SITE ACCESSIBILITY AND PRIORITIZATION OF NATURE RESERVES

Hayri Önal *

Associate Professor
Department of Agricultural and Consumer Economics,
University of Illinois at Urbana-Champaign.

Pornchanok Yanprechaset

Graduate student
Department of Agricultural and Consumer Economics
University of Illinois at Urbana-Champaign.

* Corresponding author, Tel: (217) 333-5507, E-mail: h-onal@uiuc.edu

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ABSTRACT

Spatial layout of nature reserves is important in conservation planning, but existing studies mostly ignored spatial considerations. This paper presents an integer programming approach to determine a reserve network with maximum accessibility while providing full protection to targeted species. We present an empirical application to endangered/threatened birds in Illinois.

Key words: conservation reserve, species representation, site accessibility, linear integer programming.

Introduction

Restricting the commercial use of ecologically critical lands, particularly for agriculture and urban development purposes, and managing those lands as habitats for endangered/threatened species is considered as an effective means of nature preservation. Given that conservation resources are scarce, cost-effective selection of critical habitat areas has been a main focus in the biological conservation literature in the past decade. Two key factors considered for site selection are habitat quality (such as species richness) and economic value (acquisition cost) of potential reserve sites (see, for example Ando et al. 1998). Many studies formulated the problem as either minimizing the number of sites (or total cost) for protecting a set of target species, or maximizing the number of protected species under a given budget restriction (Underhill 1994; Camm et al. 1996; Church, Stoms and Davis 1996; Williams and ReVelle 1997; Polasky, Camm and Garber-Yonts 2001; Polasky et al. 2001; Rodrigues and Gaston 2002). In practice, besides economic and ecological factors, social preferences also play an important role in species protection and funding decisions. Metrick and Weitzman (1996) point out that among over 500 federally listed endangered species in the USA, just ten species account for more than half of the total expenditures and eight of those top ten species are birds. Although some of those 10 species are actually less endangered than many other species in the spending list, they are ranked highly because of the subjective judgment of policy makers, which presumably reflect the preferences of society. Likewise, some sites may be preferred to others because of their geographical location even though they may cost more and provide less habitat services than alternative sites. This is because usually conservation sites not only protect habitat-stressed, rare or endangered species, but they also provide welfare (recreation) services, which is particularly important for people who live in urban areas. Preserving wildlife was once thought as something that happens

in distant rural areas (e.g. national parks). In recent years establishing conservation reserves within urban fringes or in reasonably close and accessible areas has been popular among urban residents as this improves the quality of urban life. When acquiring land and converting it into a nature reserve, a stronger public support can be ensured if the site is easily accessible and serves both biological conservation and social welfare objectives. Unfortunately, a win-win solution may not always be available and a trade off may exist between ecological, economic, and social objectives. Consideration of the welfare factor as an additional reserve design criterion may alter the attractiveness of potential reserve sites and place more emphasis on ecologically poor sites that might be more accessible than relatively rich but less accessible sites. Although establishing conservation reserves near urban areas is often more costly due to higher land values, particularly near metropolitan areas, substantial spending for major community-based conservation programs (such as the Chicago Wilderness Project) has been approved by voters in state and local referenda and a significant amount of privately owned lands has been converted to nature reserves within or near urban settlements (Hollis and Fulton 2002; Miller and Hobbs 2002). Analyzing the tradeoffs between ecological, economic, and social objectives and developing compromise strategies by considering these often conflicting objectives is the main motivation of the present study.

Research problem

Illinois is one of the major agricultural regions in the USA supplying about one third of the national corn and soybeans production. Once covered almost entirely by forests, prairies, and wetlands, the State has lost much of its biodiversity due to the conversion of land into farmland. Agricultural land dominates the landscape today, 78%, while urban settlement covers nearly 6% of the State's total area. The Shawnee National Forest in the south has a diverse ecosystem and

includes two wetlands in the Cache River basin which are among the United Nations top 15 ‘wetlands of international importance’ (Illinois Department of Natural Resources [IDNR], 2001). In contrast, the northeastern part of the State is densely populated (see Figure 1a), including the Chicago metropolitan area (the third largest in the country). Despite the wide-ranging urbanization, the ecologically rich Fox River watershed, which includes more than 100 state-endangered plant species (two of which are also listed as federally endangered), is located in the same region (see Figure 1b). A report by Illinois Endangered Species Protection Board (1999) identified 93 animal species and 265 plant species as state-endangered (16 animal species were also listed as federally endangered), while 35 animals and 66 plants were identified as state-threatened. The list is being updated continuously. As of 2003, 424 species were listed as state-endangered or threatened (E/T) and 24 species were listed as federally E/T (IDNR). Several major conservation programs have been introduced in the past decade to maintain or restore environmentally and ecologically sensitive areas. The Conservation Reserve Enhancement Program and Illinois Open Land Trust Initiative, supported by federal and state funding, are typical examples of such efforts. These programs aim at acquisition or easement of more than 150,000 acres of critical farmlands, mostly around rivers and in the floodplains, to protect and enhance the natural resource base and wildlife in the State.

The U.S. government mandates all states to develop ‘Comprehensive Wildlife Conservation Plans’ (CWCP). Responding to this need, Illinois has initiated the Critical Trends Assessment Program (CTAP) in 1991 to compile and analyze new and existing data on the State’s natural resources, ecosystems, and environment. Both field data and satellite imagery have been used to generate a comprehensive database on resource-rich conservation areas. Currently IDNR is in the process of developing the State CWCP, which is expected to form a

blueprint of Illinois' long-term conservation plan. The plan is required to address wildlife and habitat issues and place priorities on those species of greatest conservation need in light of the limited funding. The state conservation efforts focus primarily on the protection of E/T animals, particularly birds (although not stated explicitly, this is due to the fact that animals are considered as a higher form of life, which indicates the importance of subjective judgments and policy preferences in conservation planning). A substantial amount of data has been collected during the past decade to develop an inventory of suitable bird habitats scattered throughout the State. Due to both the data availability and the importance of bird populations and habitats for urban residents, this study is restricted to the state-E/T bird species only. When identifying the critical bird habitats that must be given higher priority for protection, their proximity to urban areas is taken into account as a decision factor besides the usual economic and ecological factors that drive conservation policies and plans. These three criteria are integrated in a mathematical modeling framework to determine an optimal conservation plan.

Previous studies

Selection of an efficient reserve network has been the focus of a number of studies in the biological conservation literature especially in the past decade. Many studies have approached the optimum site selection problem using heuristic methods (e.g. Margules, Nicholls and Pressey 1988; Vane-Wright, Humphries and Williams 1991; Nicholls and Margules 1993; Pressey et al. 1993; Pressey, Possingham and Margules 1996; Csuti et al. 1997; Pressey, Possingham and Day 1997; Briers 2002; Nalle et al. 2002a, 2002b). Although being practical, particularly in large scale applications, usually heuristic selections require significantly more sites than necessary and may therefore lead to an inefficient resource allocation (Church, Stoms and Davis 1996; Pressey, Possingham and Margules 1996; Rodrigues and Gaston 2002; Önal 2003). To overcome this

deficiency, formal optimization has been employed in many studies where biological and economic considerations are coupled in a linear integer programming framework. Two prototype integer programming formulations have been used extensively in the literature. The 'set covering' formulation states the problem as selecting a minimum number of reserve sites to represent (or cover) a specified set of species (e.g. Ando et al. 1998; Polasky, Camm and Garber-Yonts 2001; Polasky et al. 2001). Alternatively, the 'maximal covering' formulation states the problem as maximization of the number of species that can be protected with a given budget availability (Church and ReVelle 1974; Underhill 1994; Camm et al. 1996; Williams and ReVelle 1997). Both approaches present a static and deterministic approach to the problem. Haight, ReVelle and Snyder (2000) and Camm et al. (2002) incorporated uncertainty into the maximal covering framework while Costello and Polasky (2004) incorporated dynamic aspects of site selection decisions in a dynamic programming framework.

An important shortcoming of the prototype optimization formulations described above is the negligence of spatial factors in site selection. Typically, both the set covering and maximal covering solutions exhibit a highly dispersed reserve configuration which may not be consistent with conservation policy objectives. Building upon the two basic formulations, several optimization studies incorporated spatial aspects in site selection, such as compactness, total boundary size, reserve connectivity (adjacency), etc. (Sessions 1992; Hof and Joyce 1993; Williams 1998; Hof and Bevers 1998; Williams and ReVelle 1996, 1998; McDonnell et al. 2002; Önal and Briers 2002, 2003). In a recent study, Ruliffson et al. (2003) included public accessibility of reserve sites as an additional spatial consideration, besides the usual species representation and economic criteria, for determining optimal acquisition of privately owned lands to be converted into nature reserves in the Chicago metropolitan area. Because of the

similarities in research motivation and objectives between the present study and the Ruliffson et al. study, the latter will be discussed in some detail below and the methodological differences between the two studies will be explained.

Methodology

A linear integer programming model is developed here to determine an optimal subset of potential reserve sites that best serves the conservation policy objectives stated at the outset. Specifically, given a limited amount of conservation resources, the reserve network must be ecologically and economically feasible in that all targeted species must be protected collectively by the selected sites and the budget constraint must be satisfied by that selection. Furthermore, the network must be 'socially efficient' in that the selected sites must be accessible at minimum 'social cost'. The approach, terminology, and the underlying modeling assumptions will be described below, which will be followed by the description of the algebraic model.

The species representation requirement is modeled by employing the usual set covering approach which will be explained briefly when presenting the algebraic model. The social cost consideration is the delineating feature of the present study and needs some elaboration before introducing the model. We assume that a site is 'accessed' by an urban area when a certain proportion of the population of that urban area visits that particular site, in which case all species existing in that site are assumed to be accessed (observed) by that area. In order to assign an equal weight to the residents of all urban areas, the proportion of visitors in the total population of each area is assumed to be uniform across all urban areas and all sites. With this assumption, the cost of accessing a given site is higher for a heavily populated urban area than it is for a less populated area, and for each urban area the cost of accessing a remote site is more than the access cost to a nearby site. As a proxy to the social cost, for each urban area we consider the

‘travel cost’ to all accessed sites, which is defined as a scalar multiple (given by the visitors ratio in total population times the travel cost per unit distance) of the urban population times the total distance traveled. The aggregate social cost consists of the sum of those costs over all urban areas. Finally, when computing the minimum social cost we require that all urban areas must have complete access to all species under consideration, namely each area observes every species at least once by accessing an appropriate subset of sites. This conceptual framework favors a reserve network that is clustered around major urban settlements, to the extent possible. The optimal reserve configuration depends on: i) the location and population of urban areas, ii) the location of potential reserve sites and species’ presence in each site, and iii) the cost of land acquisition associated with each site. The present analysis incorporates the first two of those factors.

The notation used in the model is as follows: The symbols k, s and i denote urban areas, targeted species, and reserve sites, respectively. Each reserve site includes a known subset of species, which is represented by a_{is} where a_{is}=1 indicates that species s is present in site i and a_{is}=0 otherwise. The distance between reserve site i and urban area k is denoted by d_{ik} ; p_k denotes the population of urban area k; and m denotes the reserve size (number of sites). In order to improve the species persistence and effectively protect each species, at least r_s sites in which species s is present must be selected, where $r_s \geq 1$ is an integer that can be specified differently for each species. X_i is a binary variable where X_i =1 if site i is selected and X_i=0 otherwise; V_{ik} is a binary variable where V_{ik}=1 if site i is accessed by area k and V_{ik}=0 otherwise. The following linear integer programming model determines the most accessible (or least cost) reserve network with m sites while satisfying the species representation requirement:

(1) $$\text{Minimize} \sum_{i,k} d_{ik} p_k V_{ik}$$

such that :

(2) $$\sum_i a_{is} X_i \geq r_s \quad \text{for all } s,$$

(3) $$\sum_i a_{is} V_{ik} \geq 1 \quad \text{for all } k, s,$$

(4) $$V_{ik} \leq X_i \quad \text{for all } k, i,$$

(5) $$\sum_i X_i \leq m$$

(6) $$X_i, \; V_{ik} = 0,1$$

The objective function (1) represents the 'total cost of travel' to all sites accessed by all urban areas (different sites can be accessed by different urban areas). Note that the travel cost as defined here is not represented in monetary units, rather it is in miles-people, which is viewed as a proxy (up to a scale factor) to the true travel cost.

Constraint (2) reflects the usual species representation requirement, which guarantees that the selected sites collectively cover the targeted species. This constraint implies that X_i =1 for at least r_s sites for which a_{is}=1, i.e. at least r_s sites including species s must be part of the reserve network. Constraint (3) states that each urban area must have access to every species by visiting an appropriate subset of the reserve sites (to be determined by the model). Constraint (4) implies that if a particular site is accessed by any urban area, it has to be part of the network. This is so because if V_{ik} =1 for some *k*, then we must have X_i =1, i.e. site *i* must be selected. Conversely, if X_i=0 then V_{ik} =0 for all *k*, which means that if site *i* is not selected it cannot be accessed by any urban area. Note that more than one area can have access to the same site. Constraint (5) represents the reserve size restriction which may be due to a budget constraint or any other limitation. If an explicit budget restriction applies, this constraint can be modified as $\sum_i c_i X_i \leq b$, where c_i is the land acquisition cost associated with site *i* and *b* is the budget

availability. Finally, binary values are imposed for X_i and V_{ik} by (6).

The standard set covering formulation without any spatial considerations includes constraint (2) only, with r_s =1 for all s, while minimizing either $\sum_i c_i X_i$ or $\sum_i X_i$. This formulation is used first in the empirical application presented below to demonstrate the implications of spatial considerations on reserve design within the framework described above.

An important property of the model must be noted here. The binary restriction for V_{ik} can be relaxed by defining these variables as nonnegative continuous variables. Despite this relaxation, the model will always return binary values in the solution for all V_{ik} . The reason for this is as follows. First, note that (4) implies that $0 \leq V_{ik} \leq 1$. Suppose $V_{ik}>0$ for some i, k. Then there must be a unique species s that is present only in site i among all the sites for which $V_{ik}>0$ in the solution. This is so, because if there is no such species, every species covered by site i would also be covered by some other site in which case site i would be redundant since having that site in the reserve would increase the travel cost (by $d_{ik}\, p_k\, V_{ik}>0$) without any contribution to species accessibility. Also, constraint (3) can be rewritten as $\sum_{i:a_{is}=1} V_{ik} \geq 1$ for all s. Consider this equation for the unique species that is present only in site i. Since site i is the only such site, the summation reduces to a singleton and we must have V_{ik}=1. Thus, either V_{ik}=0 or V_{ik} =1. This property is numerically verified in the empirical application of the model presented below. Computational convenience offered by this property is extremely important, particularly when a large number of sites and urban areas are involved in the analysis. A large number of binary V_{ik} variables would be involved in such cases, which would increase the computational difficulty exponentially.

Ruliffson et al. (2003) have dealt with a similar problem by extending the maximal covering formulation to determine an optimally accessible open space network in a metropolitan area. Their formulation maximizes the number of urban settlements having access to the selected sites while satisfying a species representation constraint and a budget constraint. A city or town is assumed to have access to the reserve network if at least a specified number of sites within a specified distance from the city/town are included in the network. Two important factors delineate their approach from the approach presented in this paper. First, the size of urban settlements was not incorporated by Ruliffson et al. and all cities/towns were considered as the same regardless of their population. This may not be consistent with social equity considerations as it would place (implicitly) less emphasis on the welfare gains of large city residents while the opposite would occur for small towns. Second, when determining whether a city/town has access to the reserve network, habitat characteristics (i.e. species richness) of accessed sites were not taken into account. Thus, their approach is blind to the species' presence in selected sites and may not well represent the benefits (utility) derived from access to open spaces. Consider two extreme options, for instance, where in one case all the sites accessed by an urban settlement cover just one species while in the other case the sites are fully complementary and cover the entire set of species included in the analysis. These two cases must be viewed as substantially different according to any notion of utility, but the formulation by Ruliffson et al. is indifferent between them. Defining the access at species level and incorporation of travel costs reflecting both the traveled distances and the population of urban areas, as done in this paper, eliminate both of these deficiencies.

Model specification and data

The model described by (1)-(6) is applied to 32 E/T bird species that have been observed in

various habitat areas scattered throughout Illinois. The entire State map is partitioned with a grid cover, where each grid cell covers an area of about 15 square miles. Each habitat site is placed in the corresponding grid cell, which will be considered as decision making units here and will be referred to as 'sites'. A total of 744 cells were identified as potential reserve sites to cover the 32 bird species (Figure 1b). Most sites are located in major watersheds, such as Rock River (north), Fox River (northeast), Mississippi Lower Rock (northwest), Middle Illinois River and Big Rivers (central/central west), Upper and Lower Wabash River (east), the Southern Till Plain (south-central), and the Shawnee National Forest (south). Some species are rare and can be found in only a few sites (11 species are present in 10 sites or less, 6 of those are present in less than 4 sites), while some species are relatively common and are present in many sites (9 species are found in more than 70 sites). Table 1 presents the list of bird species included in the analysis and the number of sites covering each species. The location and species coverage of individual sites were obtained from IDNR. In order to restrict the model size to a manageable level, the top 25 most populated counties (with more than 50,000 residents) are considered as the urban areas. The population distribution among those counties is very uneven. As shown in Figure 1a, most counties are in the 50-200 thousand population range (7 counties have less than 100 thousand residents), while 5 counties in the northeast are densely populated (three of them have between 400-600 thousand residents, one has 900 thousand, and Cook county, where the metropolitan Chicago is located, has 5.4 million residents). For travel cost calculations a simplifying assumption was made, namely the entire population of each county was assumed to be concentrated at the center of the county. The latitude and longitude data for individual sites and county centers were used to determine the distances between each county and each site.

In order to improve the survival chances of highly endangered species, in this application

it is required that each species must be present in at least three selected sites, i.e. r_s=3 for all s, except *Common Tern* and *Wilson's Phalarope*, which are present in only two sites and one site, respectively (see Table 1). Accordingly, the minimum site selection requirements for the latter two species were specified as 2 and 1, respectively. With these specifications, the mixed integer programming model described above included 19,434 equations and 19,345 variables 744 of which were binary variables. *GAMS* (Brooke et al. 1998) incorporated with *CPLEX* was used to solve the model. Despite this very large model size, CPLEX.8.1 worked incredibly well in this particular problem and could determine the exact optimum solution within seconds without performing any branch and bound iterations.

Results

To demonstrate the effects of spatial considerations on optimal reserve network configuration, we first solved the standard set covering problem by minimizing the number of selected sites with the model specifications described above. Then we solved the problem with the same specifications, but this time incorporating spatial considerations within the modeling framework described by (1)-(6). The spatially unconstrained solution obtained from the set covering formulation included 32 sites (this is just a coincidence and has nothing to do with the number of species, which is also 32. When double representation is required, for instance, instead of triple representation, the optimal reserve size would be 20. Quadruple representation would require 45 sites). This solution is shown in Figure 2a. Of those 32 selected sites 12 were in the northeast, where the ecologically rich Fox River watershed is located, 10 were in the Shawnee National Forest (south), and the remaining sites were scattered quite sparsely in other regions. If this selection was implemented and individual counties minimized their ‘ex-post travel costs’ by accessing some subsets of those 32 sites in order to observe each and every species, the total

travel cost for all 25 counties would be 13,063. This objective function value was found by fixing the site selection variables X_i at their set covering solution values and solving the model (1) - (6) for optimum values of V_{ik}'s that minimize (1).

Typically, plain set covering solutions are not unique, i.e. one can find alternative optimum selections with the same number of sites included in the reserve. This was the case in the present application also. To determine a socially preferred reserve network without increasing the reserve size (i.e. 32 sites), we specified the right hand side of constraint (5) as 32. Since this reserve size is minimal for the triple representation requirement there is little room for finding a spatially preferred selection (i.e. with reduced travel cost), but the model could still find a significantly improved solution. The selected sites are shown in Figure 2b. In this case 14 sites were selected in the northeast (2 sites more than the solution in Figure 2a) and 9 sites were selected in the south. This can be expected because nearly two thirds of the entire population of Illinois resides in the northeastern part of the State. Not only more sites are selected in the northeast, the selected sites were closer to the two most densely populated counties (namely Cook and DuPage). The total travel cost accruing to all counties was reduced nearly by 10%, from 13,063 to 11,860.

When the travel cost is minimized for each county individually, while requiring that the county observes every species at least once but without requiring triple representation of individual species, most counties would select 10 sites (some select 11 or 12 sites). However, because of the independence of site selection decisions, a total of 52 sites were selected by all 25 counties, instead of 32 sites. This solution is shown in Figure 3a. In this case, 5 sites included in the minimal reserve selection (Figure 3b) were not selected by any county, whereas 25 additional sites were included in the county solutions. The excluded sites were mostly in the south (4 out of

5), but the extra sites did not exhibit any particular spatial pattern. Despite the increase in the number of selected sites, not all species were adequately represented. Specifically, two species, *Little Blue Heron* and *Snowy Egret* would be covered by only one site, while *Least Tern* and *Swainson's Warbler* would be covered by only two sites (in both cases the sites were different for different species). This is particularly due to the omission of 4 sites in the south, which were included in the set covering solution in order to meet the triple representation requirement. The total travel cost accruing to all counties was found as 11,722, only slightly less than the minimum travel cost found in the fully cooperative solution with minimal reserve size (i.e. 11,860). This shows the importance of coordinated decision making in conservation planning, that is state-wide coordination can be substantially more efficient in terms of both economic objectives (total cost to society, including the travel costs and land acquisition costs) and biological conservation objectives (survival likelihood of individual species). What is best for individual counties may not be best for the State and for society as a whole.

When 52 sites were allowed in the reserve network and those cells were selected cooperatively by all counties in order to minimize the aggregate travel cost accruing to all counties while again requiring the full representation of all species, the model selected 51sites, one less than the allowed reserve size. This finding shows that the socially optimal and fully representative (i.e. triple representation of individual species) reserve network requires 51 sites. This finding could also be obtained by solving the model without constraint (5). Of those 51 sites, 22 were located in the northeast. Both the number and location of those sites were identical with the configuration obtained in the optimal plans of individual counties. This could be expected intuitively since the urban settlement is heavily concentrated in the northeast and what is optimal for this region is likely to be optimal for the entire State. One site in the west-central

area was dropped and although the number of sites in the south was the same as in Figure 3a, their locations were somewhat different. The total travel cost obtained in this solution was 11,724, which is nearly identical with the total cost implied by the individual county plans and only 1% less than the total travel cost of the minimal representative reserve. Therefore, contrary to the intuition, the larger reserve network did not help much to reduce the travel cost. Since a higher cost is required for setting aside more land (i.e. 51 sites instead of 32), a larger reserve is not justified on economic grounds. However, selection of many sites in a small area can be beneficial not only for the people, but it can also contribute to the protection of endangered/threatened species as this would allow species to disperse and colonize neighboring sites more easily. This would also reduce the cost of management and maintenance of the reserve network. In conclusion, the justification of large reserve networks lies in the ecological benefits, rather than economics or human welfare (i.e. preservation utility) considerations.

Summary and Conclusions

This paper presented a methodology for incorporating ecological, economic and social objectives in a unifying framework to determine an optimal nature reserve design. A large scale linear integer programming model was developed for this purpose and applied to the state-endangered/threatened bird species in Illinois. Despite the large size of the model, the computational experience in this particular application proved that it could be solved within seconds by *GAMS/CPLEX*, which may well be the case in other applications. The empirical results show that all the targeted species can be protected in a small reserve network with 32 sites if triple representation of individual species is required. This minimal reserve network is not unique, however, and there are multiple reserve configurations with the same reserve sites. We

determined an alternative reserve network that minimizes the social cost of accessing selected reserve sites, which reduced the total travel cost by 10% with respect to the minimal reserve configuration. Several remote sites were replaced with alternative sites that are in close proximity to urban areas, which may be socially preferable as nature reserves also provide welfare (recreation) services and accessibility of those sites can be an important factor in both design and implementation of the conservation policies. Further reduction in social cost is possible by enlarging the reserve network, but the cost savings were marginal (only 1%). These results may be specific to the particular case studied here, and they may vary in similar case studies depending on the location of potential reserve sites and their species richness characteristics as well as the location and population characteristics of urban settlements. At least for the particular species conservation problem studied here, the results suggest that a large reserve network is not justified on economic grounds, as setting aside more sites did not significantly reduce the total travel cost while increasing the cost of land acquisition. However, a large reserve network can be beneficial for many species, as they can easily disperse and colonize nearest sites if a spatially compact reserve network can be developed. This may also be helpful for reducing monitoring and maintenance costs, which are not incorporated in this study.

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References

Ando, A., Camm, J.D., Polasky, S. and Solow, A., 1998. Species distribution, land values and efficient conservation. *Science* **279** 2126-2128

Briers, R. A. 2002. Incorporating connectivity into reserve selection procedures. *Biological Conservation* **103** 77-83.

Brooke, A., D. Kendrick, A. Meeraus, and R. Raman. 1998. *GAMS- A User's Guide*. GAMS Development Corporation, Washington DC.

Camm, J.D., S. Polasky, A. Solow, and B. Csuti. 1996. A note on optimal algorithms for reserve site selection. *Biological Conservation* **78** 353-355.

Camm, J.D., S.K. Norman, S. Polasky, and A. Solow. 2002. Nature reserve site selection to maximize expected species covered. *Operations Research* **50** 946-955.

Church, R.L. & C. ReVelle. 1974. The maximum covering location problem. *Papers of the Regional Science Association* **32** 101-118.

Church, R.L., D.M. Stoms, and F.W. Davis. 1996. Reserve selection as a maximal covering location problem. *Biological Conservation* **76** 105-112.

Costello, C. and S. Polasky. 2004. Dynamic reserve site selection. *Resource and Energy Economics* **26** 157-174.

Csuti, B., S. Polasky, P. H.Williams, R.L. Pressey, J.D. Camm, M. Kershaw, R. Kiester, B. Downs, R. Hamilton, M. Huso, and K. Sahr. 1997. A comparison of reserve selection algorithms using data on terrestrial vertebrates in Oregon. *Biological Conservation* **80** 83-97.

Haight, R.G., C.S. ReVelle, and S.A. Snyder. 2000. An integer optimization approach to a probabilistic reserve site selection problem. *Operations Research* **48** 697-708.

Hof, J.G. and L.A. Joyce. 1993. A mixed integer linear programming approach for spatially optimizing wildlife and timber in managed forest ecosystems. *Forest Science* **39** 816-834.

Hof, J.G. and M. Bevers. 1998. *Spatial Optimization for Managed Ecosystems*. Columbia University Press, New York.

Hollis, L.E. and W. Fulton. 2002. Open space protection: conservation meets growth management. Washington D.C.: The Brookings Institution Center on Urban and Metropolitan Policy.

Illinois Department of Natural Resources. 2001. Critical Trends in Illinois Ecosystems. Springfield, IL. http://dnr.state.il.us/orep/ctap.

Illinois Endangered Species Protection Board. 1999. Checklist of Endangered and Threatened Animals and Plants of Illinois. Springfield, IL.

Margules, C. R., A.O. Nicholls, R.L. Pressey. 1988. Selecting networks of reserves to maximise biological diversity. *Biological Conservation* **43** 63-76.

McDonnell, M. D., H.P. Possingham, I.R. Ball, and E.A. Cousins. 2002. Mathematical methods for spatially cohesive reserve design. *Environmental Modeling and Assessment* **7** 107-14.

Metrick, A. and Weitzman, M.L., 1996. Patterns of behavior in endangered species preservation. *Land Economics* **72**, 1-16.

Miller, J.R. and R.J. Hobbs. 2002. Conservation where people live and work. *Conservation Biology* **16**:330-337.

Nalle, D. J., J.L. Arthur, C.A. Montgomery, and J. Sessions. 2002a. Economic and spatial impacts of and existing reserve network on future augmentation. *Environmental Modeling and Assessment* **7** 99-105.

Nalle, D. J., J.L. Arthur, and J. Sessions. 2002b. Designing compact and contiguous reserve

networks with a hybrid heuristic algorithm. *Forest Science* **48** 59-68.

Nicholls, A. O. and C.R. Margules. 1993. An upgraded reserve selection algorithm. *Biological Conservation* **64** 165-169.

Önal, H. 2003. First best, second best, and heuristic solutions in conservation reserve selection. *Biological Conservation* **115** 55-62.

Önal, H. and R.A. Briers. 2002. Incorporating spatial criteria in optimum reserve selection. *Proceedings of the Royal Society of London B* **269** 2437-2441.

Önal, H. and R.A. Briers. 2003. Selection of a minimum boundary reserve network using integer programming. *Proceedings of the Royal Society of London B* **270** 1487-1491.

Polasky, S., B. Csuti, C. A. Vossler, and S. M Meyers. 2001. A comparison of taxonomic distinctness versus richness as criteria for setting conservation priorities for North American Birds. *Biological Conservation* **97** 99-105.

Polasky, S., J.D. Camm, and B. Garber-Yonts. 2001. Selecting biological reserves cost-effectively: an application to terrestrial vertebrate conservation in Oregon. *Land Economics* **77** 68-78.

Possingham, H., I. Ball, and S. Andelman. 2000. Mathematical methods for identifying representative reserve networks. In *Quantitative Methods for Conservation Biology* (ed. S. Ferson & M. Burgman), pp. 291-306. Springer, New York

Pressey, R. L., C.J. Humphries, C.R. Margules, R.I. Vane-Wright, and P.H. Williams. 1993. Beyond opportunism: key principles for systematic reserve selection. *Trends in Ecology and Evolution* **8** 124-128.

Pressey, R. L., H.P. Possingham, and C.R. Margules. 1996. Optimality in reserve selection algorithms: when does it matter and how much? *Biological Conservation* **76** 259-267.

Pressey, R. L., H.P. Possingham, and J.R. Day. 1997. Effectiveness of alternative heuristic algorithms for identifying indicative minimum requirements for conservation reserves. *Biological Conservation* **80** 207-219.

Rodrigues, A. S. L. and K.J. Gaston. 2002. Optimisation in reserve selection procedures - why not? *Biological Conservation* **107** 123-129.

Ruliffson, A.A., R.G. Haight, P.H. Gobster and F.R. Homans. 2003. Metropolitan natural area protection to maximize public access and species representation. *Environmental Science and Policy* **6** 291-299.

Sessions, J. 1992. Solving for habitat connections as a Steiner Network problem. *Forest Science* **38** 203-207.

Underhill, L.G. 1994. Optimal and suboptimal reserve selection algorithms, *Biological Conservation* **70** 85-87.

Vane-Wright, R. I., C.J. Humphries, and P.H. Williams. 1991. What to protect? Systematics and the agony of choice. *Biological Conservation* **55** 235-254.

Williams, J. C. 1998. Delineating protected wildlife corridors with multi-objective programming. *Environmental Modeling and Assessment* **3** 77-86.

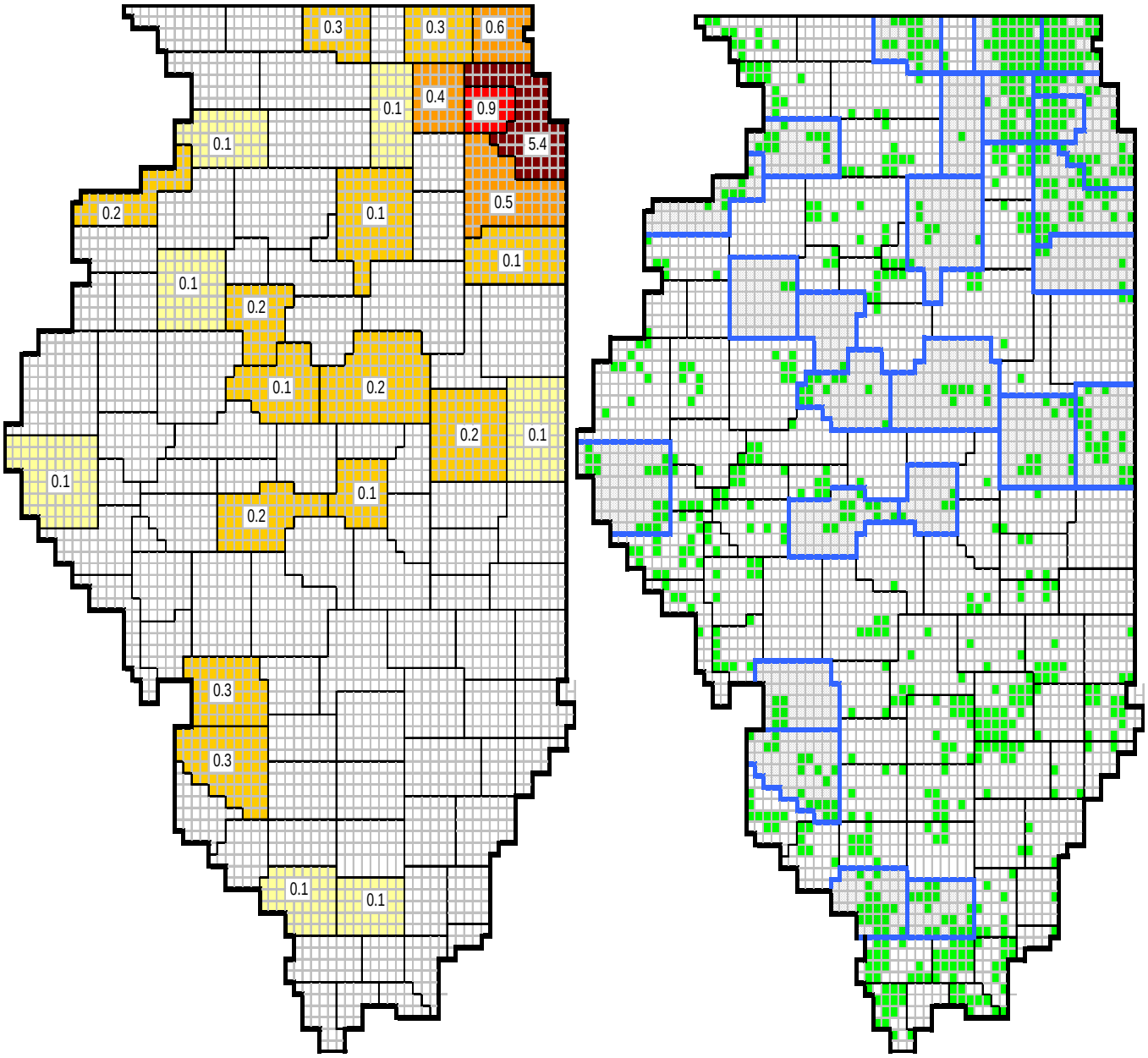
Williams, J. C. and C.S. ReVelle. 1996. A 0-1 programming approach to delineating protected reserves. *Environment and Planning B* **23** 607-622.

Williams, J. C. and C.S. ReVelle. 1997. Applying mathematical programming to reserve selection. *Environmental Modeling and Assessment* **2** 167-175.

Williams, J. C. and C.S. ReVelle. 1998. Reserve assemblage of critical areas: A zero-one programming approach. *European Journal of Operational Research* **104** 497-509.

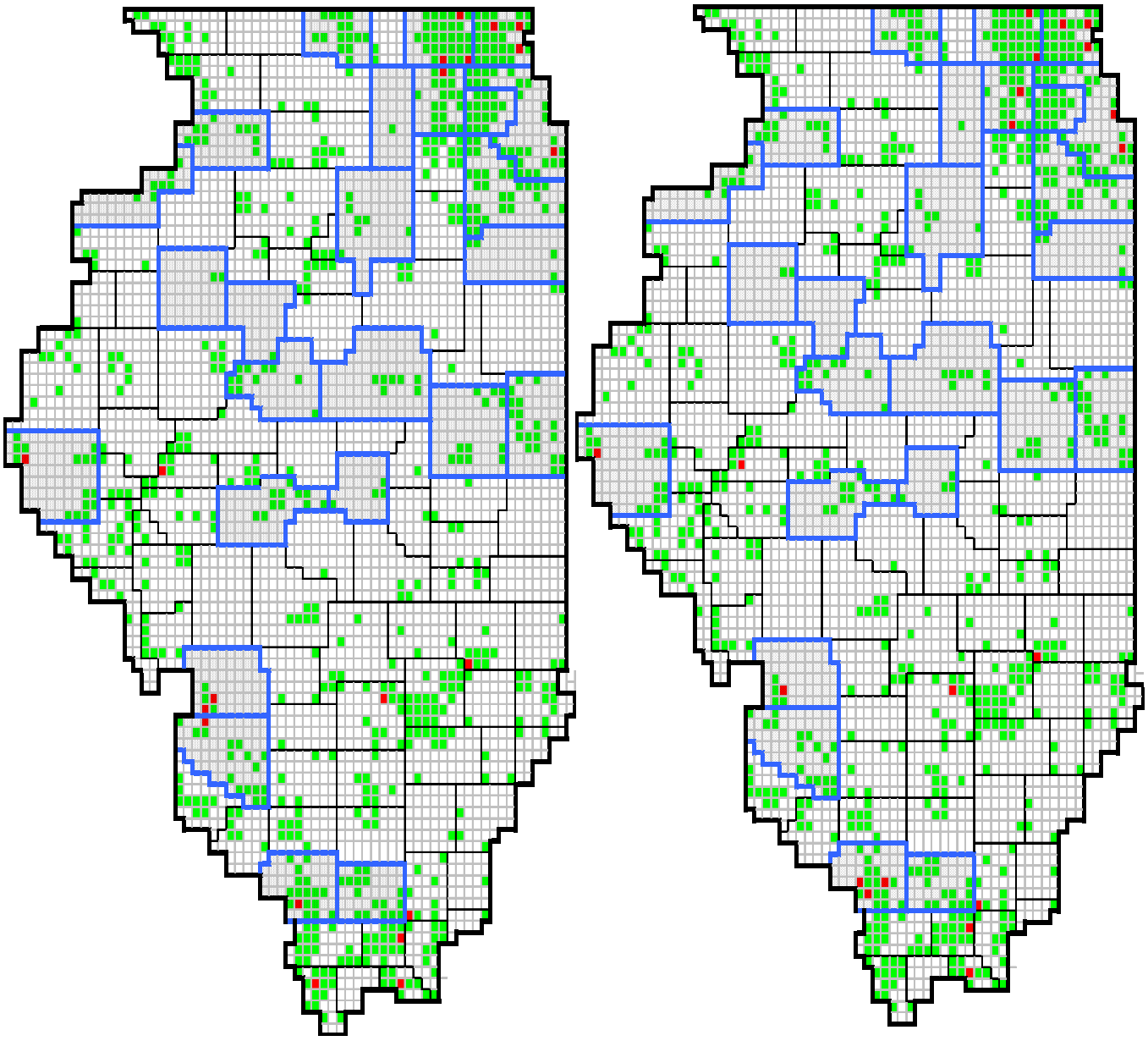
Table 1: List of state-endangered/threatened birds of Illinois and the frequency of their presence in 744 habitat sites.

Scientific name	Common name	Number of sites
Ammodramus henslowii	Henslow's Sparrow	85
Asio flammeus	Short-eared Owl	13
Bartramia longicauda	Upland Sandpiper	87
Botaurus lentiginosus	American Bittern	12
Buteo lineatus	Red-shouldered Hawk	79
Buteo swainsoni	Swainson's Hawk	9
Certhia Americana	Brown Creeper	29
Chlidonias niger	Black Tern	35
Circus cyaneus	Northern Harrier	34
Egretta caerulea	Little Blue Heron	7
Egretta thula	Snowy Egret	4
Falco peregrinus	Peregrin Falcon	7
Gallinula chloropus	Common Moorhen	90
Grus Canadensis	Sandhill Crane	52
Haliaeetus leucocephalus	Bald Eagle	142
Ictinia mississippiensis	Mississippi Kite	43
Ixobrychus exilis	Least Bittern	77
Lanius ludovicianus	Loggerhead Shrike	177
Limnothlypis swainsonii	Swainson's Warbler	5
Nyctanassa violacea	Yellow-crowned Night Heron	12
Nycticorax nycticorax	Black-crowned Night Heron	42
Pandion haliaetus	Osprey	4
Phalaropus tricolor	Wilson's Phalarope	1
Podilymbus podiceps	Pied-billed Grebe	133
Rallus elegans	King Rail	18
Sterna antillarum	Least Tern	7
Sterna forsteri	Forster's Tern	4
Sterna hirundo	Common Tern	2
Thryomanes bewickii	Bewick's Wren	18
Tympanuchus cupido	Greater Prairie Chicken	7
Tyto alba	Barn Owl	29
Xanthocephalus	Yellow-headed Blackbird	86



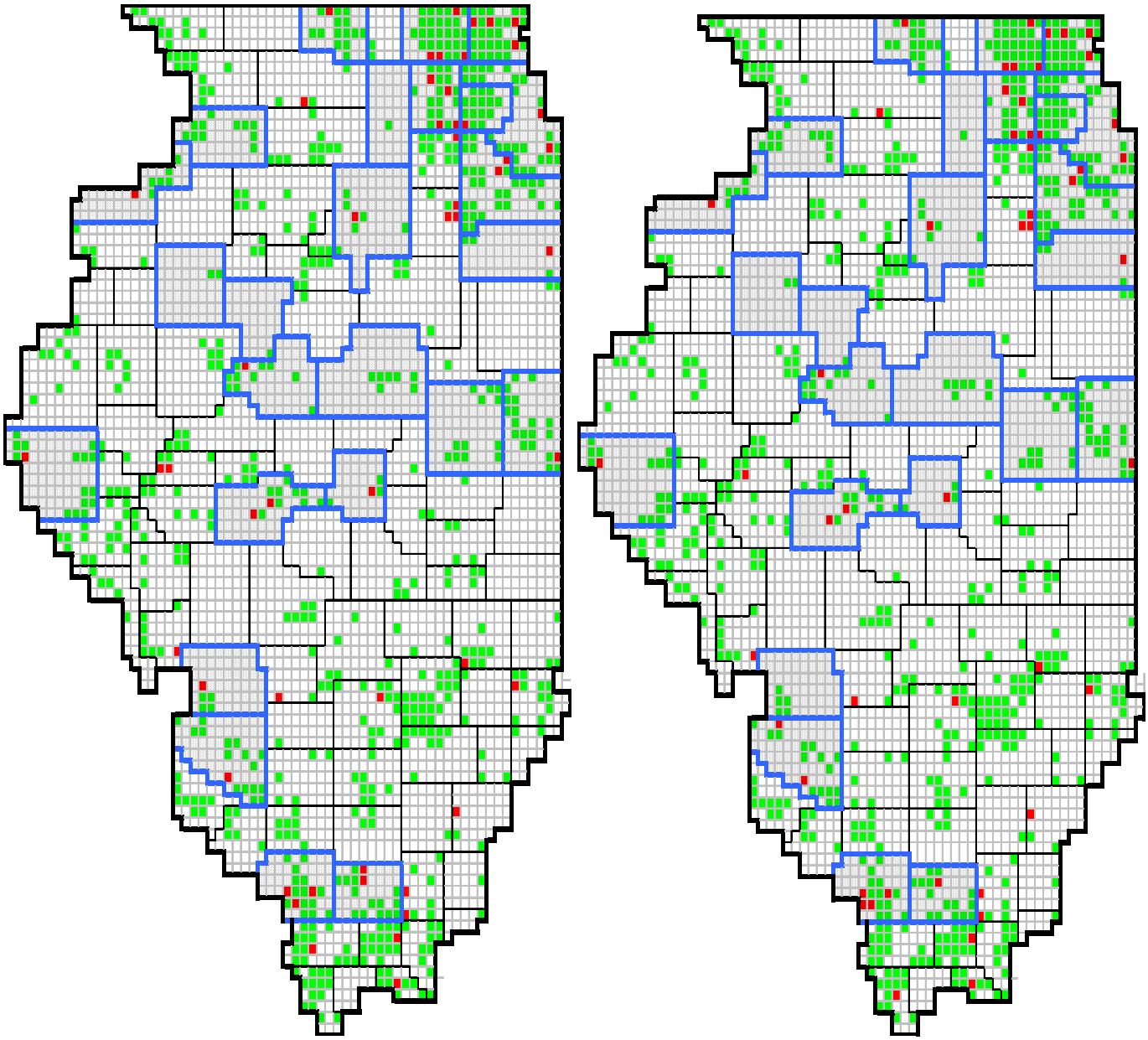
1a **1b**

Figure 1: Location of Illinois counties with more than 50 thousand population (colored cells in **1a**) and grid cells including habitat sites that support at least one of the 32 endangered or threatened bird species (green colored cells in **1b**). The thick lines indicate State borders; thin solid lines indicate county borders; in **1a** the numbers in boxes show the county populations (in million, rounded to the first decimal place).



2a **2b**

Figure 2: A spatially unrestricted minimum triple set covering solution (**2a**) and an alternative triple set covering solution (**2b**) that also minimizes the total travel cost (red cells indicate the selected cells, see text for the details of triple representation specification and travel cost).



3a **3b**

Figure 3: The reserve configuration that minimizes travel costs for individual counties (**3.a**), without requiring all species to be adequately (triple) represented, and the same-size reserve that minimizes the total travel cost for all counties cooperatively while satisfying the triple representation requirement.