A "GAP" ANALYSIS OF BIRD DISTRIBUTIONS IN SOUTHERN ONTARIO USING SIMULATED ANNEALING

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ABSTRACT.—In this paper we demonstrate the use of simulated annealing (an optimization technique) on large-scale field survey data to inform the design of protected area networks. We used Ontario's Breeding Bird Atlas (BBA) data because it has distribution information for 290 species during the breeding season. In southern Ontario, where landscapes have been largely transformed by agriculture and urban development, the BBA data covers 2,360 Universal Transverse Mercator (UTM) grid squares (approx. 10*10km/square). In this study we identified all species that did not occur in the major parks of the Province. We then identified the minimum number and location of UTM grid squares that would represent 5 percent of the breeding occurrences of these species in southern Ontario. There are a number of possible combinations of grid squares that meet the criteria. Four particular squares were selected in every run of the model. We visualize results in a geographic information system (GIS) to provide some insights on potential gaps in bird representation in the southern Ontario park network. We also describe implications and other possible applications.

INTRODUCTION

The government of Ontario has recently embarked on a review of its protected area network through the Lands for Life initiative (OMNR 1997). The Natural Heritage Areas Framework and Action Plan is aimed at developing a comprehensive system of parks and protected areas: "This natural heritage areas system will strive to represent the full range of natural diversity in the Province and will provide protection for other special natural heritage values important to society for their intrinsic worth" (OMNR 1996). This plan explicitly identifies one key theme as "[to conduct] the science and [identify the] methodologies needed to identify significant areas" [our interpretation]. In recent years, considerable spatial data on aspects of biodiversity have been developed in Ontario. Insights for designing protected area networks could be gained through the application of operations research techniques to much of this data. Results could be of use not only to the Ontario Ministry of Natural Resources and forest industry but also to groups like the Nature Conservancy, the Federation of Ontario Naturalists, the Canadian Wildlife Service, and other groups that have limited resources and want to more effectively focus their conservation efforts.

One purpose of protected areas or nature reserve networks is to represent and hence help to sustain biological diversity in a regional context (Margules et al. 1994; see also Mackey et al. 1989). Thus, an element of a protected area review is an assessment of how well current parks and/or reserves sample enduring landform features and the distribution of plant and animal species. The corollary of this problem is to identify locations of species that are not protected by reserves. This is not a trivial problem. For example, Canada has 3,269 species of native plants, 81 species of reptiles and amphibians, and approximately 426 bird species (Mosquin and Whiting, 1992). Pinning down actual and potential distributions is challenging given the wide range of influences affecting species (e.g., climate, nutrients, species interactions, land use—see Gaston 1990 for a review).

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Much has been written about both the theory and practice of designing ecological reserves (e.g., Soulé 1986). The topic is becoming increasingly mathematical (Pressey et al. 1997). Aside from the specific issue of designing a network of reserves, the broader issue of land allocation and management can be boiled down to problems in mathematical programming. Advantages of formulating these decisions as mathematical programming problems include a framework for organizing relevant data, an explicit statement of objectives and constraints, and a suite of tools for finding solutions. While considerable effort has also gone into the development of mathematical methods to help design protected area networks, they have had limited application in Canada. These methods make use of various types of environmental data (e.g., biological surveys, vegetation classifications, bioregionalizations) and range from scoring models (Bedward et al. 1992) and integer programming (Cocks and Baird 1989) to other types of heuristic algorithms (e.g. Lewis et al. 1991, Nicholls and Margules 1993, Csuti et al. 1997).

In this paper we demonstrate the use of simulated annealing to interrogate Ontario's Breeding Bird Atlas (BBA) data to inform the protected area planning process at a regional scale. The application has broader implications since BBA's have been developed for many states and Provinces in North America, Europe, and Australia. The specific methods used to create each atlas vary in detail but have many similarities, the most important being that they summarize the distribution of breeding of a diverse taxon over a large area. The BBA contains data on the distribution during the breeding season of all bird species known to inhabit the Province (summarized on a roughly 10*10 km basis). To demonstrate the approach, we addressed the question of what is the minimum number and locations of BBA squares that sample 5 percent of the breeding observations of all species not represented by parks in Ontario. This is just one possible question that can be addressed with these methods and data. The actual target for representativeness assessments and GAP analyses is to some extent problematic. Figures of 10 to 15 percent are commonly quoted but are subject to debate.

DATA AND METHODS

Breeding Bird Atlas of Ontario

The purpose of a bird atlas is to present the known breeding distribution of species found in the area of interest. The area of interest is usually divided into sampling grid squares. The sizes of these grid squares vary, but for Ontario they are UTM (Universal Transverse Mercator) squares of approximately 10 km x 10 km with some modifications for areas that cross UTM zones (Cadman et al. 1987). Grid squares were sampled for evidence of possible, probable, or confirmed breeding of all bird species. All sampling was conducted during the breeding season. In Ontario, each grid square included in the atlas had a minimum of 16 hours of sampling by volunteers between 1981 and 1985. The Atlas of the Breeding Birds of Ontario (BBA) (Cadman et al. 1987) represents the most comprehensive data on the distribution of breeding birds in Ontario. Ontario is a large Province (approx. 891,190 km^2) with most of the human population residing in its southern portions. There are 14,289 UTM squares in Ontario, of which 3,281 (23 percent) were sampled. We conducted our analyses only on the southern portion of the Province where the coverage was almost complete (2,109 of 2,360 possible grid squares) and habitat preservation is a more immediate concern given the extent of the transformation of its landscapes by agricultural and urban development (Fig. 1). Of the approximately 290 breeding bird species in Ontario (which represent approximately 75 percent of all species breeding in Canada), between 221 and 241 species breed in southern Ontario. This area consists of three major forest regions: Boreal Forest (mainly coniferous), Great Lakes-St. Lawrence Forest (mixed forest), and Carolinian Forest (dominated by broad-leaved trees) in which very few extensively wooded areas remain due to human modification.

The question addressed here concerns species that are not represented in parks. We obtained a digital GIS coverage of major Ontario parks from the World Wildlife Fund that contains boundary information for some, but not all, of the reserves (Table 1 and Fig. 2). For example, there are 13 migratory species reserves in Ontario totaling 33,132 hectares that are not part of this coverage (OMNR 1996).

Species that occurred in grid squares in Ontario parks were removed from the species list. Because our question related only to southern Ontario, species not found in any grid squares in southern Ontario were also removed (Table 2). The final data matrix for the analysis reported here contained 46 species and 2,191 BBA grid squares. We selected the confirmed breeding data in an attempt to be conservative in identifying important areas for birds since we considered confirmed breeding more important than possible breeding.

The Simulated Annealing Analysis

Simulated annealing is an optimization technique based on an iterative improvement algorithm (Kirkpatrick et al. 1983). It is based on an analogy of the annealing of metals. It works by searching through the solution space looking for continual improvement of the solution, but with a large enough random element included so that it is not likely to become stuck prematurely at a local minima. The random element starts off quite large and is then reduced to zero in the same way that temperature starts out high and is reduced in annealing.

A simulated annealing algorithm was used to identify the minimum number of locations that would represent 5 percent of the species' confirmed breeding locations in southern Ontario. This is an admittedly arbitrary target but should serve to illustrate the analyses. We should note that there is no guarantee that species not included in this analysis have 5 percent of their confirmed breeding locations in the current park network. This is just a function of our initial selection criterion and could be easily modified for future analyses. The algorithm was run on the data matrix 100 times since we expected that more than one solution would be generated and were interested in investigating robustness in terms of the relative importance of UTM squares. The frequency with which a particular square is included in a solution is indicative of its importance to complete representation of the bird fauna.

The iterative improvement algorithm is itself very simple, consisting of the following steps:

1. A random selection of the UTM squares is chosen from the complete list of squares.
2. This selection receives a score. This score consists of one part, the number of squares in the system (which we wish to minimize), plus another part, the deficit in representation for species.

   In a case where we simply want to represent each species at least once, this second value is the number of species that aren't represented. When we want to represent some species more than once (as in the 5 percent problem) this second number includes a measure for each under-represented species indicating how many extra squares would be needed to represent that species. For example, if a species was seen on 95 squares in total then 5 percent representation would mean that we need at least 5 squares to adequately represent this species. If we already had 2 squares with the species on it then the penalty for that species would be 3.
3. Squares from this complete list are chosen at random to check if they should be included or excluded. If the square is part of the selection, we consider excluding it. If the square is not in the current selection, we consider including it.
4. We determine the change to the selection's score that would occur if the chosen square were either included or excluded.
5. By this formulation it is best to have as low a score as possible. Hence we accept the change if it lowers the score and reject it if it doesn't lower the score.
6. We go back to step (3) and repeat until no more changes are possible.
7. Having finished, it is possible that some species are still not represented. This occurs when the only way to include each new species is to add a square. Since we only get one new species for each added square, the score isn't lowered and the change isn't accepted. This is a desirable conclusion because it can often leave us with a suite of possible selections that represent each species all being of equal value.

The algorithm can be described more precisely as follows:

Starting with the cost system,

$$c = \sum_{i=1}^{m} x_i + p \sum_{j=1}^{n} STEP(\sum_{i=1}^{m} a_{ij}\, x_i)$$

1

where

$$STEP(x) = \begin{cases} 1 \; x > 0 \\ 0 \; x \leq 0 \end{cases}$$

c is the cost that we wish to minimize, and x_i are the states of the site vector $\boldsymbol{X}$ (1 if site i is included in the system and 0 otherwise). The penalty scalar (p) for not representing a bird, is typically set to either 1, or even 1.001 to make the representation of a bird worth slightly more than one site. The elements a_{ij} in matrix $\boldsymbol{A}$ are set to 1 if bird j has been seen in site I, and 0 otherwise.

The cost function for the 5 percent problem is a variation on this one with a more complicated method to determine the penalty, analogous to the one above, for not representing a bird.

1. Randomly choose an initial reserve system **X** and set initial 'temperature' $T = T_0$ and 'temperature length' $\boldsymbol{L}$ (an integer).
2. Select a site I at random.
3. Calculate Dc, the change in the value of c if the state of x_i were to change, i.e., from 1 to 0 or from 0 to 1.
4. If $Dc < T$ (the change criteria) then change the state of x_i.
5. Repeat steps 2 to 4 L times.
6. Reduce T and increase L by the appropriate factor. Go to 5. This is repeated until $T = 0$ after which the process terminates.

The resultant vector $\boldsymbol{X}$ is the solution.

This is just one realization of iterative improvement, but it is the one that fits in nicely with simulated annealing. The problem of iterative improvement algorithms is that they could get 'stuck' in a local minima rather than the global one. This would occur where changing any one square might not lead to an improvement but by changing two or more simultaneously you could get an improvement. Simulated annealing is a method that can decrease the chance of getting stuck in any local minima by allowing some moves that do not improve the value of the solution. The probability of bad moves decreases as the annealing process continues so that the final moves are all improvements (Otten and van Ginneken 1989).

The main subtlety in the simulated annealing technique is determining an appropriate annealing schedule. The type of annealing schedule determines how long the algorithm needs to run in order to produce valuable results. In our implementation, we have used a simplified negative exponential function as the basis for annealing. Although this increases the number of repetitions needed, it simplifies computation.

RESULTS AND DISCUSSION

Seventy bird species were not found in the UTM squares sampled by the entire Ontario park network. Eleven of these species did not have any observations in the south and were eliminated. Ten more species did not have any breeding observations in the south and were also eliminated from the analyses (Table 2). Thirteen of the remaining

species are listed as threatened, endangered, or vulnerable by the Canadian Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and hence are considered to be of particular concern (Cook and Muir 1984).

In 100 runs, the mean number of grid squares required to sample 5 percent of the breeding distribution of all 46 species was 29. As noted, given the nature of simulated annealing, there is some variation in the number and configuration of grid squares in the final solutions. More than 50 percent of the grid squares were selected 1 or 2 times in the 20 solutions reported in Figure 3. These grid squares are the least critical or the most easily replaced by other UTM locations. Four locations were selected in all of these 20 runs. These sites have been selected because they seem to represent four particular species: Cinnamon Teal (*Anas cyanoptera*), Mountain Bluebird (*Sialia currucoides*), California Gull (*Larus californicus*), and Peregrine Falcon (*Falco peregrinus*). The first three of these are actually outside of their normal range (i.e., western species) so their appearance in Ontario could be considered as not very important (an anomaly). The Peregrine Falcon does not breed in Ontario anymore except where it has been introduced. The BBA data is out of date in this regard. These results highlight the need for judicious species selection in this type of analysis. Bird species could be further filtered to include only those for which Ontario has a "conservation responsibility" (Cheskey 1996).

One advantage of an approach that generates multiple solutions is that more options or choices can be illustrated for decision makers. The fact that there are alternative solutions also demonstrates some flexibility in the approach. However, as the problem is articulated in a more sophisticated manner (e.g., criteria involving minimum distance from roads, contiguity), the number of choices would likely decrease because fewer sites would meet the specified criteria.

A map of the locations for one simulated annealing run shows no concentration of the selected UTM squares in any particular area, although many of the selected sites (14) occur along shorelines, areas more likely to offer high habitat diversity (Fig. 4). Some sites were more frequently included in solutions than others; the most critical squares are those that occur in the most solutions. For this simulation, there are no selected UTM squares in the vicinity of Algonquin Park (#43 in Fig. 2), the largest forested park in the study region. While this may seem counterintuitive to those familiar with Ontario birds, most of the species that do occur in this area are likely found in Algonquin park and would therefore not be included in the analysis. In addition, forest dwelling species would likely be represented in the northern park network (albeit not necessarily 5 percent of their distributions).

CONCLUDING COMMENTS

There is currently a review of the reserve network in Ontario. Methods and data are required to assess the effectiveness of current reserve network in representing Ontario's natural heritage. Formulating the reserve design problem as a mathematical programming problem and solving it using simulated annealing (or any other operations research method) has the advantage of providing a framework to organize relevant data and of making objectives explicit. Simulated annealing is one method well suited to large problems like the one presented here. BBA data provide a lot of information about the distribution of all bird species that occur in the Province. The analyses reported here identified areas of the Province that are not part of the current reserve network but that seem to be important for representing breeding locations. These particular locations could be considered for monitoring and/or conservation programs. For example, these may be areas that could be protected or where incentives could be given to landholders to reduce their use of pesticides or other bird-unfriendly activities.

We have presented an example of the sort of problem that needs to be addressed to review protected area networks. Some of the information necessary for a comprehensive Ontario analysis is still being developed, including a complete digital coverage of current protected areas. Also, specific questions could be more refined. For example, schemes to establish priority species are now under development (Cheskey 1996). The "importance" of species could then be incorporated into this type of analysis.

More importantly, the methods are not restricted to BBA data, this scale of analysis, or this particular problem configuration. For example, the methods we used could be applied at a scale more familiar to those working in forest operations. Consider a problem in which a forest manager wants to maintain a specified level of habitat for some large number of species. Spatially explicit habitat maps are being developed in Ontario and elsewhere by linking vegetation cover (e.g., Forest Resource Inventory) data to species life history information. At this scale, the spatial configuration (e.g., adjacency considerations) of habitat could be more critical. In principle, such analyses could also identify important locations in a manner that minimizes the impact on other land uses.

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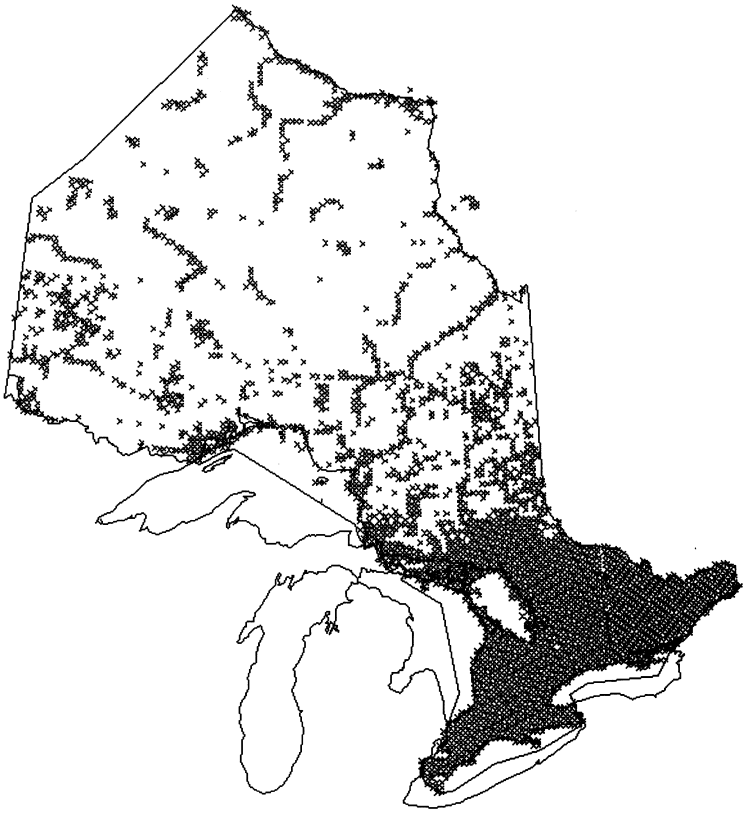

Figure 1.—Locations of BBA survey squares in Ontario.

Figure 2.—Boundaries of Provincial and National Parks available in digital form.

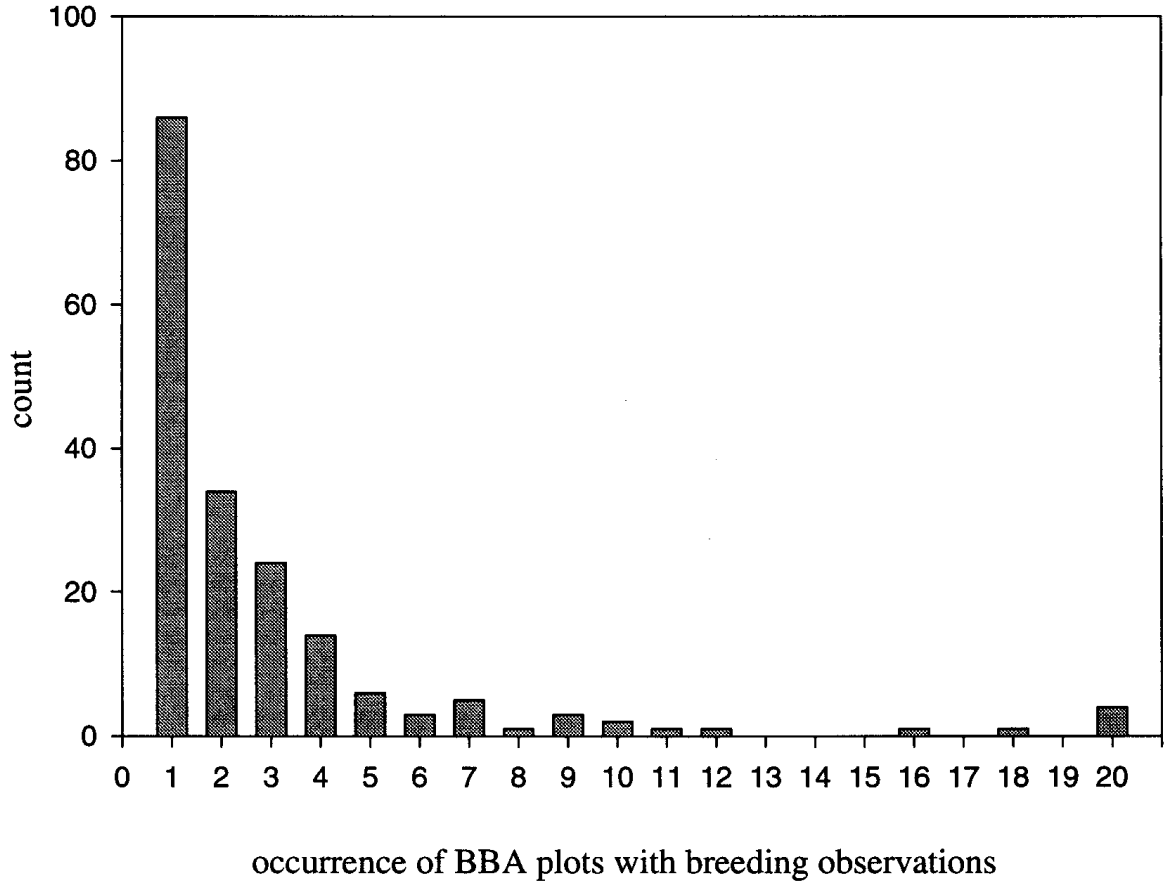

Figure 3.—Frequency histogram of the occurrence of BBA plots with breeding observations in 20 simulated annealing runs.

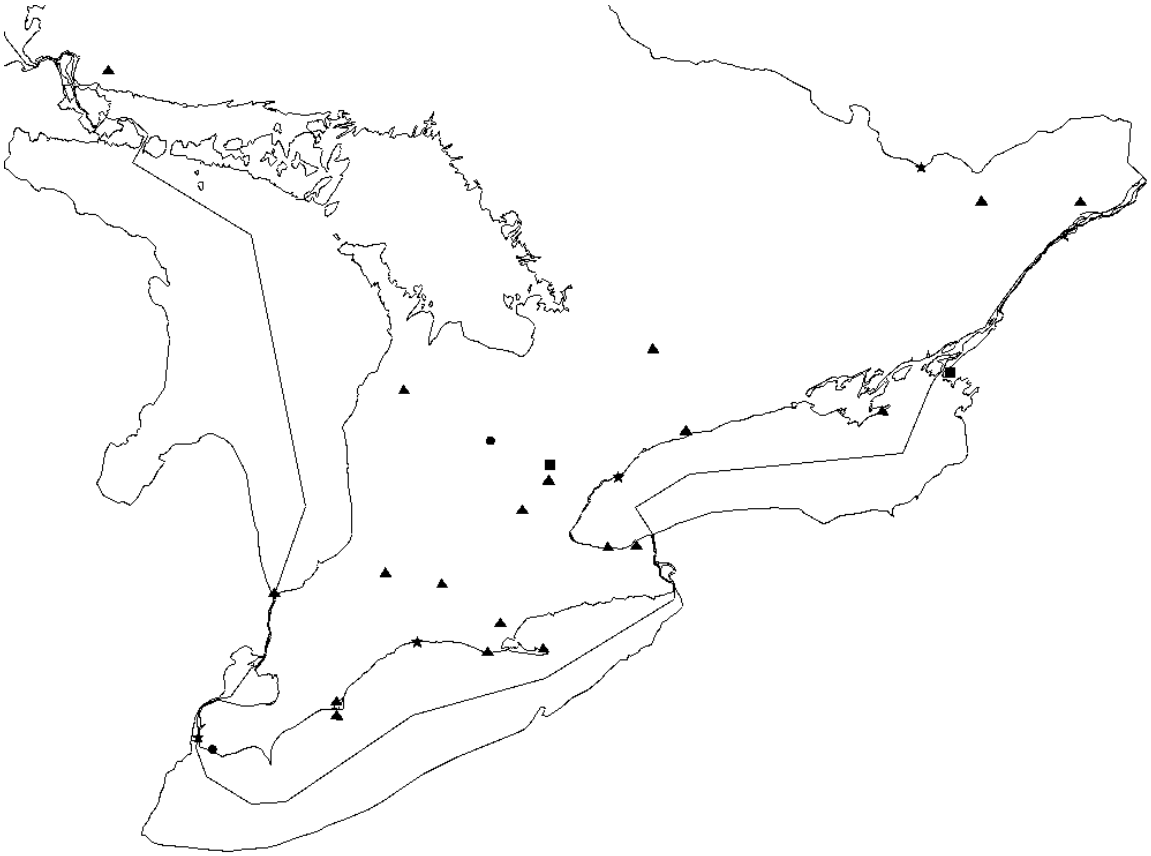

Figure 4.—Breeding BBA locations selected in one simulated annealing.

Table 1.—Provincial and national parks

Park no. and name	Area	Park no. and name	Area	Park no. and name	Area
	km²		*km²*		*km²*
1 Polar Bear	22,880.7	24 Sleeping Giant	223.0	46 Restoule	6.0
2 Winisk River	2,884.1	25 Pukaskwa	1,861.5	47 La Cloche	46.7
3 Opasquia Wilderness	4,734.3	26 Missinaibi River	531.8	48 Grundy Lake	36.8
4 Woodland Caribou	4,520.3	27 Kakabeka Falls	4.8	49 Dividing Lake	2.6
5 Kesagami Wilderness	807.4	28 Esker Lakes	34.4	50 Arrowhead	9.1
6 Wabakimi	1,676.1	29 Pie Islands	59.0	51 Killbear	12.8
7 Ojibway	23.2	30 Obatanga	91.3	52 Fathom Five	18.6
8 Winnange Lake	51.7	31 The Shoals	91.6	53 Bon Echo	55.8
9 Fushimi Lake	59.4	32 Lake Superior	1,313.2	54 Silent Lake	19.8
10 Little Abitibi	189.5	33 Michipicoten Island	184.6	55 Murphy’s Point	3.9
11 Sandbar Lake	46.3	34 Lady Evelyn-Smoothwater	739.4	56 Kawartha Highlands	19.5
12 Lake Nipigon	10.4	35 Wakami Lake	89.1	57 Awenda	21.2
13 Rene Brunelle	24.7	36 Aubrey Falls	51.4	58 Frontenac	48.1
14 Nagagamisis	46.2	37 Halfway Lake	48.7	59 Charleston Lake	10.5
15 Greenwater	49.1	38 Wanapetei	33.7	60 Petroglyphs	17.2
16 Quetico	4,447.7	39 Mississagi	62.8	61 Presquile	2.6
17 Ouimet Canyon	8.1	40 Mattawa River	75.3	62 Sandbanks	18.2
18 Silver Falls	46.3	41 Samuel de Champlain	15.5	63 Bronte Creek	7.6
19 Neys	34.5	42 Mashkinonje	9.5	64 The Pinery	23.8
20 White Lake	17.4	43 Algonquin	6,331.0	65 Rondeau	19.2
21/22 Slate Islands	38.7	44 South Bay	15.1	66 Point Pelee	21.6
23 Kettle Lakes	8.5	45 Killarney	442.9		

Digital park boundaries were provided by the World Wildlife Fund and derived from the 1:2,000,000 scale National Atlas Information Service.

Table 2.—Species not recorded in Breeding Bird Atlas squares in Ontario parks (only parks in Table 1 have been included in analysis). In parentheses (COSEWIC status[a], no. of obs., NB indicates spp. with no breeding obs. in southern region of Ontario).

Species	Species
Horned Grebe, *Podiceps auritus* (N,3,NB)	Red-headed Woodpecker, *Melanerpes erythrocephaus* (V,729)29)29)
Red-necked Grebe, *Podiceps grisegena* (N,11)	Acadian Flycatcher, *Empidonax virescens* (E,29)
Great Egret, *Casmerodius albus* (N, 20)	Carolina Wren, *Thryothorus ludovicianus* (N,39)
Cattle Egret, *Bubulcus ibis* (N,1)	Marsh Wren, *Cistothorus palustris* (N,427)
Yellow-crowned Night Heron, *Nyctanassa violacea* (N,2,NB)	Blue-gray Gnatcatcher, *Polioptila caerulea* (N,248)
Canvasback, *Aythya valisineria* (N,7)	Loggerhead Shrike, *Lanius ludovicianus* (E,145)
Redhead, *Aythya americana* (N,33)	White-eyed Vireo, *Vireo griseus* (N,19)
Rudy Duck, *Oxyura jamaicensis* (N,45)	Cerulean Warbler, *Dendroica cerulea* (V,108)
Cinnamon Teal, *Anas cyanoptera* (N,4)	Prothonotary Warbler, *Protonotaria citrea* (E,15)
Muted Swan, *Cygnus olor* (N,17)	Kirtland's Warbler, *Dendroica kirtlandii* (E,1,NB)
Golden Eagle, *Aquila chrysaetos* (N,4,NB)	Kentucky Warbler, *Oporonis formosus* (N,9,NB)
Peregrine Falcon, *Falco peregrinus* (E,3)	Blue-winged Warbler, *Vermivora pinus* (N,139, NB)
Gray Partridge, *Perdix perdix* (N,112)	Lawrence's Warbler, *Vermivora chysotera x V. pinus* (N,4)
Sharp-tailed Grouse, *Tympanuchus phasianellus* (N,54)	Brewster's Warbler, *Vermivora chrysotera x V. pinus* (N,24)
Ring-neck Pheasant, *Phasianus colchicus* (N,331)	Hooded Warbler, *Wilsonia citrina* (T,21)
Wild Turkey, *Meleagris gallopavo* (N,19)	Louisiana Waterthrush, *Seiurus motacilla* (V,40)
Northern Bobowhite, *Colinus virginianus* (E,79)	Yellow-breasted Chat, *Icteria virens* (V,45)
Piping Plover, *Charadrius melodus* (E,3)	Summer Tanager, *Piranga rubra* (N,2,NB)
Upland Sandpiper, *Bartramia longicauda* (N,709)	Dickcissel, *Spiza americana* (N,2,NB)
Wilson's Phalarope, *Phalaropus tricolor* (N,47)	Grasshopper Sparrow, *Ammodramus savannarum* (N,442)
California Gull, *Larus californicus* (N,1)	Henslow's Sparrow, *Ammodramus henslowii* (E,38)
Greater Black-backed Gull, *Larus marinus* (N,15)	Western Meadowlark, *Sturnella neglecta* (N,80)
Black Tern, *Chlidonias niger* (N,344)	Orchard Oriole, *Icterus spurius* (N,113)
Yellow-billed Cuckoo, *Coccyzus americanus* (N,352)	House Finch, *Carpodacus mexicanus* (N,187)
Eastern Screech Owl, *Otus asio* (N,617)	Purple Gallinule, *Porphyrula martinica* (N,2,NB)
Northern Hawk Owl, *Surnia ulula* (N,9,NB)	Mountain Bluebird, *Sialia currucoides* (N,1)
Common Barn Owl, *Tyto alba* (V,6)	Yellow-headed Blackbird, *Xanthocephalus xanthocephalus* (N,14)
Chuck-will's-widow, *Caprimulgus carolinensis* (N,6)	
Red-bellied Woodpecker, *Melanerpes carolinus* (N,115)	

[a] COSEWIC (Committee on the Status of Endangered Wildlife in Canada) status: N = no status, E = endangered, T = threatened, V = vulnerable.