Optimum Reserve Design for Multiple Species with Connectivity Consideration at Species Level

Hayri Önal

University of Illinois at Urbana-Champaign

Yicheng Wang

Qingdao Agricultural University

ILLINOIS

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Introduction

- First reserve design models formulated the optimum site selection problem in the framework of set covering and maximal covering problems.
- Typically, these models lack desirable spatial properties.
- Spatial coherence is important for effective functioning and efficient management of the reserve.

- In the past decade substantial progress has been made to incorporate spatial attributes in optimum site selection.

Connectivity and Compactness

- Connectivity: eliminate isolation and detachment, facilitate species' movement through the landscape of protected areas.
- Compactness: Shape simplicity (circular configurations) helps species to move in random directions, reduces edge effects, promotes interaction.

Difficult attributes to model in a computational MIP framework!

Functional Connectivity

- Earlier connectivity models equated connectivity to physical contiguity (continuous paths of adjacent sites).
- Typically ground bound species tend to stay within their habitats, do not venture into unfriendly areas (with poor habitat quality). Physical connectivity may not be meaningful if some selected sites do not provide habitat themselves, they just physically connect good quality sites.

Functional connectivity: selected sites must facilitate easy movement of species within and between protected areas, selected sites must have a minimal threshold habitat, the more the better.

Problem Statement

Determine an optimum 'compact and functionally connected' reserve that satisfies specified conservation goals with minimum amount of resources.

Modeling Compactness

- Minimize the total distance between selected sites from a centrally located site.
- This is a p-median problem, modeled as a linear MIP.

$$\text{Minimize } \sum_k \sum_i d_{ki} \cdot X_{ki}$$

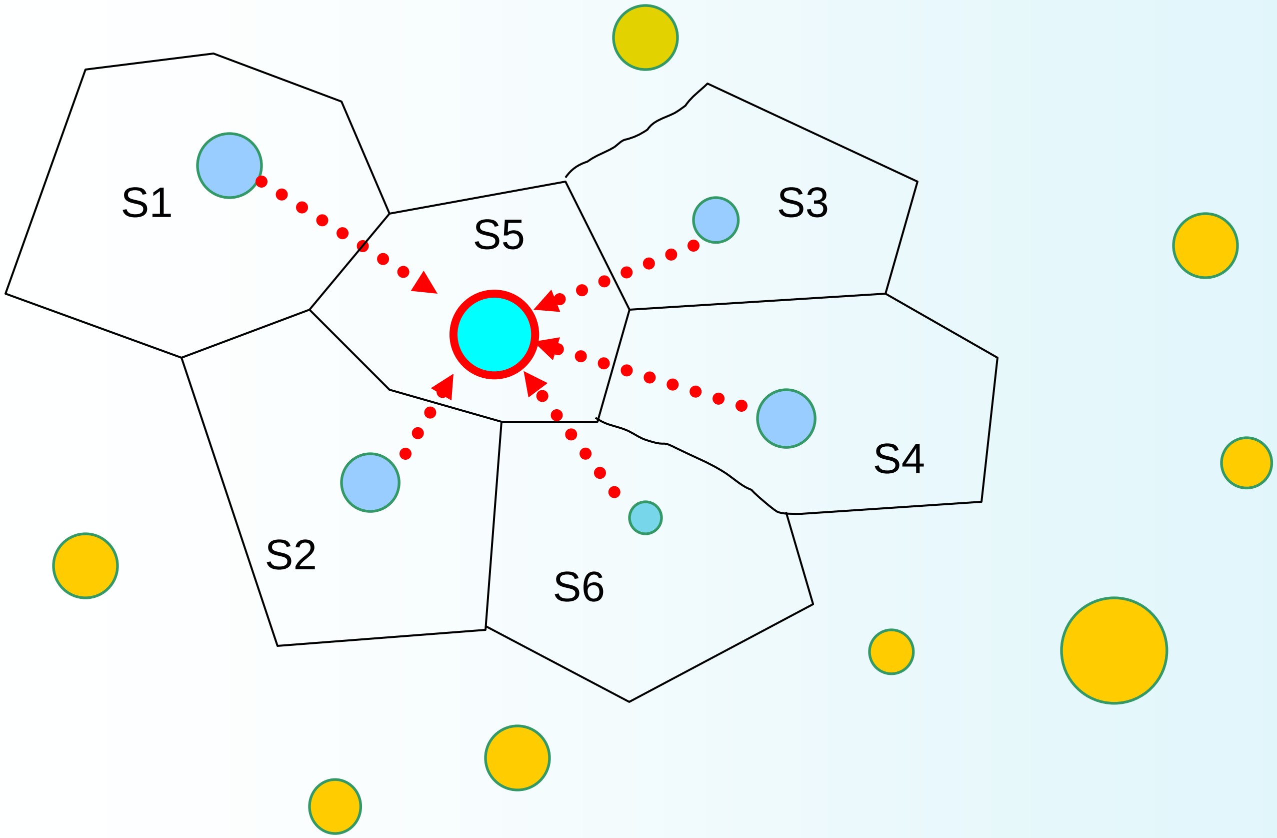
$$\sum_k X_{ki} \le 1 \quad \text{for all } i$$

$$\sum_k X_{kk} = n$$

$$\sum_i X_{ki} \le m \cdot X_{kk} \quad \text{for all } k,$$

$X_{ki} = 1$ if site i is selected & belongs to reserve centered at k, else $= 0$

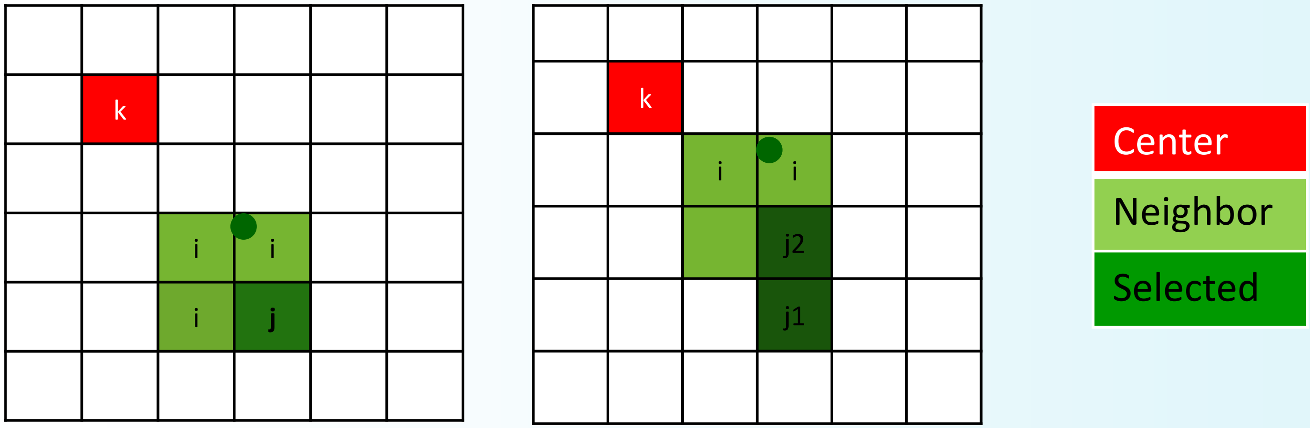
A Graphical Illustration (w/one reserve)



Modeling Spatial Connectivity

$$X_{kj} \le \sum_{\substack{i \in N_j \\ d_{ik} < d_{jk}}} X_{ki} \quad \text{for all } k, j \text{ that are not adjacent}$$

If site *j* is selected and belongs to a reserve centered at *k*, then at least one of its immediate neighbors closer to the center , *i*, must also be selected and belong to the same reserve – physical contiguity



Functional Contiguity

- Species' movement is an issue when considering connectivity and distances between sites. A site with moderately good habitat is preferred to a poor connector site (with little or no habitat) even if its inclusion in the reserve requires a longer connecting path. If no habitat exists, that site may not be passable/crossable, functional connectivity will not be established!
- Instead of ordinary distances, use functional distances :

$$f_{ij} = \begin{cases} d_{ij} / [0.5(h_i + h_j)], & \text{if } h_i, h_j > l \\ m & \text{otherwise} \end{cases}$$

m=a large number

Extension to Multiple Species

$$Min \quad w_d \sum_{s,i,j} \tilde{d}_{ij} X_{sij} + w_c \sum_j c_j U_j$$

$$X_{sij} \le X_{sii} \quad \text{for all } s, i, j$$

$$\sum_i X_{sii} = n_s \quad \text{for all } s$$

$$\sum_i X_{sij} \le U_j \quad \text{for all } s, j$$

$$U_j \le \sum_{s,i} X_{sij} \quad \text{for all } j$$

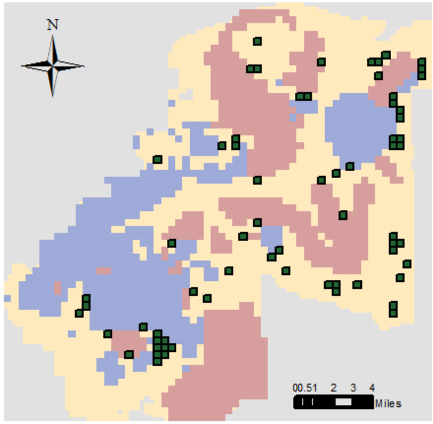
$$X_{sij} \le \sum_{\substack{k \in N_j \\ f_{sik} < f_{sij}}} X_{sik} \quad \text{for all } s, i, j \notin N_i$$

$U_j = 1$ if site j is selected

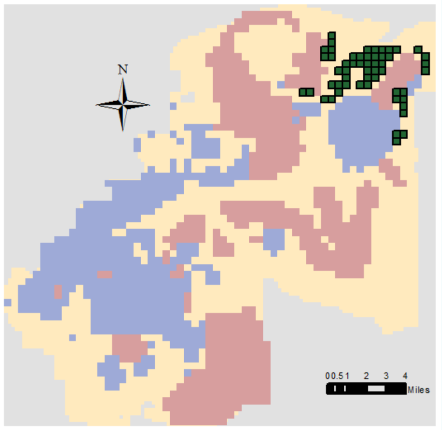
$X_{sij} = 1$ if j is selected & belongs to subreserve centered at i

SOME RESULTS

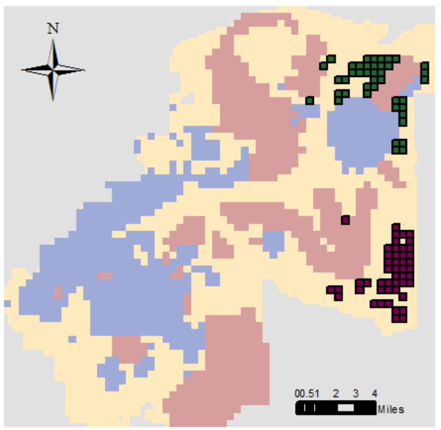
Alternative Reserve Configurations for Gopher Tortois at Ft. Benning



No spatial consideration, th≥20,000

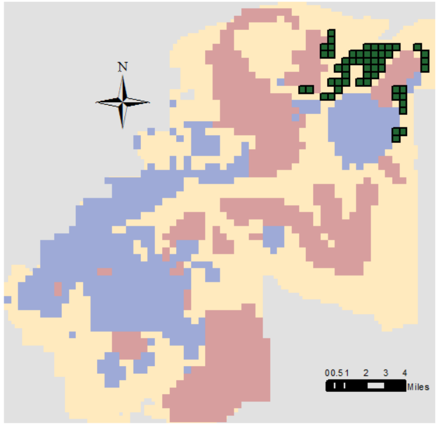


Single Compact Reserve, th≥12,000

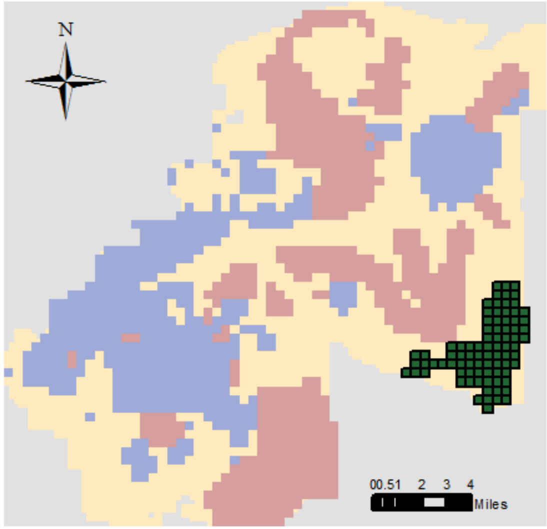


Two Compact Reserves, vh≥6,000, th≥20,000

Compact Reserves (A) vs Physically and Functionally Connected Reserves (B,C)

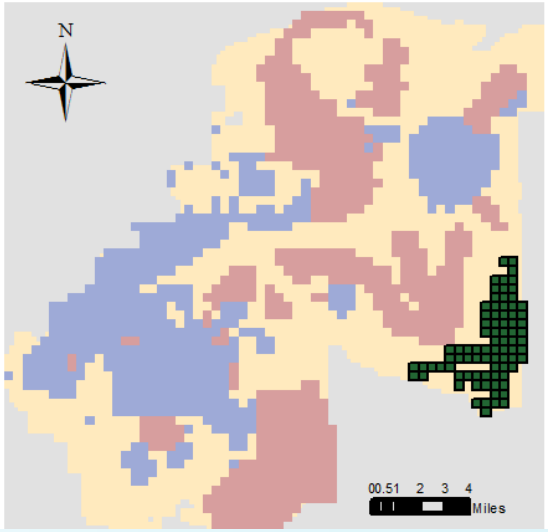


A



B

C



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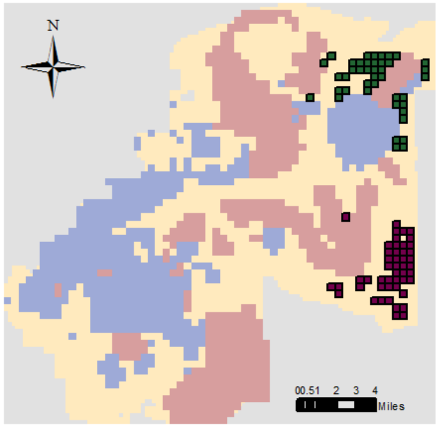
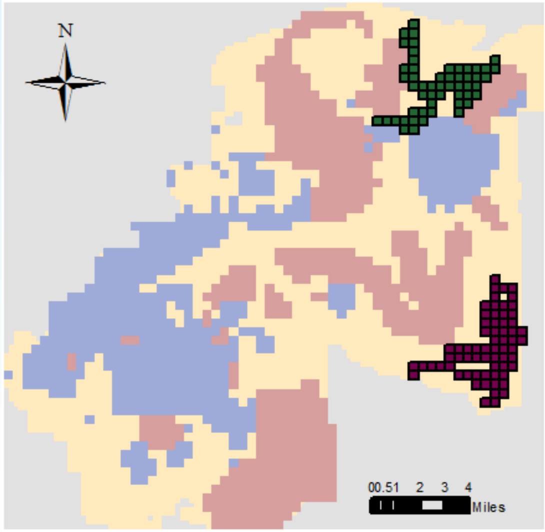
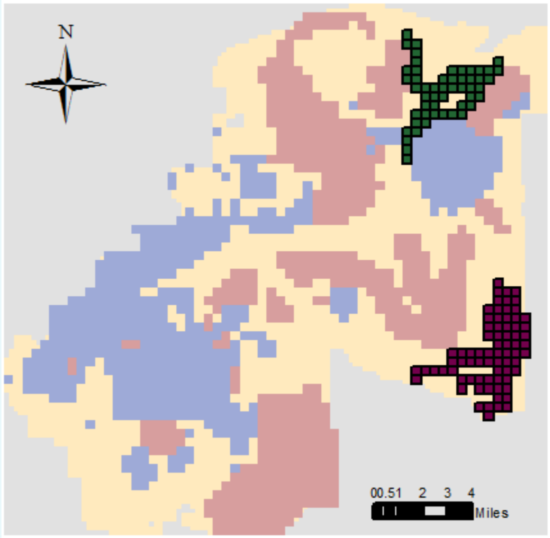


A

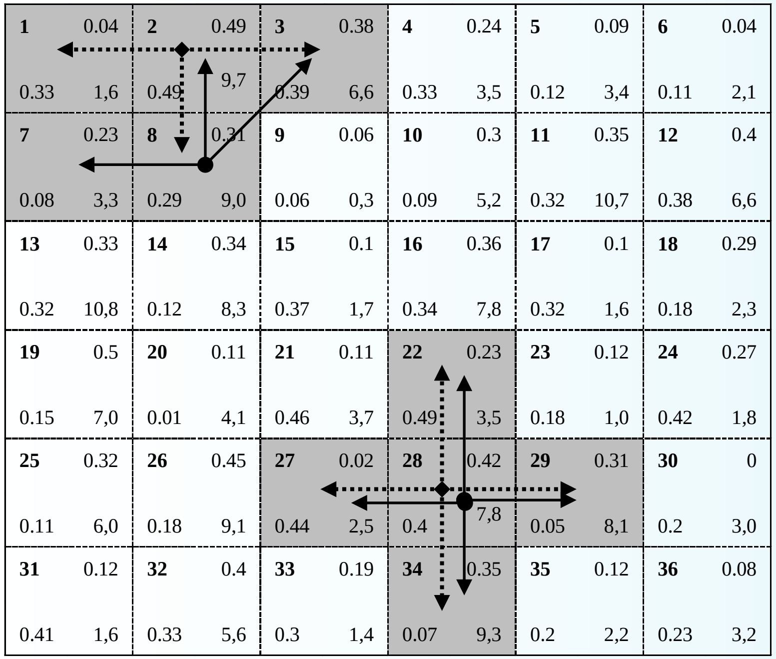


B



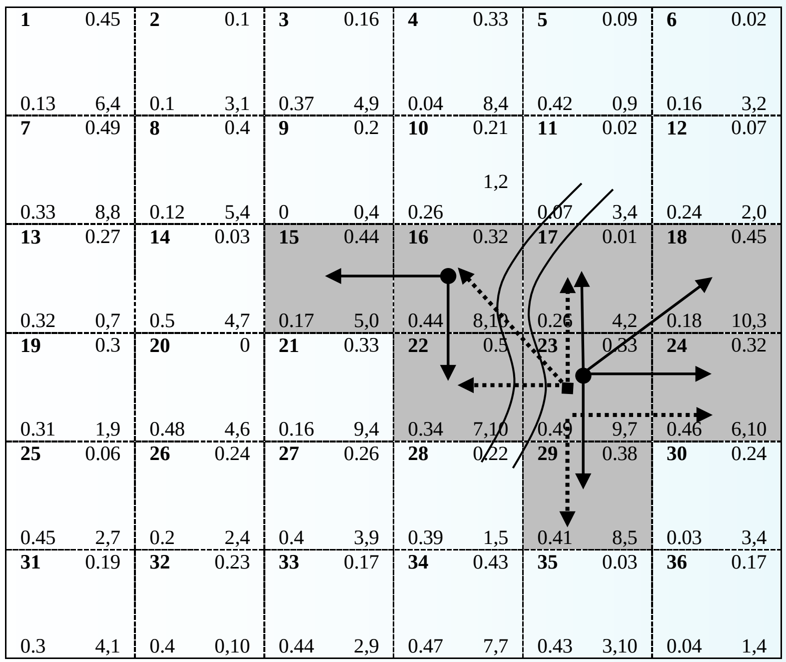
C

Two Species, Two Reserves
(each species must be covered in two sub-reserves in the entire reserve system)



Solid and dotted arrows show connections for individual species

Two Species (one terrestrial, one avian), One reserve, Three Sub-reserves



Solid arrows are connections for terrestrial species, dotted arrows are for avian species, the curve in the middle is a river

Computational Aspects

Table 1: A comparison of the model sizes for alternative formulations before and after GAMS/GUROBI Presolve

Number of Sites	Present Model		Duque et al. Model-3 [c/]				Jafari-Hearne Model [d/]
	Before Presolve [a/]	After Presolve [b/]	k=1	k=2	k=3	k=4	
25	1,173	1,138	539	1,051	1,563	2,075	529
	626	608	431	561	691	821	317
100	19,643	6,966	5,974	11,846	17,718	23,590	2,304
	10,001	3,654	5,511	6,071	6,631	7,191	1,382
400	318,483	69,357	5,974	167,686	251,328	334,970	9604
	160,001	35,401	5,511	84,441	86,761	89,081	5762
900	1,616,523	285,709	414,214	827,526	1,240,838	1,654,150	21,904
	810,001	144,466	409,831	415,111	420,391	425,671	13,142
1600	5,113,763	256,934	1,296,484	2,591,366	3,886,248	5,181,130	39,204
	2,560,001	131,526	1,288,641	1,298,081	1,307,521	1,316,961	23,522

Solution Times

Table 2: A comparison of the computational efficiency of alternative model formulations

Grid Size	Number of Cells	Present Model: Number of Reserves 1	2	3	Duque et al. Model-3: Number of Reserves 1	2	3	Jafari-Hearne Model: Number of Reserves 1	2	3
5*5	25	0.3	0.2	0.2	1.2	5.5	16.7	0.8	0.6	0.5
10*10	100	1.6	0.9	1.1	a/	a/	b/	20.9	20.3	19.0
20*20	400	49.0	29.0	27.3	a/	a/	a/	1,149.0 c/	945.3 c/	967.4 c/
30*30	900	110.9	116.3	114.5	d/	d/	d/	e/	e/	e/
40*40	1,600	201.4 f/	156.3 f/	140.9 f/	d/	d/	d/	e/	e/	e/

Results of an Empirical Application

163 sites, 10 species, 3 reserves, each including up to 2 sub-reserves

Table 3 A summary of selection results in the empirical application

Problems [a]	Total distance [b]	Increase in total distance (%) [c]	Total cost ($million) [d]	Increase in total cost (%) [e]	Solution time (seconds) [f]
1	0	-	139.5	-	177.1
2	0	na	188.4	35.1	114.7
3	4	-	183.6	-	48.7
4	6	50.0	213.0	16.0	268.3
5	0	-	119.9	-	67.9
6	15	na	358.9	199.3	158.9

Observations and Conclusions

- Using ordinary distances to achieve physical contiguity may lead to a small number of high quality sites with possible gaps between them. A reserve with such gaps would not serve the purpose if species cannot move through those gaps, the reserve actually includes multiple detached sub-reserves.
- Using functional distances incorporates movement resistance and does not allow undesirable gaps in the reserve choosing good quality sites that are fully connected by means of good quality areas/corridors. This can be done for a single species in a single reserve, or for multiple species protected in multiple sub-reserves.
- The model is amazingly easy to solve. Problems with hundreds of sites could be solved in a reasonable processing time both in synthetic test problems and actual implementations to real data sets.

THANK YOU!