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Prioritizing conservation targets in a rapidly urbanizing landscape

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ABSTRACT

We used an optimization modeling framework to devise spatially explicit habitat acquisition and restoration strategies for 19 remnant-dependent butterflies in a rapidly urbanizing county in the Chicago area. We first identified the smallest sets of protected sites that would contain at least one population of each species, and two populations for species present in multiple sites. We then identified undeveloped properties contiguous with these sites whose acquisition would further enhance conditions for focal species. Next, we considered parcels in the surrounding landscape that could potentially be acquired and restored to provide additional habitat. Assuming that the conservation value of additional habitats would increase with their proximity to protected sites, we examined tradeoffs between distance to sites and the cost of acquisition and restoration. The tradeoff curves generated by the model represented choices among sets of reserves that varied widely with regard to cost and distance. Among the non-dominated solutions for a given total area budget, the best solutions depend on the decision makers preference for these two objectives. Sets along the frontier of these curves differed in total cost due to the variation in the number of wetlands per parcel, the number and cost of parcels that must be acquired to provide sufficient habitat, and restoration costs. Several parcels appeared in all solutions and should be prioritized for acquisition. Our general approach is readily adaptable to other locations and planning objectives, but the models would need to be modified to accommodate different target species and their habitat requirements.

1. Introduction

Habitat loss is widely recognized as the most pervasive threat to biodiversity in the United States (Wilcove et al., 1998). Counteracting this threat will require a sizeable investment in habitat protection and restoration, yet habitat conservation spending by federal and state governments has fallen far short of the funding levels necessary to develop effective conservation networks (Shaffer et al., 2002; Lerner et al., 2007). A more promising trend in land conservation has emerged over the last decade in the form of open-space protection. Ballot measures generated $27.1 billion for open-space conservation between 1996 and 2004, and enjoy widespread public support, particularly in regions experiencing high levels of urbanization (Szabo, 2007). Yet land availability is highly dynamic in rapidly urbanizing areas and local government agencies often face stiff competition from developers for open space (Haight et al., 2005; Miller, 2006; Skibbe and Miller, 2008). It is therefore imperative that local agencies have a strategy in place to help guide acquisition efforts as opportunities arise. If these lands are to provide habitat for native species, it is equally important that conservation scientists become involved during the early stages of devising such strategies (Szabo, 2007).

From the perspective of biodiversity conservation, acquisition efforts would ideally focus on large contiguous areas to mitigate the adverse effects of commercial and residential development (Soulé, 1991; Duerksen et al., 1997; Dale et al., 2000). In some regions, however, large blocks of natural or semi-natural land cover may no longer be an option. This is often the case when urbanization occurs in landscapes that have previously experienced widespread conversion to agriculture, such as in the Midwestern United States (Schwartz and van Mantgem, 1997). In these landscapes, planners must add the feasibility and cost of ecological restoration to the list of considerations on which land acquisition is based.

Since the 1980s, researchers have developed planning tools to assist with the location of conservation areas to ensure the persistence of biodiversity and other natural values (see Rodrigues and Gaston, 2002; Sarkar et al., 2006; Williams et al., 2005; Moilanen et al., 2009 for reviews). Algorithms for solving 'reserve selection' problems are either "optimal" or "heuristic." The former mathemat-

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ically guarantees finding the optimal solution. Heuristic algorithms aim for a feasible solution which, in objective function terms, is close to optimal. Several software programs for reserve site-selection use optimization heuristics (see Moilanen et al., 2009 for examples). Although these programs can be applied to problems with multiple conservation objectives, nonlinear constraints, and tens of thousands of candidate sites, they do not guarantee finding optimal solutions.

Here, we use an optimization modeling framework to devise spatially explicit habitat acquisition and restoration strategies in a rapidly urbanizing county on the western fringe of the Chicago metropolitan area. We focus on a suite of butterfly species considered to be remnant-dependent, or having obligatory associations with natural area remnants (Panzer et al., 1995, 1997). This taxon is particularly appealing as a conservation target in this context because butterflies have relatively modest requirements in terms of habitat area, play a key role in ecological communities, and are increasingly popular among the public (New et al., 1995; Snep et al., 2006). Our specific objectives were (1) to identify a set of properties that are currently protected and could serve as core habitat areas for these butterfly species, (2) to identify parcels that could be targeted for acquisition in order to buffer these protected areas from adverse impacts of development, and (3) to identify sets of properties in the landscape matrix surrounding core areas that could potentially be restored to provide additional habitat. These additional habitat patches may also serve as recolonization sources if populations in currently protected areas go extinct (Hanski and Gaggiotti, 2004). Our optimization modeling framework is a set of linear-integer programming problems, which we solve using a branch-and-bound algorithm. This framework adds to the body of literature on reserve site-selection models by including habitat restoration as a management option and defining separate but related decision variables for the conservation targets (wetlands) and units of acquisition (land parcels).

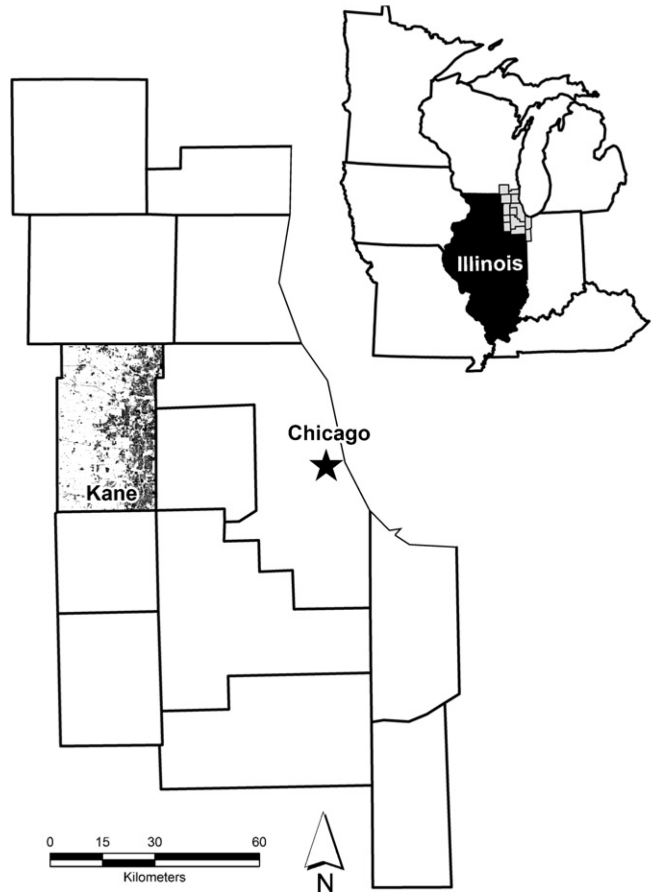

Fig. 1. Kane County relative to the City of Chicago, IL and the 13-county Chicago Wilderness. Dark areas within Kane County's borders indicate the extent of urban and suburban development.

2. Methods

2.1. Study area

Kane County, IL, covers 1325 km^2 on the western fringe of the Chicago metropolitan area (Fig. 1). Prior to European settlement, approximately 60% of the county was tallgrass prairie, with the remainder comprising oak savannas, riparian woodlands, and wetlands (Kilburn, 1959). Widespread conversion to agricultural uses all but eliminated native land cover, particularly in the uplands, during the 19th and 20th centuries. Growth rates have sky-rocketed over the last few decades, with the population expanding by 27.3% from 1990 to 2000 and then by 21.1% from 2000 to 2006 (U.S. Bureau of the Census, 2007). By 2030, the county's population is projected to exceed 718,000 people (NIPC, 2006). While >60% of the land here remains in agricultural uses, Chicago's expanding footprint has resulted in the conversion of Kane County's easternmost quarter to urban and suburban development (Fig. 1). The probability that the remainder of the county's eastern half will be developed by 2030 ranges from moderate to high (Openlands Project, 1999).

The Kane County Forest Preserve District (FPD) was established in 1925 and, like its counterparts in other Illinois counties, initially focused on acquiring and managing lands that contained "natural" forests (Greenberg, 2002). Since then, the agency has been given greater latitude in the land types that they can purchase and their mission has broadened to include habitat restoration. Land acquisition by the FPD is driven by a variety of considerations that reflect different aspects of its mission; these include protecting habitat for native species, providing recreational opportunities for the public, and preserving cultural and historic resources. Until recently, sharply escalating real estate prices and the swift pace of land conversion made it difficult for the FPD to compete with developers, particularly in the eastern half of the county. In 1999, a county-wide bond initiative provided $106 million that allowed the FPD to purchase 2226 ha of open space over a 5-year period, representing a 78% increase in total holdings. Two additional ballot referendums passed in 2005 and 2007 provided $70 million and $85 million, respectively, for the FPD to expand the network of protected open space (Kane County, 2007). Currently, the FPD manages 91 properties covering approximately 5% of the county.

2.2. Focal species

The selection of our focal butterfly species was based on data for Kane County FPD properties provided by the Illinois Butterfly Monitoring Network (http://www.bfly.org/), whose members have been conducting surveys there since 1987. Each survey is conducted by a trained monitor walking along transects traversing major habitat types at each site and identifying all butterflies within 9 m (Taron, 1997). Sites were surveyed a minimum of four times each summer, although not all sites were surveyed each year due to turnover in volunteer monitors (for further details on survey protocols, see the Illinois Butterfly Monitoring Network Guidelines, http://www.bfly.org/).

Survey data (current through 2006) indicated that 19 remnant-dependent species have been detected on 13 FPD properties (Fig. 2). Remnant-dependent species were observed at nine of the sites up to and including the last survey date, and within a month of the last survey date at the other four sites. All of these species are associ-

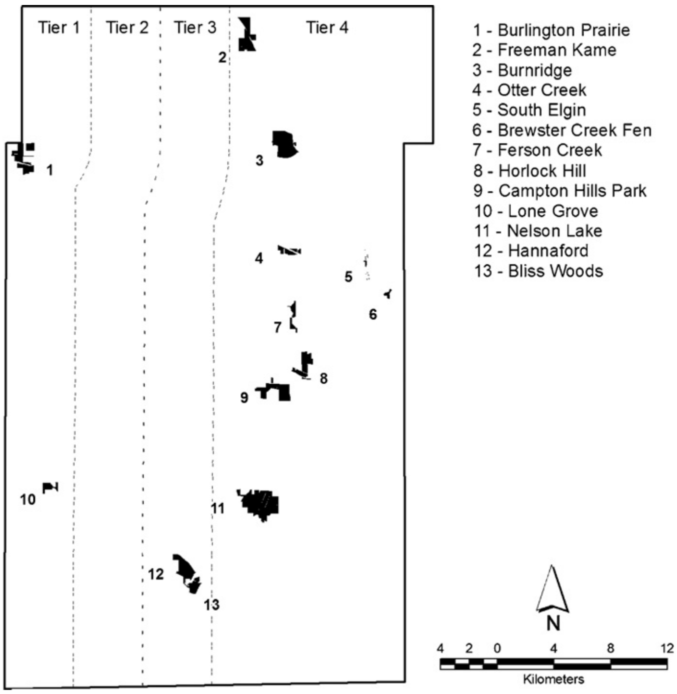

Fig. 2. Kane County Forest Preserve District properties ($n = 13$) with populations of remnant-dependent butterflies based on annual survey data collected since 1987 by the Illinois Butterfly Monitoring Program. The vertical dotted lines delineate four tiers reflecting different categories of land prices in the county (see Section 2.4 for details).

ated with open habitats, with the majority showing an affinity for wet prairies or sedge meadows bordering wetlands with emergent vegetation (Table 1; D. Taron, Director of the Illinois Butterfly Monitoring Network, personal communication). The exceptions to this pattern are *Amblyscirtes vialis*, *Thorybes pylades*, *Chlosyne gorgone*, and *Satyrodes appalachia*, which tend to be associated with open woodlands or more xeric prairies. The more mesic habitats were all relatively small in area, although at some sites they were embedded in more expansive grasslands; the size of grassland tracts contiguous with open wetlands ranged from <1 ha to approximately 120 ha.

Table 1
Remnant-dependent butterfly species (Panzer et al., 1995) observed on surveys of Kane County Forest Preserve District properties between 1987 and 2006 by the Butterfly Monitoring Network of northeastern Illinois.

Species	Common name	Habitat affinities[a]
Amblyscirtes vialis	Common roadside-skipper	Sand savanna, prairie/woodland edge
Euphyes dion[b]	Dion skipper	Sedge meadow, fen
Euphyes conspicua	Black dash	Sedge meadow
Poanes massasoit	Mulberry wing	Sedge meadow
Poanes viator[b]	Broad-winged skipper	Sedge meadow
Polites origenes	Crossline skipper	Xeric/wet prairie
Polites mystic	Long dash	Sedge meadow, wet prairie
Thorybes pylades	Northern cloudywing	Sand savanna, xeric/mesic prairie
Satyrium titus	Coral hairstreak	Xeric/mesic prairie
Satyrium acadica	Acadian hairstreak	Wet prairie
Lycaena hyllus	Bronze copper	Wet prairie
Lycaena helloides[b]	Purplish copper	Wet prairie
Chlosyne nycteis	Silvery checkerspot	Wet prairie/savanna
Chlosyne gorgone[b]	Gorgone checkerspot	Xeric prairie
Euphydryas phaeton	Baltimore checkerspot	Fen, wet prairie
Boloria selene[b]	Silver-bordered fritillary	Wet prairie
Boloria bellona	Meadow fritillary	Wet prairie
Satyrodes eurydice	Eyed brown	Sedge meadow
Satyrodes appalachia	Appalachian brown	Savanna, prairie/woodland edge

[a] Based on Scott (1986), Panzer et al. (1995), and Glassberg (1999).
[b] Listed as a species of greatest conservation need in Illinois (Illinois Department of Natural Resources, 2005).

2.3. Land cover

Kane County provided digital parcel data describing zoning designations, as well as data layers depicting primary and secondary roads, and FPD lands (current as of January 2007). We acquired a 30-m digital elevation model (DEM) from the GeoCommunity data depot (http://www.geocomm.com). Digital data layers for soils, compiled by the Natural Resource Conservation Service, and land cover, based on the 1999–2000 Land Cover of Illinois developed by the Illinois Department of Agriculture, were obtained from Natural Connections: Green Infrastructure (http://www.greenmapping.org), which is affiliated with the Openlands Project in Chicago. Land use/land cover categories included row-crop agriculture, hayfield, pasture, woodland, residential, commercial and industrial.

Grassland–wetland complexes (hereafter, core areas) on the 13 FPD properties where the focal species occurred were included in data layers obtained from Kane County and we used National Wetland Inventory data to identify existing open-water wetlands in the landscapes surrounding these sites. To determine the locations of potentially restorable depressional wetlands in these landscapes, we used an approach developed by McCauley and Jenkins (2005) which is based on the correspondence between hydric soils and basins, identified using the DEM.

2.4. Acquisition and restoration

Ideally, one would use information on the movement behavior of each focal species occurring at a given core area to define the spatial extent of the landscape within which properties might be acquired to serve as additional habitat. Although most metapopulation models rely on Euclidean distance to quantify connectivity among patches, the use of functional connectivity (Tischendorf and Fahrig, 2000), which takes movement behavior and response to different types of land cover into account, may have better predictive power for butterflies (Chardon et al., 2003; Sutcliffe et al., 2003; McIntire et al., 2007; Pellet et al., 2007). Unfortunately, data on movement behavior within or among habitat patches is lacking for the majority of species (Dennis et al., 2006). We therefore used Euclidean distance, recognizing the simplifying assumptions inherent in this choice, and considered parcels within 3.2 km of each core area as its landscape matrix. We based this distance on the observation that movements up to several km are fairly common, even among relatively sedentary butterfly species (Kuussaari et al., 1996; Davis et al., 2007). Although longer colonization distances have been observed (Harrison, 1989; Thomas and Hanski, 1997; Debinski et al., 2001), these are considered relatively uncommon.

In identifying potential sites for acquisition, we considered only undeveloped parcels bordering core areas, which might serve as additional habitat or buffers, and those parcels in the matrix that comprised prairie, hay fields, pastures, or row crops. The set of eligible parcels was further reduced by including only those that contained one or more existing or restorable wetlands, or were within 112 m of existing or restorable wetlands. This buffer distance assured that wetlands near a parcel boundary would still have at least 4 ha of terrestrial habitat immediately adjacent to it. We assumed this to be the minimum patch area for our focal species based on the range of remnant sizes where populations still occur in the county and throughout the Chicago metropolitan area (R. Panzer, Northeastern Illinois University, and D. Taron, personal communications).

A key element of any strategy aimed at expanding reserve networks is the financial cost of doing so, and this may be substantial in rapidly urbanizing regions. We therefore estimated the costs of acquiring and restoring parcels, and incorporated these expenditures into our decision modeling framework. Acquisition costs were based on an appraisal of market values provided by real estate agents for the eastern (urban) and western (rural) portions of Kane County. We further expanded this binary 'high' and 'low' classification by dividing the county into four sections. We assigned property values in the eastern, most highly developed section ($98,800/ha) and then divided the remainder of the county into sections of approximately equal size (Fig. 2). Property values in the western section ($24,700/ha) were assigned on the basis of the realtors' estimates. We then interpolated values in equal increments from east to west for the two middle sections, assigning values of $71,400/ha and $49,400/ha, respectively.

To our knowledge, restoration costs have not been considered in previous site-selection applications aimed at biodiversity conservation. We consulted two private firms that specialize in habitat restoration in the Midwestern U.S. and have extensive experience in the Chicago area (Applied Ecological Services, Brodhead, WI and Driftless Area Stewardship, Glenhaven, WI). They provided cost estimates for the various steps in prairie restorations using relatively high numbers (80–100) of plant species. Clearly, these plant mixes would ultimately need to be tailored to the resource needs of focal species in a given core area, both in terms of larval food plants and nectar sources, at minimum. We averaged the estimates to derive a total cost of $4133/ha for parcels in row-crop agriculture or non-native grasses and constrained the total area of habitat adjacent to a particular wetland that would be restored to 10 ha. This is considered a 'large' habitat patch for butterflies (Ockinger and Smith, 2006) and is more than twice the size of typical patches where the focal species in this study are found in the region. Because the Kane County FPD has typically restored wetlands by breaking drainage-tile lines, we did not assign a dollar amount to wetland restoration. We recognize, however, that more may be required, depending on the extent of prior modifications affecting surface and sub-surface flows in a particular location.

While the unit of acquisition is the ownership parcel, we were largely interested in the wetland habitat complexes embedded within each parcel. To this end, we computed the total cost of acquisition and habitat restoration for each existing or restorable wetland as follows. First, we identified the set of parcels (if >1) that had to be acquired to provide sufficient terrestrial habitat around each wetland, then summed the costs of acquisition and restoration. Next, we identified groups of wetlands that shared the same sets of parcels. For each group, we divided the total costs of acquisition and restoration by the number of wetlands in the group to derive an average cost per wetland. Finally, we ranked the wetlands according to cost and distance to nearest core wetland as indices of desirability.

2.5. Model 1: prioritizing core areas

We developed a two-stage modeling approach. In the first stage, we identified a subset of the 13 core areas around which to focus land acquisition and restoration decisions in the second stage. We assumed that the prospects of persistence for butterfly species currently present in the core areas would be enhanced by providing additional habitat in the surrounding landscape. We also assumed that the habitat value of these areas would vary inversely with distance from the cores (New et al., 1995; Shepherd and Debinski, 2005), reflecting an increased probability of colonization for nearby habitats. Allowing acquisition decisions around all 13 core areas with a limited budget could result in a scattered set of newly protected parcels that did little to meet conservation goals. Of the 19 species, 5 were found in only 1 core area, while the remaining 14 were present in multiple cores. Given this, the goal in the first stage of modeling (Model 1) was to identify the smallest set of existing core areas that collectively contained a population of each species in at least one core. We further required that each of the 14 species known to be present in >1 core would have at least 2 of their core areas selected, thus improving the odds of long-term viability. The subset(s) of core areas which provided the specified primary and secondary coverage would serve as the focus for land acquisition choices in the second stage of modeling.

Model 1 was an application of the species set covering problem (Underhill, 1994), an adaptation of the location set covering problem to habitat site selection, which is a classic model from the location science literature (Toregas et al., 1971). Elements of another standard from this literature, the backup covering model (e.g., Hogan and ReVelle, 1986), were also incorporated into Model 1 through the requirement of secondary representation of some of the species. ReVelle et al. (2002) provide a good discussion of the linkages between classic facility location optimization models and habitat reserve site-selection problems. Model 1 was defined with the following notation:

i, I = the index and set of existing core areas;
j, J = the index and set of butterfly species;
$j1$ = the subset of butterfly species present in only one core;
$j2$ = the subset of butterfly species present in two or more cores;
S_{ij} = a 0–1 parameter indicating whether species j is present in core i;
X_i = a 0–1 decision variable: 1 if core i is selected for inclusion in the subset subsequently considered for land acquisition decisions, and 0 otherwise.

Model 1 was formulated as follows:

$$\text{minimize } Z = \sum_{i \in I} X_i \tag{1}$$

Subject to:

$$\sum_{i \in I} X_i S_{ij} = 1 \quad \forall j \in j1 \tag{2}$$

$$\sum_{i \in I} X_i S_{ij} \geq 2 \quad \forall j \in j2 \tag{3}$$

$$X_i \in \{0, 1\} \tag{4}$$

The objective (Eq. (1)) minimizes the total number of core areas considered in subsequent land acquisition decisions which provides the specified level of protection for each of the 19 species. Eq. (2) ensures that each of the five species known to be found in only one core is 'represented' through the selection of cores. Eq. (3) provides for redundant or backup representation for the other 14 species, requiring that at least two cores that contain a population of each species are selected. Eq. (4) is an integrality condition that requires the decision variables to take on a value of 0 or 1; i.e., a core is selected or not.

2.6. Model 2: selecting parcels for acquisition and restoration

Once the minimum set of core areas was identified through the solution of Model 1, the second stage model was constructed to identify adjacent (buffer) parcels and those parcels in the surrounding matrix for acquisition and restoration. We were interested in minimizing the distance of wetlands to their closest core area when acquiring parcels, given our assumption that habitats closer to existing cores enhanced prospects for colonization. We were also interested in minimizing the cost of parcel acquisition and restoration. Therefore, we formulated a two-objective model subject to a constraint on the minimum area of wetlands and contiguous habitat selected, a constraint that all parcels adjacent to core areas be selected, and a constraint that one wetland and its contiguous habitat be selected for each of the core areas. By incrementally changing the weights given to the two objectives and re-solving the problem many times, tradeoff curves were generated showing budget expenditures and total distance measures for a given area of protected wetlands. The model was defined with the additional notation:

k,K = the index and set of existing and restorable wetland areas;
l,L = the index and set of parcels available for acquisition;
M_i = the subset of parcels directly adjacent to core i;
N_i = the subset of wetlands within 3.2 km of core i;
R_k = the subset of parcels that must be acquired and restored to provide sufficient habitat adjacent to wetland k;
A_k = the area of wetland k (ha);
$AMin$ = the minimum area (ha) of wetlands and contiguous habitat that must be acquired and restored;
B = the upper bound on the budget that can be spent to acquire and restore parcels;
C_l = the cost of acquiring and restoring parcel l;
D_k = the distance (m) between the edge of wetland k and the edge of the nearest core area;
Q_1 = the total cost of acquired and restored parcels;
Q_2 = the total pairwise distance between acquired and restored parcels and the nearest cores;
w = the objective function weight ($0 \le w \le 1$);
P_l = a 0–1 decision variable: 1 if parcel l is selected for acquisition, 0 otherwise.
Y_k = a 0–1 decision variable: 1 if wetland k is fully buffered, 0 otherwise.

The model was formulated as follows:

$$\text{minimize } Z = wQ_1 + (1-w)Q_2 \quad (5)$$

Subject to:

$$Q_1 = \sum_{l \in L} C_l P_l \quad (6)$$

$$Q_2 = \sum_{k \in K} D_k Y_k \quad (7)$$

$$\sum_{k \in K} A_k Y_k \ge AMin \quad (8)$$

$$\sum_{k \in N_i} Y_k \ge 1 \quad \forall i \quad (9)$$

$$P_l = 1 \quad \forall l \in M_i \quad (10)$$

$$Y_k \le P_l \quad \forall l \in R_k, \ \forall k \quad (11)$$

$$P_l \in \{0, 1\}, Y_k \in \{0, 1\} \quad (12)$$

The objective function (Eq. (5)) minimizes the weighted sum of the total acquisition and restoration costs (Eq. (6)) and total pairwise distance from each fully buffered wetland to its closest existing reserve core (Eq. (7)). Eq. (8) requires that the total area of selected and fully buffered wetlands meets a minimum threshold. Eq. (9) requires that at least one wetland and its contiguous terrestrial habitat be selected for each of the core areas. Eq. (10) stipulates that all of the parcels adjacent to each of the cores must be selected for protection. Eq. (11) stipulates that the parcel containing the wetland is selected along with any adjacent parcels needed to provide at least 4 ha of terrestrial habitat around the wetland. Eq. (12) defines the integer restrictions for the decision variables.

Some of the logical structures of our parcel-selection model have antecedents in the reserve selection literature. Bicriteria formulations (e.g., Eqs. (5)–(7)) have been used to address spatial attributes of the reserve system (e.g., Önal and Briers, 2002), total habitat area (Snyder et al., 2004), habitat quality (Church et al., 2000), and public access or proximity (Haight et al., 2005). The objective of minimizing the distance between selected parcels and existing habitat core areas (Eq. (7)) has been used to promote the compactness of the resulting reserves (Snyder et al., 2007). The novel part of our formulation is the recognition that wetlands, which are the conservation targets, are contained within or surrounded by ownership parcels, which are the units of acquisition. By defining separate decision variables for wetlands and parcels, we can constrain the model to select parcels needed to buffer each selected wetland (Eq. (11)) and account for the cost of parcel acquisition (Eq. (6)).

2.7. Solution methods

Our analysis in the first stage of modeling focused on identifying the smallest set of existing core areas that contained populations of each of the 19 remnant-dependent butterfly species. In the second stage, we focused on identifying sets of parcels to acquire and restore around the subset of cores identified in the first stage. With Model 2, we generated tradeoffs between the total cost of acquisition and restoration and the total pairwise distance between newly protected parcels and existing core reserves, a proxy for fragmentation or isolation of protected habitat. We analyzed how the allocation of funds and selection of parcels changed as the weights for the two objectives changed. We computed these tradeoffs for total area thresholds of 425 and 660 ha for newly protected wetlands. With current land values and restoration costs, the total costs of these levels of wetland protection ($40–$150 million) were in line with the funding available from the Kane County bond measures of 1999 and in 2005.

We solved the two-objective optimization model using the multiobjective weighting method (Cohon, 1978). The objective function weight w was systematically varied between the values of 0 and 1 and the problem re-solved for each weight to generate an estimate of the tradeoff curve between the total cost of acquisition and restoration of wetlands and the total pairwise distance between each selected wetland and its nearest protected core. As the value of w increased, more weight was given to the objective of minimizing cost resulting in larger total pairwise distances.

All of the problems were solved on an IBM Pentium™ 4 personal computer, using the integrated solution package GAMS/CPLEX 9.0 (GAMS Development Corp., 1990). Solution time was less than a minute for all runs. Input files were created using GAMS (General Algebraic Modeling System), a program designed to generate data files in a standard format that optimization programs can read and process. The models were solved using CPLEX, an optimization solver designed for linear and integer problems. The revised primal simplex algorithm, in conjunction with the branch-and-bound algorithm for integer-variable problems, was used to solve the models.

3. Results

Solving Model 1, we identified 2 sets of 7 core areas that provided primary protection for all 19 species and secondary coverage for the 14 species that occurred in >1 core. Both sets included six core sites (Burlington Prairie, Freeman Kame, Otter Creek, Lone Grove, Nelson Lake, and Bliss Woods; Fig. 2) and differed in the inclusion of one core area (Ferson Creek or Horlock Hill; Fig. 2). The two sets were alternative optima in that they both provided the specified species' representation with a minimum of seven core areas. We performed subsequent analyses using the set that included Ferson Creek.

There were 29 existing and 194 restorable wetlands occurring on 282 eligible parcels in the landscapes surrounding our set of core areas. The costs of parcel acquisition and wetland restoration varied from $0.2 to $10.0 million per wetland with an average of $2.3 million. Existing wetlands were more expensive on average ($3.7 million per wetland) than restorable wetlands ($2.1 million per wetland), and only one existing wetland was in the least expensive quartile of all wetlands. Existing wetlands were more expensive than restorable wetlands because existing wetlands did not occur in groups sharing the same sets of parcels, as restorable wetlands often did, and because the parcels containing existing wetlands were relatively large and expensive. Over all 223 wetlands, the distance to the nearest core area varied from 0.1 to 3.2 km with a mean of 2.4 km. Existing and restorable wetlands had about the same average distance to core areas.

Repeatedly solving Model 2, we produced curves showing the tradeoffs between total pairwise distance to core areas and total cost for two different levels of total minimum protected wetland area (Fig. 3). The curves have convex shapes with distance decreasing as cost increases. The points on each curve represent non-dominated sets of parcels (and their associated wetlands) selected for protection and their relative performance with respect to the two objectives under a given level of the area budget. For each non-dominated set of parcels, improvement in one objective cannot be achieved without simultaneously causing degradation in the value of the other objective. As a result, the points on each tradeoff curve represent a frontier below which no better solutions can be found.

Among the non-dominated solutions for a given area budget, the best depends on the decision maker's preference for the two objectives. For example, if minimizing total cost is most important and the area threshold is 425 ha, the best choice is solution A (Fig. 3), in which total pairwise distance is 108 km and total cost is $40 million. A move from solution A to solution B reduces pairwise distance 39% while increasing total cost 35%. Further reductions in pairwise distance require much greater expenditures. Moving from solution B to solution C reduces pairwise distance 18% with a 94% increase in cost.

Increasing the total area protected from 425 ha to 660 ha shifts the tradeoff curve up and to the right while maintaining its shape. A vertical line connecting the two curves represents the increase in total distance to cores associated with protecting more wetland area at a given cost. This makes sense because protecting more wetland area increases the total distance measure.

To complement the tradeoff curves, it is important to see how the decision maker's preference for the two objectives affected wetlands that were selected for protection. With an area budget of 425 ha, each solution included a total of 43 wetlands with each wetland covering about 10 ha of terrestrial habitat. The nine solutions between points A and B on the tradeoff curve (Fig. 3), in which more weight is given to minimizing cost, were composed almost entirely of restorable wetlands because they were less expensive to acquire and restore than existing wetlands. The solutions between points B and C on the right-hand side of the tradeoff curve in which more weight was given to minimizing distance to core areas included 3–8 existing wetlands, all of which ranked in the top quartile of shortest distance but cost considerably more than restorable wetlands.

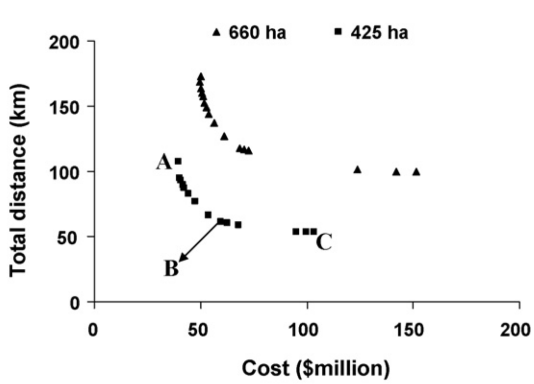

Fig. 3. Comparison of the tradeoff between total distance of acquired parcels from core areas and the total acquisition cost for two different thresholds of total area.

The solutions along the tradeoff curve (Fig. 3, area = 425 ha) varied substantially in terms of the number of wetlands selected for protection near a given core site (Table 2). In the minimum-cost solution (A), over half of the selected wetlands were near Bliss Woods (Fig. 4). Even though these wetlands were located in the second highest price tier (Fig. 2), they were clustered in small parcels (i.e., >1 wetland per parcel) so that the cost per wetland was relatively low. As the weight shifted to include the objective of minimizing total distance to cores (solution B), a small number of selected wetlands shifted from Bliss Woods to Nelson Lake in the eastern tier and from Lone Grove to Burlington Prairie in the western tier (Fig. 4). In addition, the wetlands associated with Bliss Woods in solution B are closer to the core area than those in solution A. Moving from solution B to solution C in which distance was minimized, fewer wetlands were selected near Bliss Woods and more wetlands were selected near Freeman Kame in the expensive eastern tier of the county (Fig. 4).

Four restorable wetlands and 1 existing wetland were present in all 14 solutions along the tradeoff curve for area = 425 ha. Three of these wetlands were relatively inexpensive and close to core areas: they ranked in the top quartile in both cost and distance. The other two were ranked highest in cost and distance among a small number of wetlands within 3.2 km of two core areas (Freeman Kame and Ferson Creek; Fig. 4). Because these wetlands were present in all of the solutions, their protection and restoration should be prioritized regardless of the weights assigned to the objectives of minimizing cost and minimizing distance-to-core, as they represent 'robust' choices.

4. Discussion

In conservation planning, it is important to match targets with opportunities for site acquisition and protection in a realistic fashion. We have developed a decision-support tool that is well-suited to conservation in an area undergoing rapid urbanization, where remnant habitats are relatively small, and newly acquired parcels will likely require some degree of ecological restoration. We focused on a suite of native species valued by the general public that have persisted in a set of small remnants in Kane County despite widespread land conversion, first to agriculture and more recently to suburban development.

Meir et al. (2004) observe that the effectiveness of optimal reserve networks is reduced if the network must be implemented over time. Our model and analysis were based on the assumption that all selected parcels would be acquired in a single time period. If land is acquired over a longer time period, then it is likely that conditions on the landscape will change (e.g., butterfly abundance, land availability, habitat quality). Given this, the models could be rerun periodically with updated data to determine if parcel-selection strategies also change. It is noteworthy that the properties we have identified could be acquired as opportunities arise and still contribute to the conservation of the focal species. In other words, their conservation value is not predicated on the purchase of other parcels, with the exception of those requiring the acquisition of

Table 2
Number of wetlands selected for protection by core site for solutions on the tradeoff curve for total pairwise distance versus total cost, with area held constant at 425 ha (see Fig. 3).

Solution	Objective values		Number of wetlands protected by core site						
	Cost ($million)	Distance (km)	Burlington Prairie	Lone Grove	Freeman Kame	Otter Creek	Ferson Creek	Nelson Lake	Bliss Woods
A	40	108	4	7	1	1	1	6	23
B	54	66	8	4	1	1	1	9	19
C	104	54	7	5	8	2	1	10	10

adjacent properties to provide a sufficient amount of terrestrial habitat. This contrasts with our findings for grassland birds, another conservation target in the county (D. Ullberg, Kane County FPD, personal communication), which highlight the need for acquiring relatively large numbers of contiguous parcels to create reserves of sufficient size (Snyder et al., 2007). The strategies for land acquisition offered here also have the potential to help the FPD achieve their goal of more widespread public access to open space across the county.

An optimization modeling framework is well-suited to the task of helping planners and decision makers assess conservation alternatives. These models necessarily require a concise formulation of the challenges, are transparent with regard to underlying assumptions, identify tradeoffs associated with different conservation priorities, and generate a range of solutions that can be depicted visually to aid in further evaluation (Kingsland, 2002; Williams et al., 2004). In this application, we formulated a model to prioritize core areas around which to focus land acquisition and restoration decisions. Once the minimum set of core areas was identified, a second model was constructed to identify adjacent (buffer) parcels and those parcels in the surrounding matrix for acquisition and restoration. The conservation objectives of the parcel-selection model were expressed as the number and cost of newly protected wetlands and their proximity to already-protected core habitat areas while the opportunities for site protection were ownership parcels that could be acquired by the FPD. A key strength of the parcel-selection formulation was using ownership parcels that contain or surround the wetlands as decision variables, which allowed us to make a better accounting of the costs of habitat protection.

Both the core-selection model and the parcel-selection model had linear-integer structures, which allowed us to use an exact optimization algorithm (CPLEX 9.0) available in a commercial pro-

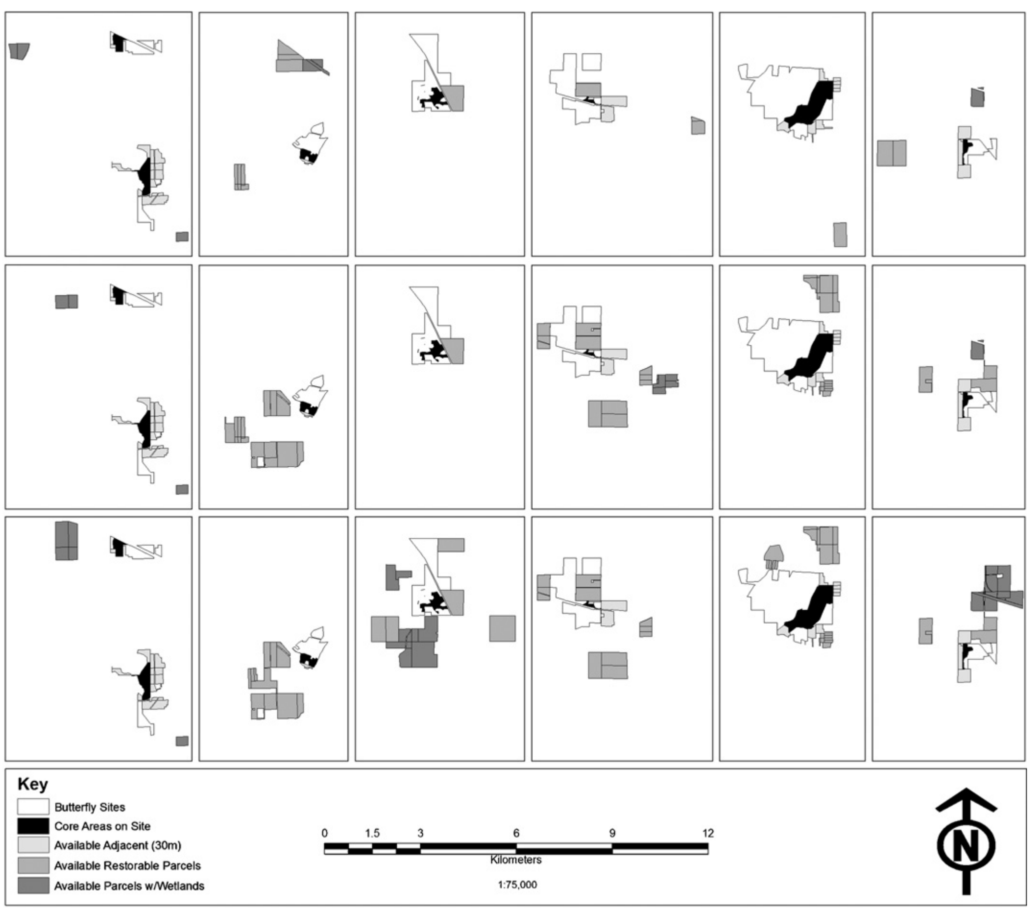

Fig. 4. Parcels selected for protection proximate to each butterfly site for three solutions on the tradeoff curve for total pairwise distance versus total cost, with area held constant at 425 ha (see Fig. 3). The top row corresponds to solution A (minimize cost), the middle row corresponds to solution B, and the bottom row corresponds to solution C (minimize distance). Columns depict changes in parcels selected in these solutions in the vicinity of individual butterfly sites. The panels in the far left column depict both the Otter Creek (top) and Ferson Creek sites, with remaining columns (left to right) each depicting one site in the following order: Bliss Woods, Freeman Kame, Burlington Prairie, Nelson Lake, and Lone Grove. See Fig. 2 for the relative locations of these sites in Kane County. Selected parcels are assigned to one of three categories: those adjacent to core areas on butterfly sites, those with potentially restorable wetlands, and those with existing wetlands. Parcels in the latter category may include >1 wetland (see Section 2.4 for details).

gramming language (GAMS Development Corporation, 1990). We formulated our problems with linear-integer structures because we wanted to find exact, optimal solutions and map the tradeoffs between conservation objectives. Many software programs for reserve site-selection use optimization heuristics (see Moilanen et al., 2009 for examples). Although these programs address problems with multiple conservation objectives, nonlinear constraints, and tens of thousands of candidate sites, none guarantee finding optimal solutions. The choice between an optimal or heuristic algorithm to solve reserve selection problems depends in part on whether the problem size is beyond the computational limit of an exact optimization algorithm and whether the analyst wants to spend the computational effort needed to solve the problem optimally. Our models for prioritizing core areas (13 candidate cores) and selecting parcels for acquisition and restoration (282 eligible parcels covering 19 existing and 194 restorable wetlands) were well within computational limits and solved very quickly (<1 min).

The tradeoff curves generated by the parcel-selection model represent choices among sets of wetland reserves that vary widely in total cost and distance to core areas. Sets along the frontier differed in total cost because of the variation in the number of wetlands per ownership parcel, the number and size of the parcels that must be acquired to provide sufficient habitat, and the unit costs of acquiring the parcels. None of this detail could have been obtained without identifying the potential wetland sites within the ownership parcels, which define the opportunities for site protection. Analysis of the tradeoff curves also showed that the marginal cost of reducing the distance of newly protected wetlands to core areas increases sharply as total distance to core is reduced. As a result, the benefits of a more compact set of reserves need to be carefully assessed to determine if they justify the high cost.

Site-selection models for multiple species have traditionally emphasized the representation of these species in a conservation network, but not their long-term persistence (Cabeza and Moilanen, 2003; Nicholson et al., 2006), whereas studies that have addressed population processes affecting persistence tend to be limited to single-species applications (Moilanen and Cabeza, 2002). We have addressed persistence by prioritizing the acquisition of buffers contiguous with existing core areas and additional habitat in the surrounding landscape. Ultimately, however, persistence will depend on the resource requirements and mobility of these butterfly species relative to habitat quality, the spatial configuration of the protected open space, and the nature of the intervening matrix. This suggests the need for a resource-based view of protected lands and the landscapes in which they are embedded (Dennis et al., 2006; Miller and Hobbs, 2007).

Dennis et al. (2006) note that a resource-based assessment of habitat quality for butterflies requires an emphasis on consumables (larval food plants, nectar sources) as well as utilities (physical sites for mate location and pupating, suitable conditions for development, and enemy-free space). Movement among protected habitats will likewise be affected by the distribution of resources in the landscape matrix, as well as the characteristics of habitat borders (Ries and Debinski, 2001; Schultz and Crone, 2001; Schtickzelle and Baguette, 2003) and population densities in the source and recipient areas (Kuussaari et al., 1996; Ockinger and Smith, 2008). It comes as no surprise then, that the use of spatially explicit population models to estimate persistence tend to focus on species that are relatively well-studied (Moilanen and Cabeza, 2002; Westphal et al., 2003; Nicholson et al., 2006; McIntire et al., 2007).

For many butterfly species, we do not even have a reliable list of host plants, much less information on factors such as thermal constraints and egg-laying, or their ability to move among resource sets (Dennis et al., 2006). Clearly, this creates a tension between waiting until such data are collected and taking action based on incomplete data with the risk of making less than ideal decisions. In a rapidly urbanizing environment, the choice seems clear. The window of opportunity to acquire additional open space is likely to be narrow and once land is developed, it is likely to remain so. It follows that in urbanizing areas the most sensible course of action is to augment the existing open space network as opportunities arise (McKinney, 2002), based on the best information available, then focusing on improving habitat quality and connectivity (also see Wood and Pullin, 2002).

To the greatest extent possible, it will be easier to maintain existing connectivity, or what humans perceive as connectivity, than to try to retrofit corridors once the landscape has been developed. Such connections might include riparian areas or grassed roadsides that could be planted to native species (Ries et al., 2001). Ultimately the goal is to restore functional connectivity, but given the difficulties in achieving this objective, whether due to lack of knowledge or diminishing options caused by development, translocation of focal species to newly acquired and restored habitats may be necessary. The methods for successful translocation or reintroduction are not yet well-developed (Taron, 1997; Seddon et al., 2007). As is the case with restoration ecology, however, reintroduction biology is a rapidly developing field and although past efforts may have been unsuccessful, better methods may be developed in the future.

We developed a decision-support tool for biodiversity protection in a highly dynamic landscape, not a blueprint for conservation action. Our approach is to identify relevant conservation objectives, decision variables, and resource constraints, formulate corresponding linear-integer optimization problems, and solve them with exact (rather than heuristic) algorithms. This general approach is portable, but the particulars will vary in other locations, as well as in Kane County, as changes in conservation objectives, land use, and acquisition budgets proceed. Certainly, butterflies will not be the only species of interest in conservation decisions. As opportunities to expand open space networks arise, planners should prioritize not only parcels considered 'robust' because they appear in multiple solutions for butterfly species, but also based on their inclusion in site-selection models for other taxa of conservation interest. In the case of Kane County, the results of this study could be compared with results from a similar effort focused on grassland birds (Snyder et al., 2007) to identify such priority sites.

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