cost-effective, open-space acquisition strategies that satisfy specific contiguous habitat area restrictions is the subject of the present study. Although work on explicitly modeling this spatial attribute is limited, several *indirect* methods have been incorporated into exact optimization procedures. Indirect methods promote but not guarantee the protection of habitat patches that exceed minimum contiguous area thresholds. One approach is to maximize the proximity of individual reserves by minimizing either the sum of the pairwise distances between them (e.g., Önal and Briers, 2002; Snyder et al., 2007) or the sum of the distances between neighboring sites (Önal and Briers, 2005). The assumption is that reserves close together are likely to be structurally or functionally connected. A second approach is to maximize the compactness of the reserve system with the assumption that compactness promotes contiguity. Several authors noted that boundary minimization, which is the primary tool to increase compactness, can promote large contiguous reserves as long as an appropriate minimum total reserve size is specified (e.g., Fischer and Church, 2003; Önal and Briers, 2003; Tóth and McDill, 2008). A third approach is to model reserve connectivity either directly (Williams 2002; Cerdeira et al., 2005; Önal and Briers, 2006) by forcing the network to be fully connected (i.e., one can walk between any pair of protected sites without leaving the reserve) or by maximizing the number of adjacent pairs of sites in the reserve (Nalle et al., 2002), which does not guarantee full connectivity. A fourth approach utilizes core and buffer zone requirements for site selection. The model proposed by Williams and ReVelle (1996, 1998) maximizes the size of core areas that must be surrounded by buffers. In an optimal solution, the number of buffers will be minimal given the size of the core to reduce acquisition costs, which in turn leads to compactness and contiguity. Finally, Önal and Wang (2008) proposed a linear integer programming model that uses graph theoretical concepts to select a minimal subset of sites subject to species representation requirements. Reserve fragmentation is kept to a minimum by minimizing the sum of gap sites in the reserve.

The limitation of the above models is that none guarantee the protection of habitat patches whose contiguous sizes exceed predefined limits. This is a critical issue because habitat protection plans for threatened or endangered species often include guidelines for protecting contiguous habitat patches that exceed a certain size. Further, this limitation prevents the demonstration of the financial implications of purchasing sites that lead to habitat patches of increasing minimum contiguous sizes, which is useful for conservation planners to evaluate the economic cost of increasing persistence of a species at a particular location.

Another limitation of spatial reserve design models to date is that they do not consider the location and contiguity of habitat patches within the sites. Since selection units often follow ownership rather than habitat boundaries, purchasing two adjacent sites does not necessary mean that the habitat patches within these sites will also be adjacent. The model proposed in this study will address this issue.

Techniques that promote reserve contiguity have been incorporated into *ad hoc* optimization heuristics (Cerderia et al., 2005; Moilanen et al., 2005; Moilanen, 2005). Cerderia et al.'s (2005) heuristic maintains spatial connectivity and species coverage while selecting the smallest possible number of sites. Moilanen et al.'s (2005) *zonation algorithm* iteratively eliminates sites from the periphery of the candidate pool and thus maintains structural cohesion in the remaining reserve. Finally, Moilanen (2005) presents a non-linear model that indirectly promotes reserve contiguity by capturing the fact that the conservation value of a site is not limited to its internal qualities but also depends on the spatial structure of the rest of the reserve. The author achieves this by incorporating a probability function that calculates the chance of species occurrence in each potential site based on, among several other factors, the site's connectivity with areas that could also sustain and disperse viable populations of the species. The proposed model ensures proportional species coverage specifications at minimal costs. Moilanen's (2005) approach is very attractive when the habitat needs and the population dynamics of the target species are known. Again, none of these techniques warrant minimum contiguous habitat sizes. Moreover, all three methods assume a regular grid network of candidate sites and cannot guarantee finding optimal solutions.

There are two studies in which habitat area restrictions have been modeled directly and solved with exact optimization procedures. Like Moilanen (2005), Marianov et al. (2008) make use of a regular grid network of square-shaped parcels and predefine all possible spatial configurations of parcel duals and quads to represent differential habitat size needs. These duals and quads are then used in an integer programming model that ensures minimum contiguous habitat size requirements in the selected set of parcels. The limitation of this approach is obvious in situations where the parcels are irregularly shaped and dozens might be needed to form a big enough patch.

The other example in which minimum contiguous area restrictions arise is spatial forest planning. Rebain and McDill (2003a, b) develop and test an integer programming model that can help forest managers schedule harvests in such a way that mature forest patches of a minimum size and age would evolve over time and across the landscape. Their approach requires an *a priori* enumeration of contiguous clusters of harvest units whose combined area just exceed the minimum patch size. They then use these clusters to build constraints that ensure the minimum size and age requirements. The key difference between the minimum patch size problem in forest planning and the contiguity problem in reserve selection lies in the relationship between the decisions to be made on the ground and the resulting landscape. In forest planning, the primary management decision, whether to harvest a stand in a particular point in time or not, controls only the spatial age-structure of the forested landscape. Additional constraints are needed to dictate what this spatial age-structure should be like and how it should change over time. In reserve selection, the spatial attributes of the habitat patches that result from a parcel selection strategy are directly related to the selection decisions themselves. This requires a direct control mechanism between the parcel selection decisions and the spatial attributes of the resulting habitat patches.

In this study, we modify Rebain and McDill's (2003b) cluster enumeration algorithm and formulate a generalized reserve selection model that can ensure specific levels of minimum contiguous habitat sizes. We then show through a case study how the model can be used by conservation planners to formulate efficient habitat contiguity policies for suburban grasslands in the Chicago area. Finally, we discuss the potential of applying the method to other conservation projects.

Methods:

Terminology

The site selection terminology used in this study is a modified, more general version of the one introduced in Williams et al. (2005). We define *site* as a unit of land that may be selected for protection. It is usually undeveloped open space that can belong to several cover types including forest, grassland, pasture or cropland and can be spatially disjoint. We use the terms site and parcel interchangeably in this study. A *reserve* is the set of sites that has been selected for protection. Finally, a *habitat patch* is a contiguous area of habitat within a site. This terminology accounts for the possibility that sites can be spatially disjoint due to preexisting ownership structures and might not comprise solely areas of conservation interest.

Model Formulation

The proposed model is a bi-objective 0-1 mathematical program that selects a subset of habitat patches to maximize total protected habitat area while also minimizing the total acquisition or retention costs subject to minimum contiguous habitat area requirements. Habitat patches must share a common boundary to be contiguous. The model uses the concept of *cluster* from Rebain and McDill (2003b), which is defined here as a set of contiguous habitat patches whose combined area just exceeds the minimum contiguous area requirement. The model is:

$$Min \sum_{i} c_i x_i \qquad (1)$$

$$Max \sum_{i} a_i x_i \qquad (2)$$

Subject to:

$$\sum_{j \in S_i} y_j \geq x_i \qquad \text{for each } i \in I \qquad (3)$$

$$\sum_{i \in C_j} x_i \geq |C_j| y_j \qquad \text{for each } C_j \in C \qquad (4)$$

$$\sum_{i \in C_j} x_i - y_j \leq |C_j| - 1 \qquad \text{for each } C_j \in C \qquad (5)$$

$$x_i, y_j \in \{0,1\} \qquad (6)$$

where the variables are:

$x_i = 1$ if habitat patch *i* is selected, 0 otherwise;

$y_j = 1$ if cluster *j* is protected, 0 otherwise;

and the parameters are:

c_i = the cost of selecting habitat patch *i*. Coefficient c_i corresponds to the purchase price of the site that contains patch *i*. If a habitat patch is to be acquired, the full price of the site must be paid no matter how small the patch is within the site. However, to avoid double counting the costs, only one of the habitat patches that belongs to the same site was assigned the full site acquisition cost in objective function (1).

a_i = the area of habitat patch *i*;

S_i = the set of clusters that contain habitat patch *i*;

I = the set of all habitat patches;

C_j = the set of habitat patches that compose cluster j;

$|C_j|$ = the number of habitat patches that compose cluster j; and

C = the set of all possible clusters.

Function (1) minimizes the total costs, while function (2) maximizes the total area of the habitat patches in the reserve. Specifying these two conflicting objectives allows maximum flexibility for the user to analyze and weigh the tradeoffs that are associated with different budget levels.

The constraint sets (3-5) are the heart of the model; they warrant reserves that comprise clusters of habitat patches of a minimum contiguous size. Inequality (3) says that a habitat patch can only be selected for protection if it is a member of at least one cluster that is of a minimum size and selected for protection. Inequality (4) specifies that a cluster variable (y_j) may be one only if all habitat patches that compose the cluster are selected for protection. In other words, a cluster cannot be de declared to be protected unless each habitat patch that is part of the cluster is protected. Constraint (5) works in concert with constraint (4) and forces cluster variable (y_j) to turn on if all habitat patches that compose the cluster are on. Note that constraint (4), if alone, would allow y_j to remain 0 even if all the variables associated with the habitat patches in C_j were on. While a failure to recognize that cluster *j* is protected in such cases does not interfere with the proper functioning of the model (i.e., it only means that cluster *j* shares its patches with other clusters that were found via constraint (3)) , constraint (5) was retained as it restricts the feasible set of solutions that need to be evaluated during optimization. This in turn could lead to better computational performance.

Constraint set (6) defines the habitat patch and the cluster variables as binary. We note that this restriction on the x_i variables can be relaxed to continuous [0,1] bounds as equations (2), (3) and (4) already enforce integrality. Replacing the explicit binary restrictions with the bounds might improve the computational performance of the model.

Finally, if a site includes multiple, disjoint habitat patches, as is the case in the pilot study that follows, the following logical constraints must be added to the model:

$$x_n - x_m = 0 \quad \text{for } \forall\, n, m\ (n \neq m) \text{ that belong to the same parcel} \qquad (7)$$

Constraint (7) states that a habitat patch *n* can be acquired only if all other patches that belong to the same parcel are also acquired. An alternative, more elegant way to state this logical condition is the following:

$$\sum_{n \in P_u} x_n = |P_u| z_u \qquad \text{for each } u \in U \qquad (8)$$

where $z_u \in \{0,1\}$ is a variable that represents the decision whether parcel u should be purchased or not, P_u denotes the set of habitat patches that belong to parcel u and U is the set of available parcels. The advantage of the latter construct is that only one constraint of type (8) is needed for each parcel that contain multiple, disjoint patches, whereas in (7) one constraint must be written for each pair of patches that exist in each parcel. The disadvantage of construct (8) is that one parcel variable (z_u) must be added for each parcel that contains multiple habitat patches. The tradeoff is between the number of variables and constraints that are required by the two methods.

The modified cluster enumeration algorithm

The formulation of the proposed optimization model requires the generation of set *C*. Since enumerating all clusters of habitat patches whose combined area just exceeds the minimum contiguous habitat size might be computationally expensive, the use of an efficient algorithm is critical. We modified Rebain and McDill's (2003b) cluster enumeration algorithm with the intent to make it computationally more efficient. The key difference between the two algorithms is that ours, starting from a specific habitat patch, builds each feasible habitat cluster of 2-patches first. Only then does it move to the 3-patch level and keeps processing until no further patch additions are necessary to generate feasible clusters. The original Rebain and McDill (2003b) algorithm on the other hand, starts with one patch and keeps adding adjacent patches until the combined area of the patch aggregation becomes feasible. Then it backtracks by removing the last patch from the group and adds another one to evaluate a new cluster for feasibility. In sum, the difference is in the way the two algorithms explore the search tree of possible clusters.

The Case Study

We applied the model to a parcel network that contains patches of grassland habitat and potentially restorable grasslands in Kane County, Illinois (Figure 1). The parcels are located on the western edge of the Chicago metropolitan area and are under pressure of real-estate development. The gray patches (polygons) on the state map (upper right corner of Figure 1) represent municipal areas. The location of Kane County in relation to urban Chicago is indicated by a small rectangle with black boundaries on Figure 1.

We used existing GIS coverages (as described in Snyder et al., 2007) to identify parcels and habitat patches within parcels. Each parcel represents an individual ownership that is potentially available for acquisition. Habitat patches are existing and restorable grasslands found within the parcels. Existing and restorable grasslands can provide habitat for several sensitive birds such as the Henslow's Sparrow (*Ammodramus henslowii*), the Upland Sandpiper (*Bartramia longicauda*) and the Eastern Meadowlark (*Sturnella magna*). These birds are grassland obligates that lived in tallgrass prairie that once covered more than half of Kane County (Kilburn, 1959). Much of the prairie had been converted to agricultural land, however, due to the rich soils. Although most of the obligate grassland species have been able to persist in large patches of cultivated grasslands such as hayfields (Miller, 2006), these habitats are often designated as “high-risk” today due to ongoing development pressures that result from the growing Chicago metropolitan area (Openlands Project, 1999).

The silver lining of urbanization is a greater support among voters for land protection and a greater tax base to fund local conservation efforts (Trust for Public Land and Land Trust Alliance, 2004). The primary player in open space protection in Kane County is the Forest Preserve District, which owns 6,934 ha of land (5.1% of the area of Kane County) and is actively pursuing further acquisitions. The District is also committed to restoring agricultural land to natural prairie habitat. "The primary purpose of forest preserves is to protect plant and animal life so that present and future generations can enjoy their wonders," says the mission statement of the District on their website (http://www.kaneforest.com).

/Figure 1/

We analyze habitat acquisition and restoration strategies in Kane County based on the needs of grassland birds, which are some of the most visible and popular elements of the grassland fauna. They are also vulnerable as the Biodiversity Recovery Plan of the Chicago Wilderness consortium lists most grassland birds found in the region as globally critical or important (http://www.chicagowilderness.org/). As it has been pointed out earlier, a common structural feature of grassland habitat in the Midwest is its extensive spatial fragmentation. Habitat contiguity is therefore one of the most pressing needs for birds that have evolved to survive on once vast tracts of prairie. It is documented that the likelihood of occurrence as well as nest success among these birds increases with larger habitat fragments (Herkert et al., 1996). While there is a general agreement that the protection and restoration of large contiguous patches of grassland habitat should be a strategic priority for conservation planners (Snyder et al., 2007), it is not clear what contiguity thresholds should be used. Herkert et al. (1996) cite a 10-100 ha patch size range as a minimum for most grassland birds but note that a few larger species would need at least 200 ha. Herkert and his colleagues (1996) also point out that the actual area required by many species at a particular location depends on the broader land use context as well. If the overall grassland cover in the surrounding area is substantial, then smaller individual patches might be adequate. However, if the general grassland availability is minimal, then larger patches will be required. There is also some evidence that nest success is lower on smaller prairie fragments due to higher levels of nest predation and parasitism (Nelson and Duebbert, 1974; Johnson and Temple, 1986, 1990). Patches above 1,000 ha seem to offer more protection than patches below 100 ha (Herkert et al., 2003). Finally, there are a few grassland birds, such as the Western Meadowlark (*Sturnella neglecta)* that were found to be insensitive to patch size (Davis, 2004). It is obvious that a single contiguous habitat size rule to enhance grassland bird persistence is unrealistic. Planners would greatly benefit from an analytical tool that can provide them with information on how sensitive acquisition costs and other conservation criteria, such as total reserve size, are to different levels of contiguous habitat size requirements. What would the extra cost be to purchase a set of parcels that form patches of grassland habitat with each at least 200 ha in size versus buying a set with at least 100 ha minimum patch size? If there is a budget restriction, would the overall size of the reserve be compromised due to doubling the minimum patch size requirement? If it would, how much total area would have to be forgone? The case study demonstrates how the proposed model can help analysts answer these types of questions. The following steps were taken to develop the dataset for the case study, and formulate and run the optimization model.

1.) Identify Sites: Given recommendations that new acquisitions and the associated restoration efforts are more beneficial to grassland birds if they are done in the neighborhood of already existing preserves (Johnson and Igl, 2001), we chose the 409.1 ha Dick Young Forest Preserve in southeastern Kane County as the core for our site selection model (Figure 1). The first step was to identify a set of sites in the vicinity of the Preserve that contained suitable habitat. This was done by eliminating all parcels from the analysis that were either more than 6 km away from the center of the Preserve, or were classified as residential, commercial or industrial, or were entirely wooded (Figure 1). After Herkert et al. (1996), pastures and hayfields were considered suitable. Row crops were also included in the analysis as there is evidence that they can be restored, at an extra cost, to suitable habitat (Snyder et al., 2007). This classification resulted in a total of 1,136 sites (6,095.9 ha) eligible for new purchases.

2.) Identify habitat patches within sites: Since not all sites are comprised solely of suitable or restorable habitat, the effective habitat patches had to be delineated within the sites. After accounting for 50 m wide buffers between the effective and unsuitable habitats (Figure 2), we delineated 996 habitat patches totaling 4,172.4 ha. The buffers served to eliminate the negative edge effects that are of concern for some of the grassland birds (Forman et al., 2002).

3.) Eliminate habitat patches < 5ha: To minimize the anticipated computational expense of enumerating clusters and solving the optimization model, we eliminated all suitable or restorable habitat patches that were less than 5 ha. The resulting 233 polygons summed to 3,445.7 ha (Figure 1).

/Figure 2/

4.) Create adjacency matrix for habitat patches: An adjacency matrix listing all pairs of habitat patches that shared a common boundary served as input for the cluster enumeration algorithm. Although adjacency can also be defined based on proximity, we used shared boundaries for simplicity and illustration purposes. To account for the preexisting Dick Young Forest Preserve, we instructed the cluster enumeration algorithm to list all habitat patches adjacent to the Preserve as a feasible clusters if the combined area of the core and the patch exceeded the minimum contiguity threshold. In the optimization model, we designated a dummy habitat patch variable for the core and fixed its value to one implying that the core is already purchased. We accounted for the core in the objective functions with a zero acquisition cost and a zero area coefficient. If the planning analyst wants to discourage the selection of habitat clusters near the core, perhaps in an effort to establish new core areas as a means of promoting persistence, the core would have to be removed from both the formulation and the cluster enumeration process.

/Table 1/

5.) Run cluster enumeration algorithm: We ran the cluster enumeration algorithm for ten different contiguity thresholds: 100, 120, 150, 200, 250, 300, 350, 400, 450 and 500 ha (Table 1). The goal was to evaluate the financial and spatial tradeoffs that were associated with these hypothetical minimum contiguous habitat size policies. The algorithm yielded the highest number of clusters for the 200 ha limit (second column from the left in Table 1) but the number of clusters dropped rapidly as the size limit was set to be lower or higher than 200 ha. In general, as the threshold is raised, an increasing number of patch combinations are possible to form feasible clusters. However, the spatial configuration of the sites limited the extent to which the contiguity threshold could be raised: the largest possible contiguous habitat cluster in the test area was 544 ha.

6.) Calculate cost coefficients: The cost coefficients of the proposed 0-1 program were calculated based on the sums of the estimated property values in the south central section of the county (US$98,800 per ha) and averaged estimates of restoration costs (US$4,133 per ha for sites of “row crop” designation and US$2,066 per ha for mixed agriculture and grassland designations). The restoration costs were obtained from two firms that specialize in prairie restoration projects in the Midwest (Snyder et al., 2007). The restoration cost of the habitat patches within each site was based on the total habitat area and land use (e.g., row crop or mixed agriculture) of the site.

7.) Formulate model: We used custom computer programming code to formulate the optimization models populated with data that was generated in steps 1-6. Table 1 provides information about the size of the resulting 0-1 programs in terms of the number of variables and constraints.

8.) Solve model: The ten models, corresponding to the ten contiguity settings and a US$49-50 million budget range, were solved to optimality using a combination of commercial solvers and multi-objective mathematical programming techniques. The total available expenditures were defined based on the funding levels raised by the Forest Preserve District of Kane County for new land acquisitions through referenda and grants (Snyder et al., 2007). A multi-objective optimization technique, the Alpha-Delta Algorithm (Tóth et al., 2006), was used to enumerate all habitat selection strategies within the US$49-50 million budget range and subject to each of the ten contiguity thresholds. Each alternative strategy found by the algorithm was *Pareto-optimal* with respect to the dual objectives of reserve area maximization and cost minimization. A habitat selection strategy is Pareto-optimal (Pareto, 1909) or *non-dominated* in the context of this bi-objective optimization model if no other strategy is available that would improve at least one of the two objectives without compromising the other.

The Alpha-Delta Algorithm was designed to solve multi-objective optimization problems, where the available decision alternatives are discrete. In the case of reserve selection problems, "discrete" refers to the fact that conservation agencies, such as the Forest Preserve District, can either purchase a site in its entirety or not. Fractional parcel purchases are not possible. The algorithm first finds the best site selection strategy by calling a commercial solver (4-thread parallel solver, CPLEX 11.0, ILOG, 2007) that solves the optimization problem given the maximum, US$50 million budget. The algorithm then identifies the rest of the compromise site selections between the preset bounds of US$49 and 50 million by sequentially constraining the budget levels and calling CPLEX 11.0 repeatedly. The goal was to find multiple solutions at each contiguity threshold that differ in total acquisition costs. For example, a conservation organization might want to know how much less total area can be protected at a given contiguity threshold, say at 100 ha, if they wish to spend US$1 million less on new acquisitions. The mechanics of the Alpha-Delta Algorithm is described in Tóth et al. (2006): there are two parameters, alpha and delta, which were set to 1 degree and US$1, respectively. These settings ensured that all alternative site selections were found between the US$49 and 50 million budgets that are more than US$1 apart from one another in terms of acquisition costs.

We sought to demonstrate the exact nature of the tradeoffs between total land area purchased and acquisition cost for ten different levels of the minimum patch size requirement.

Results and Discussion:

The results of the case study are summarized in Figure 3 and Table 2. The diagram in the center of Figure 3 illustrates how the size of the new acquisitions is traded off against acquisition costs and minimum patch size requirements. Each point in the chart, indicated by diamonds or squares, represents a Pareto-optimal reserve selection strategy and corresponds to one entry in Table 2. The parcel selections that are associated with the same minimum contiguity threshold are connected by lines. Solutions do not exist on the lines between adjacent points. The resulting curves form the so-called *efficient* or production possibilities frontiers that visualize the tradeoffs between acquisition costs and total reserve size as a function of contiguity thresholds. These non-contiguous curves bear a unique significance for conservation planners: each separate the region where dominated site selections might exist from the region where no solutions exist. Clearly, site selections above the curves would be of no interest to decision makers because at least one of the solutions on the curves offers better achievements in terms of both objectives.

The most important result is that there is hardly any tradeoff between the minimum contiguity requirements in the 100-350 ha range and the total size of the reserve. More than tripling the contiguity threshold would only result in a roughly 10 ha (~2%) loss in total protected area (Table 2). There are no tradeoffs at all among the 250, 300 and 350 ha thresholds as the Pareto-optimal site selections are identical in the US$49-50 million budget range. In other words, if a 250 ha minimum patch size is specified, the optimal parcel selections will provide effective habitat patches that are already more than 350 ha in size. The acquisition cost savings and gains in total reserve sizes are minimal even when the minimum patch size requirement is reduced to 200 ha. The efficient frontiers that correspond to the 200 vs. the 250-350 ha thresholds are essentially identical.

/Figure 3/

A relatively large jump occurs in total new reserve size (5-8 ha) and acquisition cost savings (roughly US$500,000-800,000) when the minimum patch size requirements are lowered from the 200 ha to the 100-150 ha level (Figure 3). Looking at the maps that illustrate some of the solutions in the 100, 120 and 150 ha range (Parcel Selections 3, 4 and 5) versus the ones that correspond to the 200-350 ha range (Parcel Selections 1 and 2), and analyzing Table 2, one could speculate that the stricter contiguity requirements allow only two patches (rarely three) to be acquired where three or four patches are possible if the size requirements are lowered to the 100-150 ha range.

The vertical spacing of the frontiers for the 100, 120 and 150 ha minimum patch sizes implies that moving from 100 to 150 ha costs only US$200,000 on average or less (0.4% of the total budget) in terms of acquisition and restoration expenditures. By looking at the horizontal spacing of the three curves, one can also observe that the same change in contiguity policy would lead to a minute 3-4 ha loss in the total area of new acquisitions.

Site selections subject to the 400, 450 and 500 ha contiguity thresholds (shown on the small sub-diagram on the lower left of the main chart area) were only possible by acquiring habitat patches next to the core (see the map of Parcel Selection 6 on the lower left of Figure 3). This is because all potential contiguous habitat aggregations that are independent of the core, are smaller than 400 ha. Consequently, only very few new parcels need to be acquired if the minimum patch size is set to 400-500 ha no matter how much funding is available. The leftover budget can, of course, be used to purchase additional parcels with the caveat that none will allow habitat patches that are larger than 400 ha. After instructing the optimization model to build patches that are at least 200, 250, 300 or 350 ha in size while retaining the now >500 ha core, we found that the best option is to purchase 12 extra parcels that form 295.6 ha of contiguous grassland habitat independent of the core. This 430.6 ha new acquisition would cost the District US$49.94 million. Compared to Parcel Selection 1 (Figure 3), where a 489.9 and a 379.8 ha patch can be protected for roughly the same price (US$49.91M), this choice would mean a loss of 30 ha in total new reserve area. It is up to the District to decide if having a 544.1 ha instead of a 489.9 ha patch is worth the loss in total area or the loss in the size of the second patch.

/Table 2/

In addition to reserve sizes and acquisition costs, Table 2 provides information about the patch size distributions that are associated with each Pareto-optimal parcel selection strategy. It is notable that while three or even four contiguous patches are the norm for the 100-150 ha series, only two or maximum three patches are possible for the 200-350 ha contiguity settings. This could be viewed as the fragmentation effect of looser contiguity policies because the total reserve sizes are roughly the same in both groups. The relative rigidity and irregularity of the individual patch sizes are the result of the discrete nature of the site selection problem.

Finally, Figure 3 reveals that some of the patches have irregular shapes and potentially high perimeter-area ratios. There is evidence that the relative amount of edge versus interior habitat in a landscape might be a better predictor of occurrence of some grasslands birds than total contiguous habitat area alone (Helzer and Jelinsky, 1999; Davis, 2004). Optimization modeling techniques, developed to allow natural resource analysts to control the shape of habitat patches in conservation and forest planning (Fischer and Church, 2003 and Tóth and McDill, 2008), can easily be incorporated in the proposed model to ensure lower perimeter-area ratios. For an analysis on how much compactness of old forest habitat patches might cost to forest managers, see Tóth and McDill (2008).

The management implications of the above results for the Forest Preserve District of Kane County are clear. If it is known that more is better for grassland birds in terms of contiguous habitat size, then it might make sense to consider a 150 ha requirement versus a 100 ha one, or a 350 ha versus a 200 ha one because the associated extra acquisition costs or losses in total reserve size are minimal. There is an 8-10 ha loss in total reserve size when a 200-350 ha policy is followed instead of a 100-150 ha policy. A 30 ha loss in total reserve size must be accepted if the District wants at least one patch to be larger than 500 ha. These are helpful recommendations for a conservation planner if the wildlife biological investigations that consider grassland bird reproduction and dispersal success as a function of contiguous habitat size are inconclusive. Additional, potentially expensive, biological experiments to determine whether a species disperses better on contiguous habitat patches that are larger than 150 ha versus 100 ha might not be necessary if there are no extra costs associated with moving from a 100 ha to a 150 ha rule.

While the management implications of this particular case study are clear, none of these can be generalized to other conservation projects. The spatial arrangement and the size or shape of the parcels or the effective habitat patches might be very different even in nearby areas. Land prices and restoration costs might be different, as well as the contiguity requirements of the target species. A rigorous analytical tool, such as the one proposed in this paper, is needed to identify cost-efficient opportunities to preserve reserves with spatial attributes that are as conducive to the survival of certain species or ecosystems as possible.

Grassland birds in the American Midwest are not the only sensitive species that suffer if large contiguous patches of suitable habitat are unavailable. Fragmentation of open space, especially near urban centers, is a global problem. As an example, the Northern Spotted Owl (*Strix occidentalis caurina*) in the Pacific Northwest prefers interior old-forest habitat in large patches surrounded by edges that provide habitat for its prey. The financial ramifications of implementing forest management plans that ensure such habitat structures are forgone timber revenues. The biological conservation implications of the study presented in this paper is that opportunities might exist in the course of a site acquisition or retention effort or during forest management planning that lead to significant improvements in contiguous habitat protection at minimal costs. The proposed model can help conservation planners identify these opportunities.

Conclusion:

This article presented the first site selection model that explicitly accounts for minimum contiguous habitat size requirements regardless of the shape or the spatial configuration of the candidate sites. The model allows conservation planners to rigorously analyze and weigh the pros and cons of different minimum habitat patch size policies in open space acquisition or retention projects. A pilot application of the model to grassland conservation in the Midwestern United States clearly demonstrated that the tradeoff information provided by the approach can have a tremendous value for decision makers. In the specific example presented in this study, land acquisition expenditures as well as the total size of the potential reserves were found to be largely insensitive to broad ranges of contiguous habitat size specifications. Clearly, the management implications of this information are significant in terms of how Kane County community planners will set aside reserves in the future for grassland birds that are sensitive to habitat contiguity. The utility of the approach arises from the fact that, due to the combinatorial nature of reserve site selection problems, it is nearly impossible to foresee what the tradeoffs or costs of different habitat size specifications would be with respect to a variety of conservation criteria at a particular site.

The limitation of the method is its potentially high computational cost. Both the formulation of the model, which requires a specialized recursive enumeration, and the solution procedure can entail substantial computing times. The computational expense of the cluster enumeration effort primarily depends on the number, spatial connectivity and average size of the candidate habitat patches relative to the contiguity threshold. The more connected and more numerous the patches are and the greater the contiguity threshold is relative to the size of the patches, the more effort is needed to enumerate the clusters. The computational boundaries, in turn, limit the spatial and temporal scale at which the proposed method can be applied today. Ongoing dramatic improvements in computational power and optimization technology, however, suggest that the future role of combinatorial optimization models in conservation planning will likely become more significant than it is today.

Finally, the model presented in this paper is static in a sense that it assumes that land prices do not change over time or as a result of conservation purchases. This assumption might not hold if the availability of open space for conservation or real estate development is limited and yet the demand is high for these uses (Polasky, 2006). Although using specialized combinatorial techniques it is possible to extend the discussed model to account for land price feedback effects, we opted not to include a dynamic version of the model in this presentation in order to retain the focus on contiguity. The development of a spatially-explicit reserve selection model with adaptive cost coefficients is the subject of ongoing research.

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ILOG S.A. 2007. ILOG CPLEX 11.0. Copyright © 1997-2007. 9 Rue de Verdun, 94253 Gentilly CEDEX, France and ILOG, Inc., 1195 W. Fremont Ave., Sunnyvale, California 94087, USA.

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Captions:

Table 1. Model size and computational expense

Table 2. Acquisition cost, total protected effective area and patch size distribution for each efficient parcel selection strategy. Each row corresponds to an optimal solution in the US$49-50 million budget range. The last three or four columns list the patch sizes that make up the solution. Note that the size of an individual patch can far exceed the contiguity threshold due the interactions between contiguity and budget specifications in the model.

Figure 1. The geographical location of the Kane County study area (source: Illinois Natural Resources Geospatial Data Clearinghouse). The gray patches (polygons) on the state map (upper right corner) represent municipal areas. The location of Kane County in relation to urban Chicago is indicated by a small rectangle with black boundaries.

Figure 2. Spatial terminology: parcels (sites), habitat patches, clusters and buffers

Figure 3. Efficient parcel selections near the Dick Young Forest Preserve using 100, 120, 150, 200, 250, 300, 350, 400, 450 and 500 ha minimum contiguous patch sizes

Table 1.

Minimum Patch Size (ha)	Number of				Solution Time (hrs)	
	Clusters	Variables (columns)	Constraints (rows)	Efficient Solutions	Total	Average
100	21,443	21,374	42,632	31	20.74	0.67
120	48,762	48,477	96,838	37	66.11	1.79
150	124,012	122,891	245,685	24	273.30	11.39
200	227,692	222,162	444,227	22	266.12	12.10
250	96,418	77,425	154,766	12	19.14	1.60
300	31,412	8,223	16,392	12	0.07	0.01
350	8,900	1,330	2,627	12	0.05	0.00*
400	141	46	82	1	0.00*	0.00*
450	284	294	578	1	0.00*	0.00*
500	490	500	990	1	0.00*	0.00*

*: Solution times were 17 seconds or less

Table 2.

Minimum Contiguous Habitat: 100ha

	Cost (US$M)	Total Area (ha)	Patch Sizes (ha) Patch1	Patch2	Patch3	Patch4
1	49.97	471.1	264.8	104.8	101.5	
2	49.88	470.9	337.4	104.8	28.7*	
3	49.84	469.9	263.6	104.8	101.5	
4	49.79	469.4	337.4	103.3	28.7*	
5	49.78	469.0	247.6	120.0	101.5	
6	49.73	468.8	262.5	104.8	101.5	
7	49.73	468.8	262.4	104.8	101.5	
8	49.72	468.7	233.7	104.8	101.5	28.7*
9	49.69	468.4	337.4	102.4	28.7*	
10	49.67	467.6	278.7	120.0	28.7*	
11	49.59	467.5	232.5	104.8	101.5	28.7*
12	49.56	466.6	337.4	100.5	28.7*	
13	49.56	466.5	337.4	100.4	28.7*	
14	49.48	466.4	231.4	104.8	101.5	28.7*
15	49.48	466.4	231.4	104.8	101.5	28.7*
16	49.46	465.2	325.3	105.9	34.0*	
17	49.40	465.1	224.7	104.8	101.5	34.0*
18	49.40	465.0	232.5	102.4	101.5	28.7*
19	49.37	464.9	247.6	115.8	101.5	
20	49.36	464.7	253.0	104.8	101.5	5.4*
21	49.28	464.2	247.6	111.8	104.8	
22	49.25	464.2	325.3	104.8	34.0*	
23	49.21	463.2	251.5	104.8	101.5	5.4*
24	49.18	463.0	322.3	106.6	34.0*	
25	49.12	462.7	337.4	120.0	5.4*	
26	49.07	462.4	323.6	104.8	34.0*	
27	49.06	462.2	278.7	120.0	63.6*	
28	49.04	462.1	255.8	104.8	101.5	
29	49.01	461.8	247.6	107.3	101.5	5.4*
30	49.01	461.6	247.6	107.2	101.5	5.4*
31	49.00	461.5	247.6	112.5	101.5	

Minimum Contiguous Habitat: 120ha

	Cost (US$M)	Total Area (ha)	Patch Sizes (ha) Patch1	Patch2	Patch3
1	49.95	469.9	337.4	132.5	
2	49.94	469.2	306.4	134.2	28.7*
3	49.87	468.5	337.4	125.7	5.4*
4	49.86	468.0	266.6	132.5	69.0*
5	49.80	468.0	278.7	125.7	63.6*
6	49.79	467.7	337.4	125.0	5.4*
7	49.70	467.5	306.4	132.5	28.7*
8	49.68	466.5	337.4	129.1	
9	49.62	466.1	306.4	125.7	34.0*
10	49.61	465.5	278.7	123.2	63.6*
11	49.60	465.4	306.4	125.0	34.0*
12	49.54	465.3	306.4	125.0	34.0*
13	49.53	465.1	306.4	130.1	28.7*
14	49.51	465.0	306.4	130.0	28.7*
15	49.49	464.9	337.4	127.4	
16	49.49	464.4	266.6	134.2	63.6*
17	49.43	464.3	337.4	121.6	5.4*
18	49.42	464.2	337.4	121.4	5.4*
19	49.42	464.1	337.4	126.7	
20	49.36	463.8	278.7	121.6	63.6*
21	49.36	463.7	278.7	121.4	63.6*
22	49.35	463.2	337.4	125.8	
23	49.32	463.1	325.3	132.5	5.4*
24	49.26	463.1	337.4	125.7	
25	49.25	462.6	266.6	132.5	63.6*
26	49.24	462.5	306.4	127.4	28.7*
27	49.24	462.4	337.4	125.0	
28	49.21	462.4	278.7	120.1	63.6*
29	49.18	462.4	337.4	125.0	
30	49.18	462.0	306.4	121.6	34.0*
31	49.17	461.8	306.4	121.4	34.0*
32	49.16	461.7	306.4	126.7	28.7*
33	49.14	461.4	323.6	132.5	5.4*
34	49.09	460.9	285.5	146.7	28.7*
35	49.08	460.9	264.8	132.5	63.6*
36	49.06	460.7	294.3	132.5	34.0*
37	49.01	460.7	306.4	125.7	28.7*

Minimum Contiguous Habitat: 150ha

	Cost (US$M)	Total Area (ha)	Patch Sizes (ha) Patch1	Patch2	Patch3
1	49.99	468.5	278.7	155.8	34.0*
2	49.92	467.5	278.7	154.8	34.0*
3	49.84	466.7	278.7	154.0	34.0*
4	49.81	466.4	278.7	159.1	28.7*
5	49.81	466.2	278.7	153.5	34.0*
6	49.80	466.0	278.7	153.3	34.0*
7	49.79	465.9	278.7	158.6	28.7*
8	49.75	465.5	278.7	158.2	28.7*
9	49.72	465.2	278.7	152.5	34.0*
10	49.66	465.0	278.7	152.3	34.0*
11	49.66	465.0	278.7	152.3	34.0*
12	49.62	464.9	278.7	157.6	28.7*
13	49.57	464.6	278.7	157.3	28.7*
14	49.44	464.0	278.7	156.7	28.7*
15	49.38	463.2	278.7	155.8	28.7*
16	49.36	462.1	266.6	161.6	34.0*
17	49.31	462.1	278.7	154.8	28.7*
18	49.23	461.4	278.7	154.0	28.7*
19	49.19	460.9	278.7	153.5	28.7*
20	49.19	460.7	278.7	153.3	28.7*
21	49.11	459.8	278.7	152.5	28.7*
22	49.05	459.7	278.7	152.3	28.7*
23	49.04	459.6	278.7	152.3	28.7*
24	49.03	458.9	278.7	151.6	28.7*

Minimum Contiguous Habitat: 200ha

	Cost (US$M)	Total Area (ha)	Patch Sizes (ha) Patch1	Patch2	Patch3
1	50.00	460.8	254.5	206.4	
2	49.99	460.7	254.5	206.2	
3	49.91	460.6	379.8	80.8*	
4	49.88	460.0	247.6	207.1	5.4*
5	49.86	459.9	247.6	206.9	5.4*
6	49.83	459.8	247.6	206.9	5.4*
7	49.78	459.4	364.6	94.7*	
8	49.71	459.3	247.6	206.4	5.4*
9	49.70	459.2	247.6	206.2	5.4*
10	49.65	458.7	247.6	211.1	
11	49.53	457.8	376.9	80.8*	
12	49.49	456.5	247.6	203.6	5.4*
13	49.45	456.2	247.6	208.6	
14	49.44	456.1	224.7	202.7	28.7*
15	49.40	455.7	253.0	202.7	
16	49.29	455.7	247.6	202.7	5.4*
17	49.24	454.7	247.6	201.8	5.4*
18	49.22	454.4	247.6	206.9	
19	49.20	454.2	385.2	69.0*	
20	49.09	454.0	247.6	206.4	
21	49.08	453.8	247.6	206.2	
22	49.01	453.8	372.9	80.8*	

Min. Contig. Habitat: 250-300-350ha

	Cost (US$M)	Total Area (ha)	Patch Sizes (ha) Patch1	Patch2	Patch3
1	49.91	460.6	379.8	80.8*	
2	49.85	459.8	371.5	88.3*	
3	49.78	459.4	364.6	94.7*	
4	49.73	459.2	378.3	80.8*	
5	49.67	458.3	370.0	88.3*	
6	49.53	457.8	376.9	80.8*	
7	49.45	455.8	372.9	82.9*	
8	49.30	455.3	379.8	75.5*	
9	49.24	454.4	371.5	82.9*	
10	49.20	454.2	385.2	69.0*	
11	49.12	453.8	378.3	75.5*	
12	49.01	453.8	372.9	80.8*	

Min. Contig. Habitat: 400-450-500ha

	Cost (US$M)	Total Area (ha)	Patch Sizes (ha) Patch1	Patch2	Patch3
1	18.76	135.1	135.1*		

*: Patches smaller than the minimum contiguous habitat size specification are adjacent to the 409.1 ha core


N
Chicago
Dick Young F.P.
Legend
Dick Young Forest Preserve
Effective Habitat
Available Parcels
4
Kilometers

Figure 1.

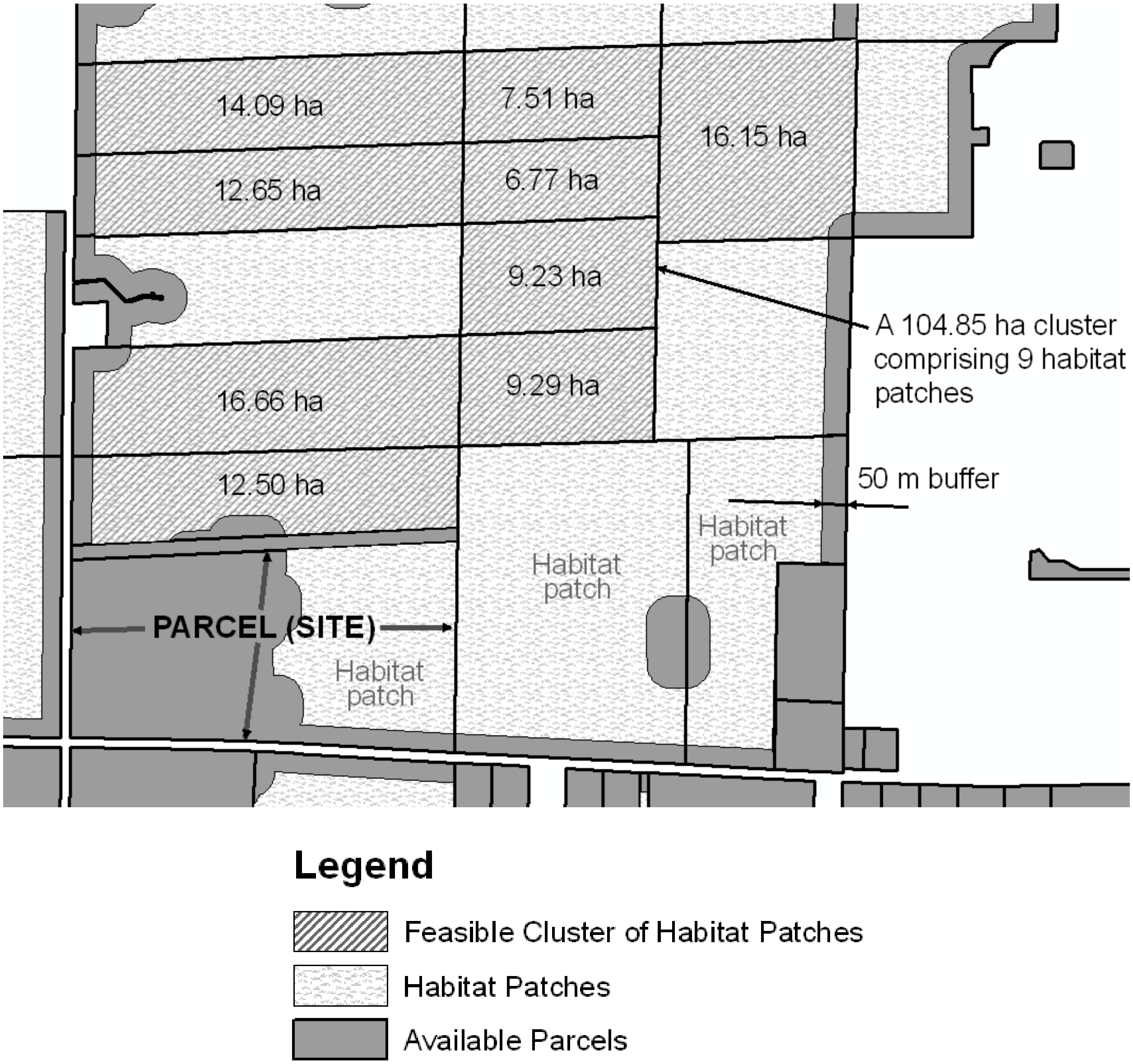
14.09 ha
7.51 ha
16.15 ha
12.65 ha
6.77 ha
9.23 ha
A 104.85 ha cluster comprising 9 habitat patches
16.66 ha
9.29 ha
12.50 ha
50 m buffer
Habitat patch
Habitat patch
PARCEL (SITE)
Habitat patch
Legend
Feasible Cluster of Habitat Patches
Habitat Patches
Available Parcels

Figure 2.

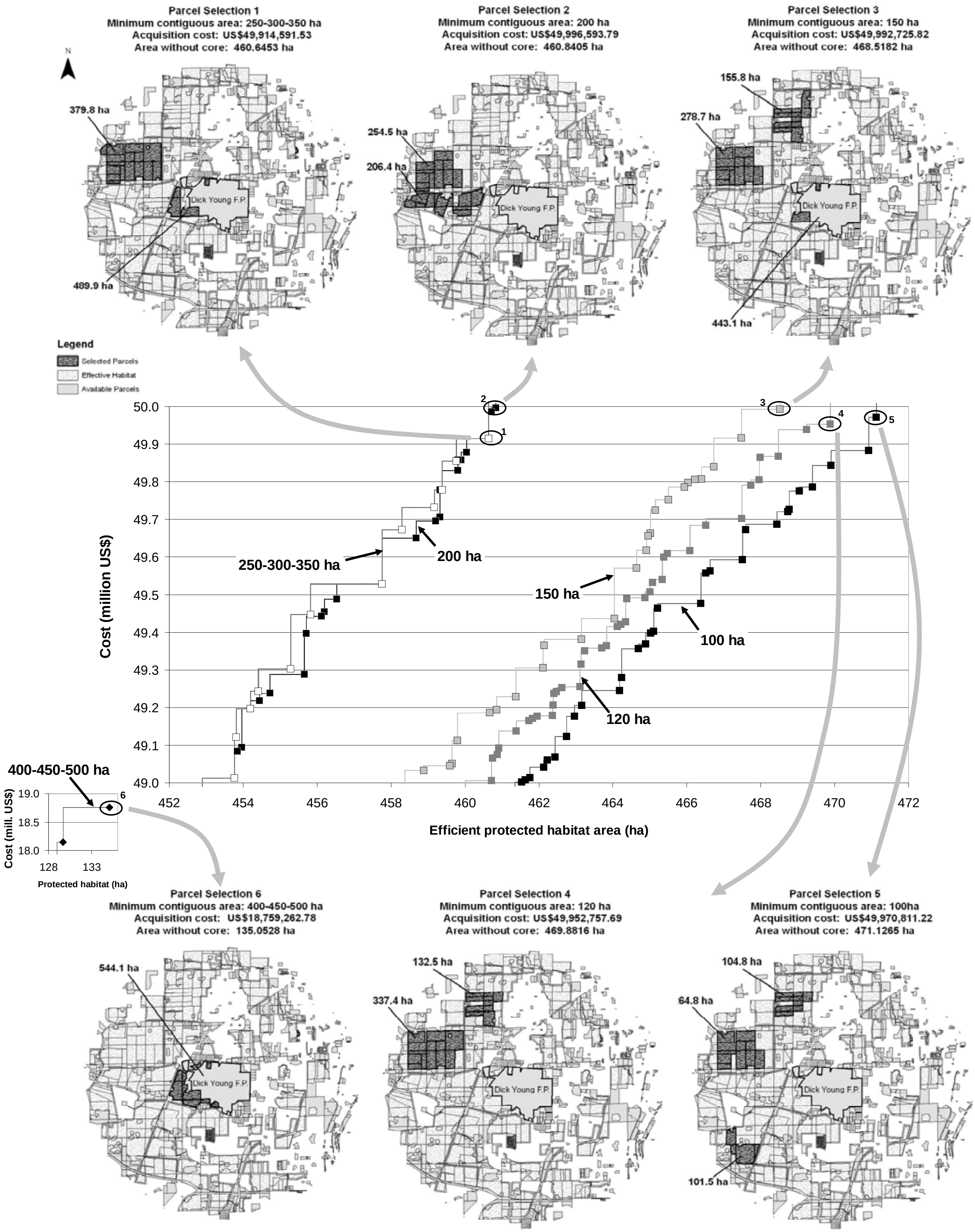
Parcel Selection 1
Minimum contiguous area: 250-300-350 ha
Acquisition cost: US$49,914,591.53
Area without core: 460.6453 ha
N
379.8 ha
Dick Young F.P.
489.9 ha
Parcel Selection 2
Minimum contiguous area: 200 ha
Acquisition cost: US$49,996,593.79
Area without core: 460.8405 ha
254.5 ha
206.4 ha
Parcel Selection 3
Minimum contiguous area: 150 ha
Acquisition cost: US$49,992,725.82
Area without core: 468.5182 ha
155.8 ha
278.7 ha
443.1 ha
Legend
Selected Parcels
Effective Habitat
Available Parcels
Cost (million US$)
Efficient protected habitat area (ha)
250-300-350 ha
200 ha
150 ha
120 ha
100 ha
400-450-500 ha
Cost (mill. US$)
Protected habitat (ha)
Parcel Selection 6
Minimum contiguous area: 400-450-500 ha
Acquisition cost: US$18,759,262.78
Area without core: 135.0528 ha
544.1 ha
Parcel Selection 4
Minimum contiguous area: 120 ha
Acquisition cost: US$49,952,757.69
Area without core: 469.8816 ha
132.5 ha
337.4 ha
Parcel Selection 5
Minimum contiguous area: 100ha
Acquisition cost: US$49,970,811.22
Area without core: 471.1265 ha
104.8 ha
64.8 ha
101.5 ha

Figure 3.