Designing Conservation Reserve Areas with Efficiency, Contiguity and Compactness Considerations

Hayri Önal[†], Sahan T. M. Dissanayake[‡], and Kevin T. Patrick[‡]

† Professor, Department of Agricultural & Consumer Economics, University of Illinois at Urbana-Champaign, email: h-onal@illinois.edu;
‡ Graduate research assistants and Ph.D. candidates, Department of Agricultural & Consumer Economics, University of Illinois at Urbana-Champaign.

Abstract:
This paper introduces a linear integer programming formulation for the spatial design of a conservation reserve incorporating compactness and contiguity considerations in habitat site selection. These two criteria are important for effective functioning of conservation areas particularly when ground-bound species are involved. Gopher Tortoise (GT), a key stone species which has an 'at risk' status at present, is such a species. A significant amount of GT habitat areas is found on a military installation, Ft. Benning, GA, where the need for new and conventional training requires identifying new suitable habitat areas. We apply the model to this problem and find an optimal subset of habitat sites to form multiple spatially coherent and sufficiently large conservation management areas that collectively support GT populations.

Keywords: reserve design, clustered site selection, spatial optimization, integer programming, compactness, contiguity.

Introduction

The reserve site selection problem is often stated as an instance of the basic set covering and maximal covering formulations (Toregas & ReVelle, 1973; Church & ReVelle, 1974) where either the cost of selected sites is minimized while achieving some specified conservation goals (e.g. species representation), or a conservation objective is maximized subject to resource constraints (e.g., Kirkpatrick, 1983; Cocks and Baird, 1989; Underhill 1994; Camm et al. 1996; Church et al. 1996; Williams and ReVelle 1997; Ando et al. 1998; Possingham et al, 2000; Polasky, et al. 2001; Rodrigues and Gaston, 2002). Typically, these formulations lead to scattered site selections (Figure 1.a). Therefore, this approach is considered as impractical because lack of spatial coherence often limits the chances of inter-site dispersal and long-term survival of species within the selected reserve sites (Macdonald and Johnson 2001; Virolainen *et al.* 1999; Rodrigues *et al.* 2000b; Araujo *et al.* 2002; Cabeza and Moilanen 2003). Furthermore, managing conservation reserve areas that are clustered together is more convenient and efficient than managing sites scattered throughout a large area. Therefore, incorporating spatial aspects is a requisite for practical, meaningful and effective reserve site selection.

Special criteria may take a variety of forms, such as reserve size, distances between selected sites, boundary size, proximity of selected sites, compactness, fragmentation, connectivity, existence of corridors, accessibility, etc. (Diamond, 1975; McDonnell et al., 2002). These considerations are usually difficult to incorporate in an optimization framework and require more sophisticated formulations and large scale optimization models. Responding to this need, several studies presented in the reserve design literature, most of which published in the past decade, have extended the basic site selection models and incorporated different spatial requirements in optimum site selection using different mathematical programming approaches including linear integer, quadratic and nonlinear programming. For instance, Rothley (1999), Nalle et al. (2002a, 2002b), Önal and Briers (2002), and Williams (2008) included pairwise distances; Wright et al. (1983), Hof and Joyce (1993), McDonnell et al. (2002), Fischer and Church (2003), and Önal and Briers (2003) incorporated the boundary length of the selected area (to be minimized); Williams (2001), Cova and Church (2000), Cerdeira and Pinto (2005), Cerdeira et al. (2005); and Önal and Briers (2006) presented alternative formulations to enforce spatial contiguity, and Önal and Wang (2008) developed a model to minimize reserve fragmentation when contiguity is preferred but not absolutely required. Williams et al. (2005) presents a review of spatial aspects in reserve site selection and optimization models addressing different spatial considerations.

The spatial criteria mentioned above may be applied alone, or may be required in combination with other criteria in which case the end results may be dramatically different. For instance, if one requires contiguity only when selecting sites, an optimum reserve network may look like in Figure 1.b (see, for instance, Cerdeira et al., 2005, and Önal and Briers, 2006). Such an elongated and narrow network of sites would increase the likelihood of exposure to less favorable conditions outside the reserve, therefore it may not be the best reserve design if species that roam around or move in random directions are involved. On the other hand, a ‘compact’ reserve as shown in Figure 1.c comprised by multiple detached sub-reserves may not be an ideal design if some of those sub-reserves cannot sustain a minimum viable population and discontinuities do not allow interaction between the populations in those areas. In this paper we focus on two particular spatial criteria, namely compactness and contiguity, that are required together. The justification of this requirement will be discussed in the next section. We develop a linear integer programming model to address this issue and apply the model to a conservation reserve selection problem where a ground-bound species is involved.

Problem Statement

Many rare, threatened, and endangered species in North America are found within the boundaries or in the vicinity of military installations in the U.S. While some habitat deterioration may have been caused by military training, it is often argued that the military control actually prevents those areas from more destructive urban and agricultural development. The Department of Defense (DoD) allocates a significant amount of capital, human resources and land for conservation efforts toward protecting and managing wildlife habitat in and around military installations. In 2006, for instance, the DoD spent $4.1 billion on environment related expenses of which $1.4 billion was for environment restoration and $204.1 million was for conservation (Benton 2008). On the other hand, new and conventional training requirements increase the importance of military lands and the pressure to manage those lands in the best possible way to balance these competing objectives. As an alternative to costly arrangements, such as purchasing additional land or acquisition of property rights around the installations, a more effective utilization of the existing lands for conservation and military purposes can be accomplished by designing an optimum landscape that best addresses these needs.

In this paper we consider a particular military installation, namely Ft. Benning in Georgia. Ft. Benning currently has an extensive population of Gopher Tortoise (*Gopherus polyphemus*), referred to as GT, a key stone species which has an ‘at risk’ status at present. The installation is currently undergoing an expansion of its military mission that requires converting more lands into military training areas. Some of the proposed new training areas are heavily populated by GT's (see Figure 2); therefore the land managers are considering relocating GTs to lesser used areas to be selected within the boundaries of the installation, which we call conservation management areas (CMA). Since GT is a ground-bound species, the selected CMAs should be as 'compact' as possible and 'contiguous' in order to allow movement of GT in those areas and facilitate interaction within and between populations. A compact reserve would also be easier to fence (if needed, so that GTs will not be allowed to return to their current habitat areas). In addition, if multiple CMAs are to be configured, each CMA is required to be large enough to sustain a minimum viable population in it. In the following section, we present a linear integer programming model that determines the most suitable CMAs while considering the spatial criteria mentioned above, namely compactness, contiguity, and minimum size.

The Model

We consider a square grid partition covering the entire area where each square land parcel[1] is assumed to be an independent spatial decision unit, which will be referred to as 'site'. When selecting sites to configure a reserve the locations of individual sites relative to other selected sites and their contributions to the conservation of GT are taken into account simultaneously.

The model employs two explicit mechanisms that ensure compactness and contiguity of the selected sites. A CMA (which will be referred to as 'reserve' from here on) is characterized by a central site in it and a set of sites clustered around the central site. Both the central site and assignment of sites to each reserve are determined by the model simultaneously and endogenously in such a way that the total distance between all sites included in a reserve and its central site is minimized, which we use as a definition for compactness[2]. If the total distance of a reserve is smaller than that of a same size reserve, its compactness is higher. Maximizing the compactness in this way promotes circular reserve configurations. If multiple reserves are to be configured the compactness measures are summed across all reserves[3]. Although this approach in general results in contiguous reserve configurations, it does not always guarantee (for instance, a high quality site which is detached from all other sites can be part of a reserve, contributing to the overall habitat quality at little cost, i.e. distance to the center). Therefore, we include an explicit mechanism in the model to ensure spatial contiguity. This is done by forcing the model to assign an immediate neighbor (adjacent site) of each selected site to the same reserve such that the neighbor is closer to the reserve center. The procedures and algebraic details of the models are described below.

We denote the set of all sites by L and denote individual sites by $k, l, m \in L$. Site selection and assignment to a reserve is represented by a binary variable X_{lk}, where X_{lk} =1 if site k is selected and belongs to the reserve centered at site l and X_{lk} =0 otherwise. Note that by construct X_{ll} =1 for all central sites l, i.e. the central site of each reserve must belong to that reserve. We also note that sites in the most heavily used military training areas (existing or new) are not considered for inclusion in any reserve, therefore we set X_{lk} =0 if site k is part of a training area. The symbol d_{lk} denotes the distance between site l and site k, and e_k denotes the existing population of GT in site k. The number of reserves to configure is denoted by n; which is specified exogenously, but varied when designing alternative optimal configurations. Each reserve is required to sustain a minimum GT population, denoted by p. Finally, the total GT population in all the selected areas is represented by tp.

Model 1 – Compact Model

We first address the problem of constructing *n* compact reserves, each covering a minimum sustainable GT population and collectively covering a desired GT population. An algebraic model that serves this purpose, which will be referred to as the '*Compact Model*' from here on, is given below.

$$\text{Minimize} \quad \sum_{l} \sum_{k} X_{lk} * d_{lk}$$

s.t.:

$$\text{i)} \quad \sum_{l} X_{ll} = n$$

$$\text{ii)} \quad \sum_{l} X_{lk} \leq 1 \quad \forall k$$

$$\text{iii)} \quad \sum_{k} X_{lk} * e_k \geq p \quad \forall l$$

$$\text{iv)} \quad \sum_{l} \sum_{k} X_{lk} * e_k \geq tp$$

$$\text{v)} \quad X_{lk} \leq X_{ll} \quad \forall l,k$$

$$X_{lk} = 0,1 \quad \forall l,k$$

The objective function involves the distances from individual sites in each reserve to the 'center' of that reserve, which in turn is summed over all reserves. Constraint i) ensures that *n* reserves are created. Constraint ii) states that each site can belong to at most one reserve centered at some site *l*. Constraint iii) requires that each reserve supports a population that exceeds the minimum sustainable size[4], while constraint iv) ensures that all reserves collectively support a desired total population. Finally, constraint v) implies that if site *k* is selected and assigned to the central site *l*, i.e., X_{lk} =1, then a reserve centered at site *l* must be formed, i.e. X_{ll} must be 1, otherwise we have X_{lk} =0. We note that the sites that are part of the existing and proposed intensive use military training areas are not eligible for selection, therefore for all such sites we set X_{lk} =0.The above base model does not include reserve contiguity as additional criteria. We address these by modifying the above mathematical programming model.

Model 2 – Contiguous and Compact Model

Contiguity is a difficult criterion to incorporate in a mathematical programming model particularly when working with a large number of spatial units. We accomplish this by requiring that if a site is assigned to a particular reserve, then at least one of its immediate neighbors (an adjacent site that has a common edge) that is closer to the center must also be assigned to the same reserve. This is done by adding the following constraint to the *Compact Model* to obtain the *Contiguous and Compact Model*:

$$X_{ij} \leq \sum_{\substack{k \in \mathrm{N}_j, \\ d_{ik} < d_{ij}}} X_{ik} \qquad \text{for all } i \text{ and } j$$

where N_j is the set of immediate neighbors of site *j*. To see how this constraint works, suppose $X_{ij} = 1$. Then the right hand side must be at least one, or for at least one of the variables in the summation we must have $X_{ik} = 1$, which implies that one of the sites adjacent to site j whose distance to central site *i* is less than the distance between site *i* and site *j*. Applying the same argument to the neighbor site implies that if site *j* assigned to a central site *i*, then there is a chain of mutually adjacent sites all of which are assigned to the same central site (i), thus site *j* is spatially connected to the central site i . If sites j and k are assigned to the same central site, then there are two paths connecting them to the central site. Tracking one of the paths in reverse direction one can obtain a path connecting sites j and k, thus the entire reserve is spatially connected.

Data

The current and future military training areas were obtained as raster files from Ft. Benning and are shown in Figure 2.a. The habitat areas suitable for GT were obtained as raster files from the national biological information infrastructure (Elliot at al., 2003). The above raster files were converted to ESRI shape files using ARC GIS 9.2. The resulting shape file is shown in Figure 2.c. A 60x60 grid file, where each grid was 600m by 600m, was created using Geoda and the grid shape file was spatially joined with the above shape files using spatial join tool in ARC GIS. The spatial join gives the grid file the attributes of the shape file. To ensure that each grid cell represents a density of the original data, the “sum” option was used when joining the GT burrow data and the habitat suitability data.

The grid cell values for Figure 2.a are specified as binary values (grid cell value = 1 if cell includes a base area or a planned expansion area). The grid cell values for Figure 2.b and Figure 2.c are given as an index. For Figure 2.b, each grid cell value is the sum of the number of observed GT burrows within the grid cell, the index ranges from 0 to 50. For Figure 2.c, the grid cell value is the sum of the suitable points (the GT suitability raster map was converted to point shape file) within the grid cell. The suitability index ranges from 0 to 100.

Empirical Results and Discussion

This section presents the results of the *Compact Model*, and the *Contiguous and Compact Model*. All models were solved using GAMS/CPLEX version 21.6 on a PC with an Intel Quad Core Processor and 8 GB of RAM running Windows Vista.

Here we assumed that the final total habitat suitability required in all reserve areas is at least 10000 units. The GT populations that are currently located in the planned military expansion areas can be moved to a single large reserve or multiple smaller reserves (all located outside the area that will be devoted to intensive military use). The model is solved with various parameter specifications for the number of reserves (*n*) and the minimum population size per reserve (*p*). The reasons for requiring more than one reserve are two-fold. First, we may want to separate the GT population into smaller populations, each being located in a different part of the reserve, to safeguard them against potential diseases that may occur in one of those protected areas and spread to the other areas. Second, setting aside one large conservation area reduces the flexibility for the military when further expansion of training areas is needed in future. These problems can be alleviated or reduced by designing multiple small conservation areas.

In all of the runs described below the minimum habitat suitability requirement for each reserve was specified as 2000 and the minimum total population was specified as 10000. The models were solved for one, and two reserves. These numbers are specified arbitrarily to illustrate the workings of the models and demonstrate the trade-offs between different spatial criteria.

Compact Model Optimal Reserve Configurations

The *Compact Model* results, with just the compactness of the selected reserves are shown in Figure 3.a and 3.c for 1, and 2, reserves. Comparing the results in Figure 3.a and 3.c with the suitability map given in Figure 2.c illustrates that the Base Model simply selects from amongst the most densely packed and best available sites to form compact reserves. The optimal solution with one large conservation area (Figure 3.a) shows that this area would be located at the northeast corner of the installation. However, the compactness of the reserve is poor; the selected sites (43 total) are meandering in shape and disconnected. This result is driven primarily by the fact that the model is forced to choose one cluster of habitat sites and the only available good quality sites that are not currently populated heavily by GT are in that part of the installation. The good quality sites in other parts of the installation are not in the solution due to two reasons: i) those sites are under extensive military use, or ii) those sites are located far apart from each other.

For the two-reserve case the model chooses two clusters with 15 and 26 sites, respectively (Figure 3.c) for a total of 41 sites. Unlike the one big reserve scenario, the two reserve configurations comprise of compact clusters of sites since inter-site distances are accounted for each cluster separately, rather than the distances between all selected sites, which allows the model to choose closely located sites from multiple locations. But there are still disconnections between the selected sites.

Compact and Contiguous Model Optimal Reserve Configurations

The results of the *Compact and Contiguous Model* are shown in Figure 3.b and Figure 3.d. The optimal solution with one large conservation area (Figure 3.b) shows that this area would now be located at the southeast corner of the installation where there is a large collection of good sites. The reserve is now connected but it contains 55 sites highlighting that as more spatial considerations are added it is necessary to choose more sites as the model is forced to choose from less suitable sites.

The results for two reserve areas are shown in Figure 3.d. Incorporating the contiguity guarantees a contiguous solution but again the total number of selected sites 50 (29 and 21 sites the two reserves) is higher than the total number of sites without the contiguity requirement.

Concluding Remarks

This paper presented two linear integer programming formulations that can be used to incorporate reserve compactness and contiguity as spatial criteria in reserve site selection and determine an optimal configuration of conservation reserves based on site characteristics (habitat suitability) and geographical locations. We applied the models to a real data set pertaining to a military installation where protection of Gopher Tortoise (a key stone species at risk) is of concern. The models are fairly complex and the empirical applications demonstrated that they are computationally convenient (can be solved within a reasonable computation time, at least for the data set used here). The results of the models are consistent with intuition and reflected the desired outcomes; the *Compact and Contiguous Model* selected reserves that were contiguous and the individual reserves were compact. It should be noted that adding the spatial requirements forced the model to select from among less suitable parcels when the best parcels did not meet the specified spatial criteria. This in general leads to the selection of larger reserves and/or poorer compactness of some reserves. Therefore, there is a trade-off between compactness, contiguity and economic efficiency in optimal selection of conservation reserves.

The grid cells (sites) considered as decision units in this study are rather large (600mx600m). In many practical reserve design problems much smaller areas may have to be considered as decision units, depending on various factors such as data accuracy, site costs, and uniformity of each site in terms of habitat characteristics. This may increase the model size considerably and computational difficulties may arise. For conservation analyses that require higher resolution, it is possible to conduct a multi-step modeling approach, where low resolution data is used to locate the general area and successively higher resolution data is used for the surrounding area in successive model runs. In each successive run the model may be restricted to the area selected in the previous run and the large grid units in that selection can be divided into sufficiently small spatial decision units to identify the specific conservation areas at desired resolution.

The reserves become smaller and more compact, and comprise higher quality sites as the allowed number of reserves is increased. However, they may be dispersed throughout the installation area. These results provide general guidelines and will be useful for on the ground decision makers. Perhaps the most important empirical finding of this study is that regardless of the spatial considerations imposed in each case, the GT habitat conservation objective can be served by designating a little amount of land, thus without significant sacrifice in the use of the military area for training purposes.

Finally, it should be noted that this paper is more than an empirical analysis of GT conservation in a military area. By successfully incorporating ecological and spatial consideration into linear site selection models, we illustrate that it is possible to generate optimally designed conservation reserve configurations using integer programming. With appropriate modifications the methods introduced here are applicable to many other conservation problems involving endangered and at-risk species and can be extended to include multiple species and multiple land uses. These methods can also be applicable to many other problems of land use/allocation, such as optimal selection of nature reserves, political or business districting, or optimal urban expansion. For instance, determining optimal locations of open spaces (nature reserves) in and around urban areas has much similarity to the problem addressed here. Therefore, we view the methodological aspects of the paper as equally valuable as its empirical findings for the particular problems we dealt with.

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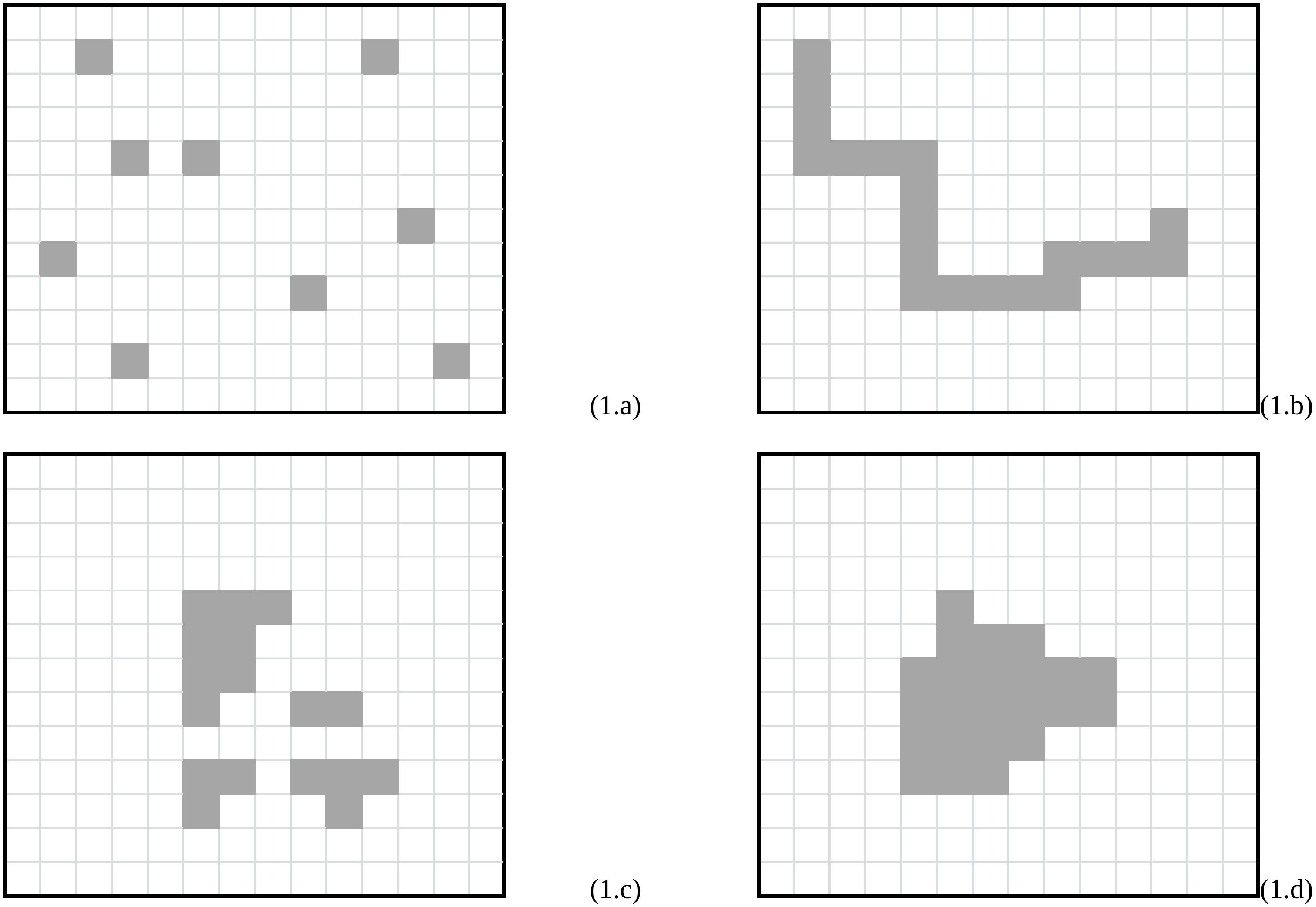


(1.a) (1.b) (1.c) (1.d)

Figure 1. Site selection alternatives: (1.a) scattered, no particular spatial pattern; (1.b) connected, but not compact; (1.c) compact, but not connected;(1.d) compact and connected [cells with shading are selected sites].

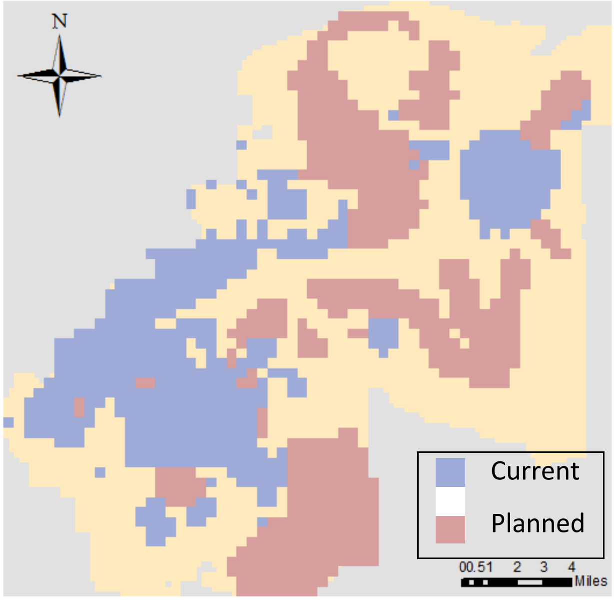


Figure 2. a: Current and Future Military Training Areas

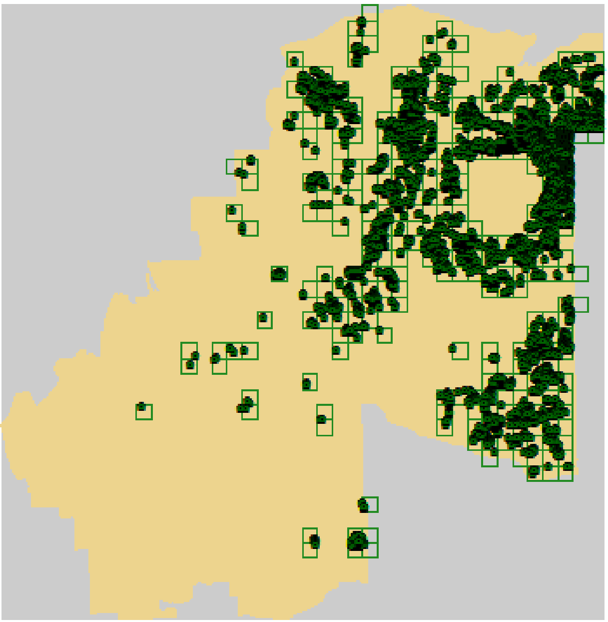


Figure 2.b: Location of current GT burrows.

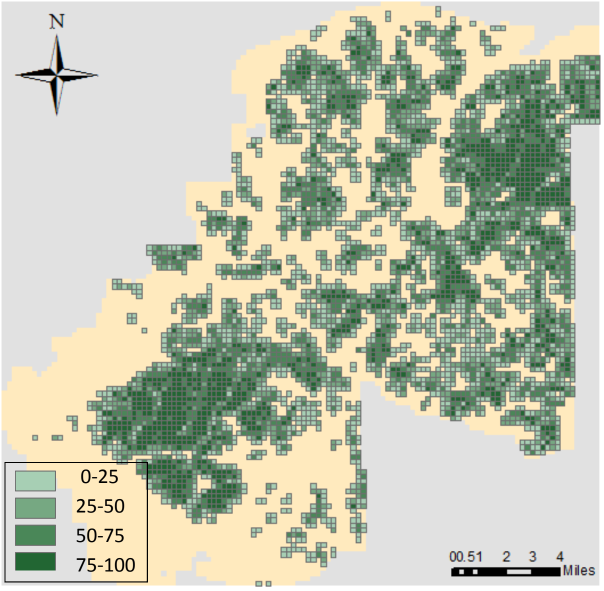
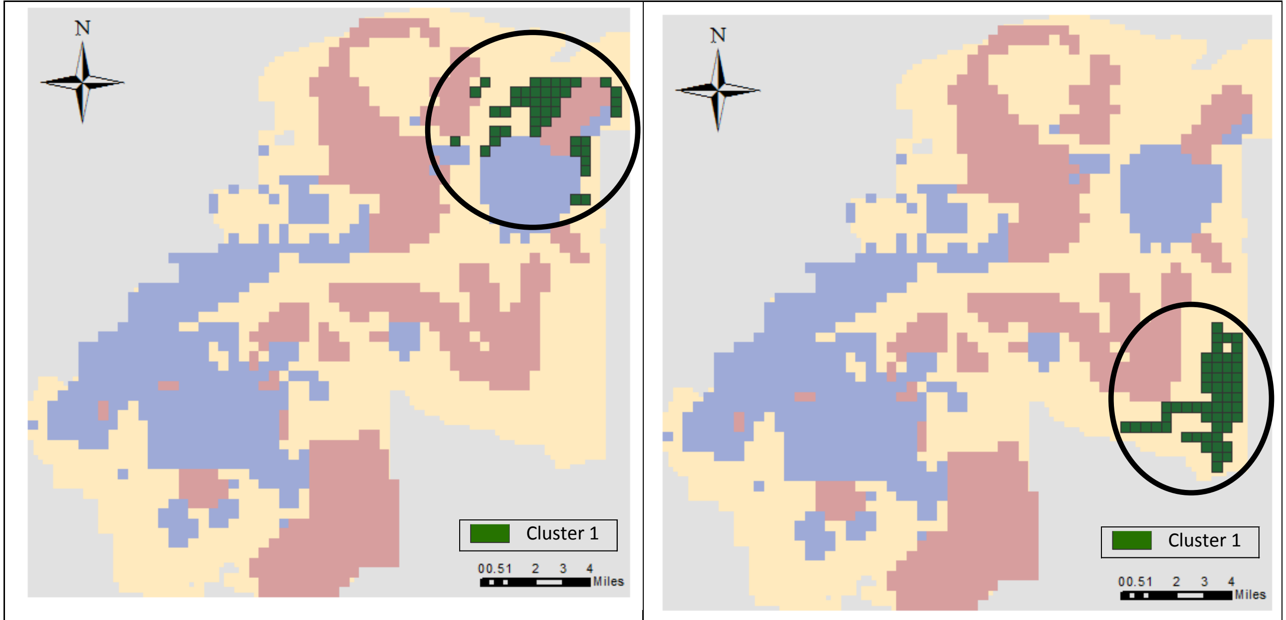


Figure 2.c: Land suitability to support Gopher Tortoise (darker areas indicate higher suitability)

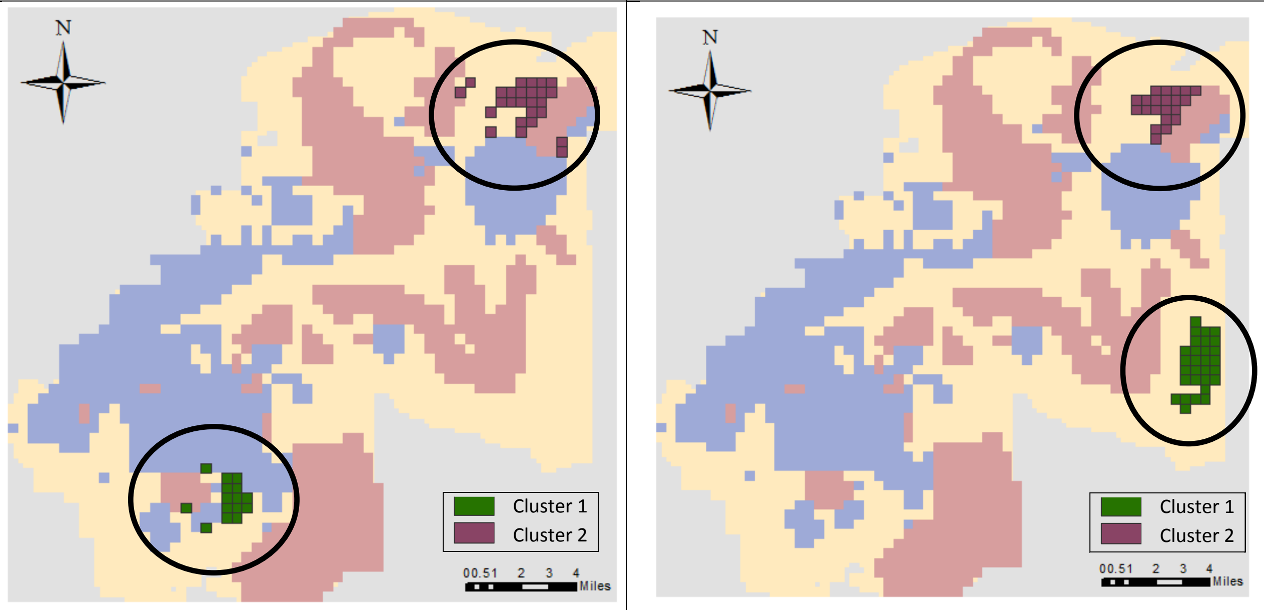
Figure 2: Maps representing the problem statement

Results for Selecting GT Habitat



3.a 1 Cluster – Compact Model

3.b 1 Cluster – Compact and Contiguous Model



3.c 2 Clusters – Compact Model

3.d 2 Clusters - Compact and Contiguous Model

Figure 3 Results for obtaining 10000 habitat units with one and two clusters

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[1] The square-cell assumption is not restrictive. The approach developed here can be applied to other geometric forms, such as triangles, rectangles, polygons, or even irregular forms.

[2] A universally agreed definition of compactness is not available (Young, 1976). Note that the absolute value of the compactness measure defined here may not mean much just by itself, rather it has to be considered together with the size of the reserve (number of sites involved). This is because a reserve with only a few distant sites may have a smaller total distance value than a reserve with too many tightly packed sites, whereas in practice the latter should be considered more compact. Although not being fully satisfactory, this definition well serves the specific purposes of the present study. Minimizing the total distance typically results in a circular and connected reserve configuration.

[3] This is an instance of disjoint clustering problem, or the p-median problem, that has been studied extensively in the operations research literature (see, for instance, Christofides, 1975; Brucker, 1978; Hansen and Jaumard, 1997). Similar problems occur in warehouse location (ReVelle and Swain, 1970) and political districting (Weaver and Hess, 1963).

[4] This constraint can also be expressed in terms of a minimum number of parcels or reserve area if the effectiveness of conservation effort is related to the reserve size.