ERDC/CERL TR-11-39

Construction Engineering
Research Laboratory

US Army Corps
of Engineers®
Engineer Research and
Development Center

Base Facilities Environmental Quality

Optimal Selection of Conservation Lands at Fort Stewart Using Integer Programming

Sahan T. M. Dissanayake, Hayri Önal, James D. Westervelt,
and Harold E. Balbach

October 2011

Approved for public release; distribution is unlimited.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **OCT 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **Optimal Selection of Conservation Lands At Fort Stewart Using Integer Programming**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineer Research and Development Center,Construction Engineering Research Laboratory,P.O. Box 9005,Champaign,IL,61826-**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**32**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

ERDC/CERL TR-11-39
October 2011

Optimal Selection of Conservation Lands at Fort Stewart Using Integer Programming

James D. Westervelt and Harold E. Balbach

Construction Engineering Research Laboratory
U.S. Army Engineer Research and Development Center
2902 Newmark Drive
Champaign, IL 61822

Sahan T. M. Dissanayake and Hayri Önal

Department of Agricultural and Consumer Economics
University of Illinois
1301 West Gregory Drive
Urbana, IL 61801-3605

Final report

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Project P2 140644, “Multi-Species PVA.”

Abstract: This report documents an application of linear integer programming for determining compact and ecologically valuable conservation management areas (CMAs) on a military installation with populations of at-risk animal species. Two models were developed and applied to the conservation efforts Fort Stewart, GA, involving the at-risk Gopher Tortoise (GT) and the tortoise-dependent Gopher Frog (GF).

The models produced solutions that are consistent with the species conservation and military training land-use objectives at Fort Stewart. They identified suitable, compact GT habitat clusters and were able to minimize the total amount of managed areas by selecting fewer and better sites. In runs that incorporated GF requirements into the GT analysis, the model was able to determine that the optimized GT CMAs also will support a small number of GF sites. However, on runs that assumed a large required number of GF sites, the GT results changed considerably in order to incorporate the GF sites. Both the single and joint species conservation management models were solvable in a short computation time, suggesting that these models may be applied to much larger data sets without significant data processing problems. The methods introduced here may be modified for application to other species, locations, and land uses.

Table of Contents

List of Figures

Preface

This study was conducted for the Office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology (ASA(ALT)) under Research, Development, Test, and Evaluation Program A896, “Base Facilities Environmental Quality (Military Training in the Presence of Species at Risk)”; Project P2 140644, “Multi-Species PVA.” The technical monitor was Dr. Victor E. Diersing, DAIM-ED-N.

The work was performed by the Ecological Processes Branch (CN-N) of the Installations Division (CF), US Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication, William D. Meyer was Chief, CEERD-CN-N; Dr. John T. Bandy was Chief, CEERD-CN; and Dr. Alan B. Anderson was the Technical Director for Military Ranges and Lands. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti and the Director was Dr. Ilker Adiguzel.

The authors express their gratitude to the participants at the AAEA Annual Meeting in 209 and 2010, the AERE session (15H) at the Annual Meeting of the Southern Economics Association in 2008, and to the participants at the Heartland Workshop in 2010 and the PERE Workshop at University of Illinois, who provided valuable review comments on an early draft of this report. This research was supported in part by Cooperative State Research, Education, and Extension Service (CREES) Project No. ILLU 05-0361.

COL Kevin J. Wilson was the Commander and Executive Director of ERDC, and Dr. Jeffery P. Holland was the Director.

1 Introduction

1.1 Background

Suitable habitat areas for many rare, threatened, or endangered species are located in the vicinity of military installations in the United States. While some habitat deterioration is caused by military training, it is often observed that the military ownership of these lands protects them from more destructive and permanent urban and agricultural development. In addition to isolating these lands from extractive economic uses, the Department of Defense (DoD) allocates a significant amount of human capital and land for protecting and managing wildlife habitat in and around installations. In 2006, 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 [1]. However, both conventional and new training requirements make it necessary to effectively balance these competing objectives and land uses. As an alternative to costly solutions, such as purchasing land or acquiring property rights, more effective utilization of the existing lands for conservation and military purposes can be accomplished by optimizing the landscape to satisfy the essential conservation and military training area needs.

Fort Stewart, GA, is one military installation that is challenged with balancing these conflicting objectives. The installation currently has an extensive population of Gopher Tortoise (*Gopherus polyphemus*), often referred to as GT. It is considered a *species at risk* (SAR) [2] on Fort Stewart, and is also a *keystone species* upon which other animals rely for their survival. One such animal is the at-risk Gopher Frog (*Rana capito*), or GF, which depends partly on GT burrows for survival. In an effort to most effectively manage the GT and GF populations, Fort Stewart is looking into the optimal selection of habitat areas that can be made available for the protection of these two species (and also others, such as Indigo Snake and Striped Newt).

The University of Illinois and the US Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL) have collaborated on developing optimal land-use strategies for Fort Stewart and other installations that incorporate both ecologically important considerations and military training requirements. Solutions to the optimum site selection problems described here have been formulated as linear integer mathematical programming models.

Since GT is a ground-bound species, the selected areas should be as compact as possible, and preferably contiguous, in order to allow movement of individuals in the selected areas and facilitate interaction within and among multiple populations in those areas. A compact conservation management area (CMA) would also be easier to fence, if needed. Furthermore, since GT is a keystone species and the GF relies on GT burrows to survive, incorporating the GF management areas into the model would further increase the efficiency of CMA selection because joint management of two species is always more efficient than independent management of individual species. Since the GF depends on access to water for a portion of their life cycle, the distances of GF sites to both ponds and nearest GT habitat sites need to be considered when determining the best GT sites.

In light of the above, specifying the most suitable CMAs for GTs must involve various important ecological and spatial considerations including the following: (1) each designated CMA must have a minimum size, either specified in terms of the land area or in terms of the GT population in that CMA; (2) each CMA should preferably have a compact (circular or square-like) shape; (3) the presence of GF should be considered for joint management efficiency; (4) the GF management areas must be close to both GT sites and existing ponds in the installation area; and most importantly (5) land uses for conservation must be compatible with the existing military land uses and training activities.

1.2 Objective

The objective of this work was to demonstrate the use of linear integer programming formulations to identify the sites for forming clustered biodiversity management areas within the boundaries of a military installation. This demonstration encompassed the development of a basic clustered site-selection model that was extended to include a secondary species; and the application of derivative models to a dataset related to the Gopher Tortoise (GT), a keystone species currently considered at risk; and the Gopher Frog, a species dependent on GTs and access to ponds, at Fort Stewart, GA.

1.3 Approach

The optimum site-selection models documented in this report were coded and solved using General Algebraic Modeling Software (GAMS)[1], a commercially available general-purpose optimization software platform used for mathematical modeling [3]. We developed two linear mixed-integer programming models: the *base model*, which selects the best sites to be managed as GT habitat areas alone; and a second model that extends the base model to include GF for joint management with GTs. The details of the models are presented in Chapter 2.

The models are applied to data from Fort Stewart and the empirical results of our analysis are presented together with a discussion of the results. The data set for the empirical application was obtained as Esri shapefiles from land managers at Fort Stewart and converted to a form accessible to GAMS using Esri ArcGIS 9.3[2]. Data processing details are presented in Chapter 3.

1.4 Scope

The methodologies presented here can be applied to many land management problems involving habitat conservation. Although the specific problem may differ from one case to another in terms of unique characteristics of each installation military training and ecological needs of the subject species, the methods are readily transferable.

Although the models are mathematically complex, the empirical applications demonstrate that they can be solved within a reasonable computation time for the data set used here.

1.5 Mode of technology transfer

The models described in this report are being presented at conferences and seminars to inform military installation land managers, land managers of conservation agencies, academics and researchers of (1) the ability to incorporate spatial considerations in optimum land selection models to select the best lands for conservation goals and (2) the availability of these models for direct application at various locations. The theoretical contri-

---

[1] GAMS Development Corporation, 1217 Potomac Street NW, Washington, DC 20007.

[2] Esri, 380 New York Street, Redlands, CA 92373.

butions of the models are being prepared as a manuscript for submittal to a peer-reviewed journal.

2 Methods and Model Development

2.1 Integer programming in conservation management

The use of mathematical programming models in biological conservation management and reserve design goes back to the late 1980s[3] [4]. In its simplest form, the problem is stated as selecting a minimum number of habitat sites that support specified populations of a set of target species, or maximizing the number of species that can be protected by selected sites under a conservation budget constraint or area limitations. Both problems are formulated as linear integer programs (IP) that are special cases of the prototype *set-covering problem* and the *maximal covering problem* [8, 9, 13 – 19]. Here we use the first approach. Given L sites, where site l provides habitat services to p_{lm} individuals of species m, and a total protected population requirement of tp_m for species m, the basic set-covering problem would take the following form:

$$\text{(1.1)} \quad \text{Minimize} \quad \sum_l S_l$$

$$\text{such that:}$$

$$\text{(1.2)} \qquad \sum_l p_{lm} S_l \geq tp_m \quad \text{for all m}$$

$$\text{(1.3)} \qquad S_l = 0,1 \quad \text{for all } l = 1,\ldots,L .$$

In the above model, S_l denotes a binary variable where S_l = 1 indicates that site l is selected as part of the CMA, and S_l = 0 otherwise.

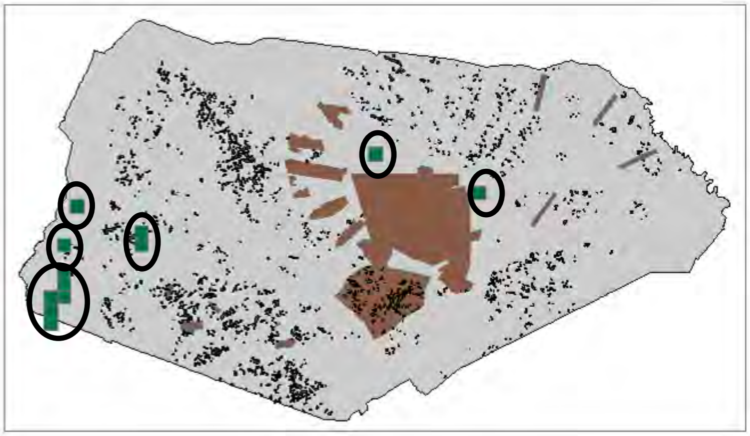
Typically, the above optimum site selection model results in highly sparse and dispersed configurations. As an example, considering only GTs, the result of the model for tp = 5,000 GTs is given in Figure 1a. Four of the six management areas (including 12 sites in all) are comprised by single parcels and they are scattered across the installation. The result for 5,000 GTs and 20 GF sites is given in Figure 1b, which again shows that the selected sites are scattered across the installation. Due to the lack spatial coher-

---

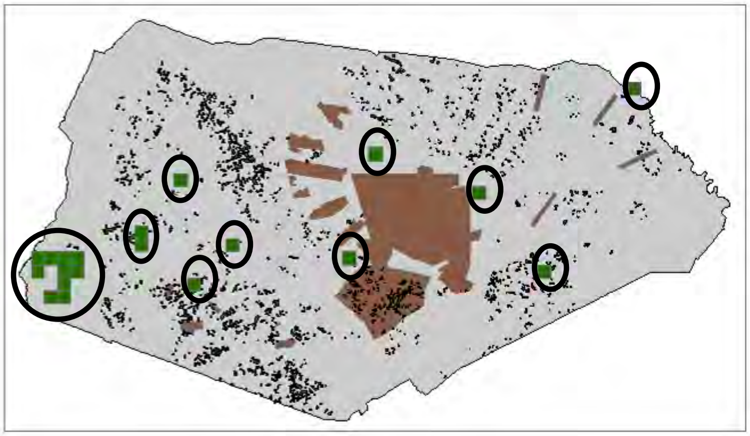
[3] Initial studies used mostly heuristic methods for this purpose [5 – 9]. Heuristic procedures may occasionally yield optimum solutions, but more often they lead to significantly suboptimal outcomes [9 – 12].

ence, neither of the two selections would be considered good solutions becaue it would be costly and ecologically impractical to manage so many small and spatially dispersed sites.

Recognizing this deficiency, several integer programming models have been developed in recent years to incorporate various forms of spatial considerations, such as connectivity, compactness, fragmentation, buffer zones, etc. ([20 – 28]; see [29] for a review). This type of consideration generally requires a more complex mathematical formulation and large-scale models. In the problem addressed here spatial coherence of the designated CMAs for GTs is particularly important. We present extended formulations below to determine an optimal selection of areas for conservation of GTs alone and then GTs and GFs together based on the habitat suitability characteristics and geographical locations of individual sites.



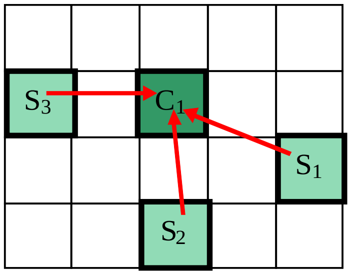
a. No Gopher Frog.



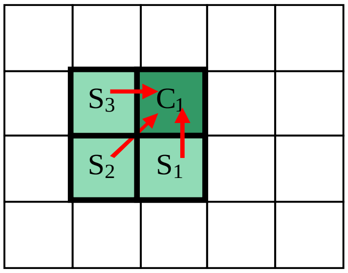
b. 20 parcels of Gopher Frog.

Figure 1. Results for basic set-covering problem with total carrying capacity of 5,000.

The models presented here consider a grid partition consisting of square land parcels[4]. Each parcel (i.e., *site*) is assumed to be an independent decision unit. When selecting sites to configure a compact CMA, the locations of individual sites relative to other selected sites and their contributions to the conservation of GT are taken into account simultaneously. More specifically, we require a CMA to be formed by a set of sites packed (clustered) around a central site. Figure 2a depicts a scattered CMA while Figure 2b shows a clustered CMA where C indicates the central site and SI indicates the sites selected as part of the CMA. Configuring CMAs as shown in Figure 2b requires determining the central site for each CMA and the assignment of individual selected sites to their CMAs in an endogenous way while satisfying the specified conservation requirements[5]. This is accomplished by the algebraic models presented in sections 2.3 and 2.4.



2a. Scattered selection.



2b. Clustered selection.

Figure 2. Scattered sites compared with clustered CMA.

2.2 Notation

We denote the set of all sites by L and individual sites by $k, l \in L$. Site selection and assignment to a CMA is represented by a binary variable X_{lk},

---

[4] 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.

[5] This model is an extension of classic p-median problem formulation [30]. Similar models for clustering have been used previously in the literature of reserve design, business districting, and political districting [23, 29].

where X_{lk} =1 if site k is selected and belongs to the CMA 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 CMA must belong to that CMA. Sites in the most heavily used military training areas (existing or potential) are not considered for inclusion in any CMA, so 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 ek denotes the existing population of GT in site k. The number of CMAs (clusters) to configure is denoted by n; which is specified exogenously, but varied when designing alternative optimal configurations. Each CMA 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.

2.3 Base model

We first address the problem of constructing n compact CMAs for GTs, each covering a minimum sustainable GT population and collectively covering a desired GT population. Here we define compactness of a CMA as the overall closeness of all sites within it. We measure the latter by the sum of distances from all sites in a cluster to the central site, which must be minimized to the greatest extent possible[6]. An algebraic model that serves this purpose, which we refer to as the *base model,* is given in (2.1) – (2.7).

$$\text{(2.1)} \quad \text{Minimize} \sum_{l} \sum_{k} X_{lk} * d_{lk}$$

such that:

$$\text{(2.2)} \quad \sum_{l} X_{ll} = n$$

$$\text{(2.3)} \quad \sum_{l} X_{lk} \le 1 \text{ for all } k$$

$$\text{(2.4)} \quad \sum_{k} X_{lk} * e_k \ge p \text{ for all } l$$

$$\text{(2.5)} \quad \sum_{l} \sum_{k} X_{lk} * e_k \ge tp$$

$$\text{(2.6)} \quad X_{lk} \le X_{ll} \quad \text{for all } l,k$$

$$\text{(2.7)} \quad X_{lk} = 0,1 \quad \text{for all } l,k$$

---

[6] Compactness is not a well defined concept. Note that the absolute value of the compactness measure defined here may not mean much by itself, but instead 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 serves the specific purposes of the present study. Minimizing the total distance typically results in a circular and connected reserve configuration.

The objective function involves the distances from individual sites in each CMA to the center of that CMA, which in turn is summed over all CMAs. Minimizing this sum of distances achieves a clustered CMA. Constraint (2.2) ensures that n CMAs are created. Constraint (2.3) states that each site can belong to at most one CMA centered at some site l. Constraint (2.4) requires that each CMA supports a population that exceeds the minimum sustainable size[7], while constraint (2.5) ensures that all CMAs collectively support a desired total population. Finally, constraint (2.6) implies that if site k is selected and assigned to the central site l, i.e., $X_{lk}=1$, then a CMA centered at site l must be formed, i.e., X_{ll} must be 1, otherwise we have $X_{lk}=0$.

The base model identifies the most suitable clusters to be considered as CMAs for GTs. However, it does not incorporate GF considerations. We next present a modification of the model that determines GT and GF management areas simultaneously.

2.4 Simultaneous selection of CMAs for GT and GF

The best CMAs for both GT and GF must have the following properties: (1) the GT CMAs must be as compact as possible; (2) each CMA must be large enough to include a sustainable GT population; and (3) individual CMAs must contain a minimum number of GF sites that are within 2 km of an existing pond. The first two criteria are already included in the base model formulation. The last criterion is necessary because the GF life cycle requires access to a reliable water source, and the maximum distance from a water source is known to be 2 km.

In addition to the notation used earlier we define a new binary variable, Y_k for site k, where $Y_k = 1$ if site k is selected as a designated GF habitat area and $Y_k = 0$ otherwise[8]. We also define the following new symbols: f denotes the desired minimum number sites assigned as GF parcels; dp_k denotes the distance between site k and the nearest pond, and denotes $\bar{d}$ the maximum allowed distance between a designated GF site and the nearest pond. Constraints (2.7) and 2.8) are added to the base model to incorporate the GF management area requirements.

---

[7] This constraint can also be expressed in terms of a minimum number of sites in each CMA if the effectiveness of conservation effort is related to the size of the CMAs.

[8] As formulated, we require that only sites selected as GT sites can be considered as GF sites

$$Y_k \le \sum_{l} X_{lk} \quad \text{for all } k \tag{2.7}$$

$$\sum_{k:dp_k \le \bar{d}} Y_k \ge f \tag{2.8}$$

$$Y_k = 0,1 \quad \text{for all } k \tag{2.9}$$

Constraint (2.7) ensures that only sites selected as GT sites can be considered as a GF site. In other words, if site *k* is designated as a GF site (i.e., $Yk = 1$) then it must be assigned to some GT CMA centered at site *l* ($X_{lk} = 1$). Constraint (2.8) ensures that the model selects at least *f* GF sites. Note that a GF site can be considered as a designated site only if its distance from a pond is at most $\bar{d}$, as implied by the condition underlying the summation in (2.8).

2.5 Data and Input

The data on current military training areas and the location of ponds were obtained as raster files from Fort Stewart. The habitat areas suitable for GT were obtained as raster files from the national biological information infrastructure [31]. These raster files were converted to Esri shapefiles using ArcGIS 9.2. The current military training areas are shown in Figure 3a, the GT suitability is depicted in Figure 3b, and the locations of the ponds are shown in Figure 3c. A 55 x 30 grid file, where each grid cell is a 1,000 m x 1,000 m square, was created using GeoDa[9] and the grid shapefile was spatially joined with the above shapefiles using the spatial join function in ArcGIS. The spatial join function gives the grid file the attributes of the shapefile. To ensure that each grid cell represents a density of the original data, the sum option was used when joining the habitat suitability data. The grid cell values for Figure 3b are given as the sum of suitable points (the GT suitability raster map[10] was converted to a point shapefile) within the grid cell. The suitability index ranges from 0 – 600[11].

---

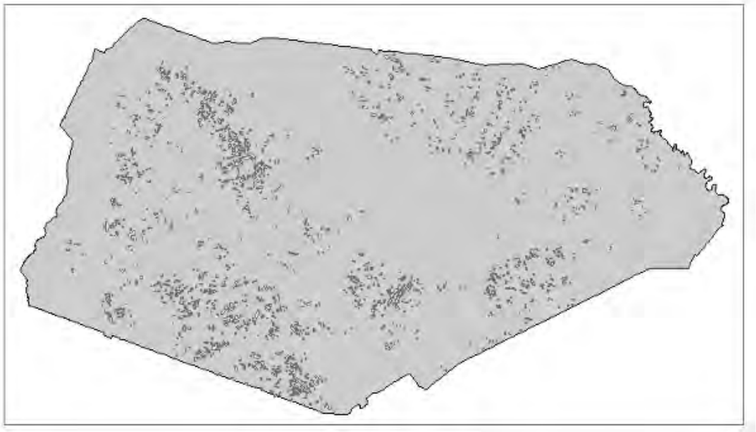
[9] Center for Geospatial Analysis and Computation, Arizona State University, http://www.asu.edu.

[10] GT Suitability values were calculated by Dr. Jim Westervelt and Dr. Tracey Tuberville.

[11] The carrying capacity values in the suitability map are GT/ha. The number of tortoise in each grid cell = (suitability value of grid cell/121)*100. A one-hectare land parcel can support between 2 to 5 GTs. This is equivalent to supporting between 200–500 GTs per site at the 1,000m x 1,000m resolution.

a. Ranges

b. Suitability Index for GTs.



c. Location of ponds.

Figure 3. Summary of data.

3 Results and Discussion

The models described by (2.1) – (2.6) and (2.7) – (2.9) were solved using GAMS/CPLEX version 21.6 on a personal computer running Microsoft Windows XP with an Intel Core 2 Duo processor and 2 Gb of RAM. It is assumed that the final total GT population in all CMAs must be at least 5,000. In theory, the GT populations can be moved to a single large CMA or multiple smaller CMAs all located outside the military training areas. The model is solved with various specifications for the number of CMAs. There are two reasons for specifying more than one CMA. First, we may want to separate the overall GT population into smaller populations, each being located in a different part of the installation area, in order to safeguard them against potential total destruction that may occur in the managed areas, such as the spread of a disease. Second, establishing a single, large conservation area reduces military land-use flexibility if further expansion of training areas is needed in future. These potential problems can be mitigated by designing multiple and relatively small conservation areas.

In all of the model runs described below, the minimum population for each CMA was specified as 1,000. The base model was solved with one, two, three, and four CMAs. The joint management model (2.1) – (2.9) was first solved for a minimum of 10 GF parcels and then for 20 GF parcels[12]. A wide range of potential parameter values were tested after discussions with the base land managers. We present the results here to highlight the model's ability to (1) optimally select the CMAs, (2) illustrate the workings of the models, and (3) demonstrate the tradeoffs between incorporating different spatial criteria in site selection.

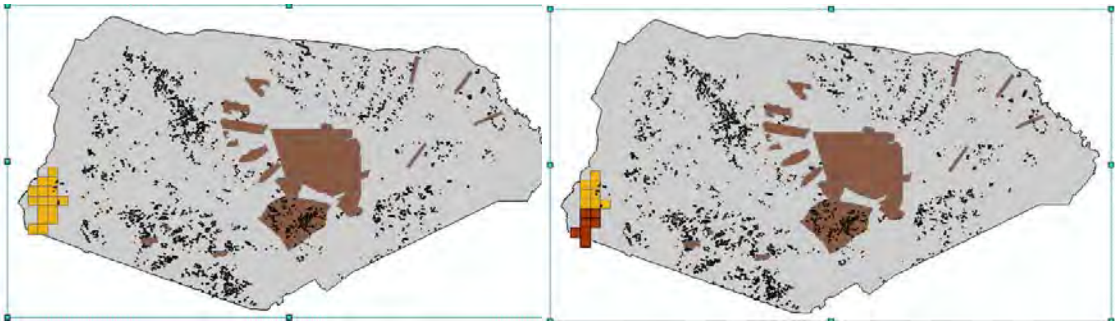
3.1 Base model results

The base model results are shown in Figure 4 for one, two, three, and four CMAs. Comparing the results in Figure 4 with the suitability map given in Figure 3c illustrates that the base model simply selects from among the most densely packed and best available sites to form contiguous and compact CMAs. The optimal solution with one large conservation area (Figure 4a) shows that this area would be located at the southwest corner of the

---

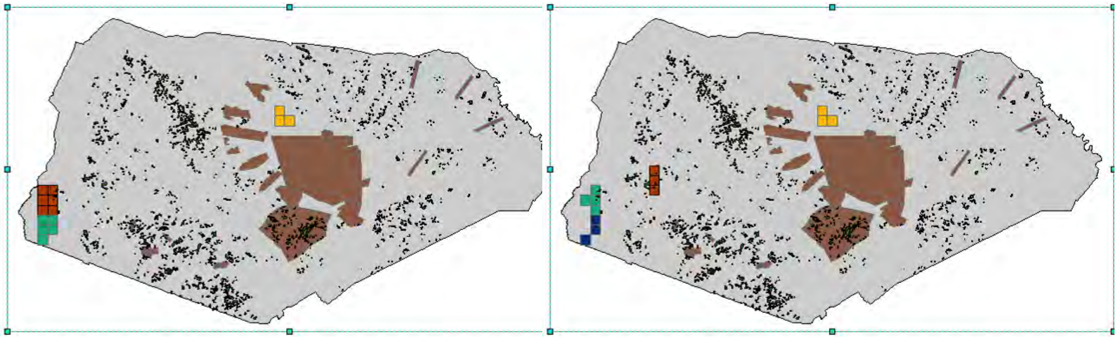
[12] The only GF criteria we required were that a GF site also had to be a GT site and be located within 2 km of a pond. These criteria can be refined using the available data (e.g., a subset of all ponds such as those that are larger than a certain size or have water during the GF breeding season).

installation. The CMA is contiguous but the compactness of the CMA is poor and the selected sites are meandering in shape. Also, the solution has 16 sites versus the 12 sites in the basic set-covering problem (see Figure 1a). The lack of compactness and the increase in the number of selected sites are both driven primarily by the fact that the model is forced to choose one cluster of habitat sites that meet the population criteria, and the only available large quantity of good-quality sites are in that part of the installation. The good-quality sites in other parts of the installation are not in the solution because (1) those sites are under military use or (2) they are located far apart from each other.



a. One CMA.

b. Two CMAs.



c. Three CMAs.

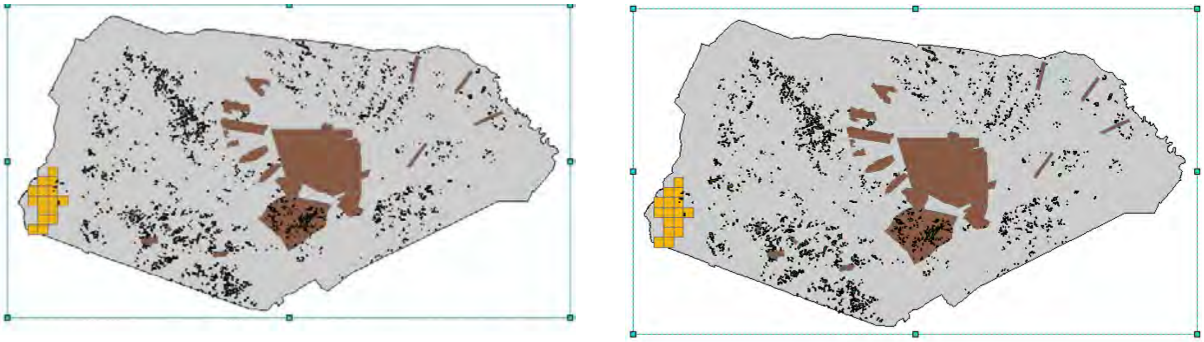
d. Four CMAs.

Figure 4. Results for total carrying capacity of 5,000.

For the two-CMA case the model chooses two clusters with seven and eight sites, respectively (Figure 4b), for a total of 15 sites. Although the two clusters are again selected in the southwest corner of the installation, allowing for two clusters enables the model to achieve the population goal with one less site than the one-cluster case. The three-CMA case selects a total of 14 sites (Figure 4c), with two clusters in the southwest part of the installation and one cluster in the north-central part. Finally, the four-CMA case selects 13 sites from three separate areas as shown in Figure 4d. This clearly demonstrates that as more CMAs are considered the model is able to choose fewer and better sites in different parts of the installation, decreasing the total area needed for the same level of conservation. Unlike the scenario involving one large CMA, the two-, three-, and four-CMA configurations consist of compact clusters as opposed to the meandering configuration in Figure 4a. Based on these results, we may conclude that if the size of the total area of all CMAs must be significantly constrained, forming four CMAs—two located in the southwest, one located in the west-central area and one located in the north-central areas—would be the best strategy as it selects only 13 sites. It is noteworthy to state that this alternative includes just one more site than the scattered configuration given in the set-covering solution (Figure 1a).

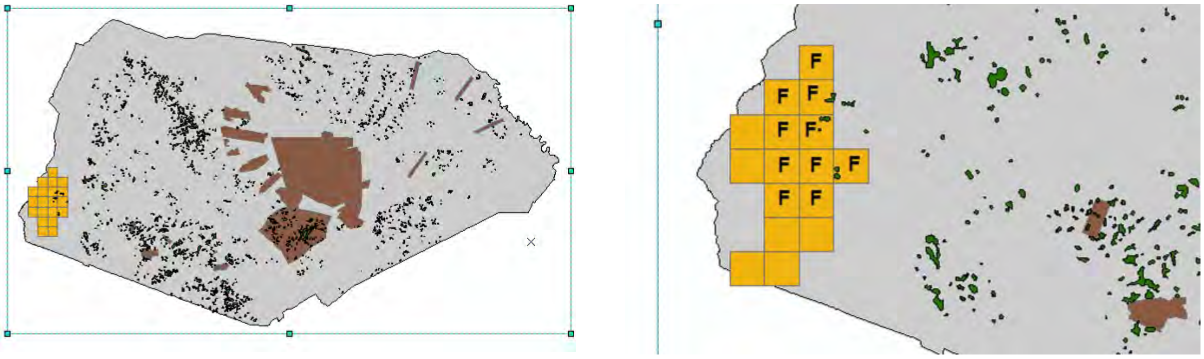
3.2 Joint management results

The results of the joint management model (2.1) – (2.9) are shown in Figure 5 – Figure 8 for one, two, three and four CMAs, respectively. In each figure, item b displays the results for at least 10 GF sites (f=10) and item c displays the results for at least 20 GF sites (f=20).



a. No Gopher Frog.

b. 10 Parcels of Gopher Frog.



c. 20 Parcels of Gopher Frog.

d. 10 Parcels of Gopher Frog (identified with F).

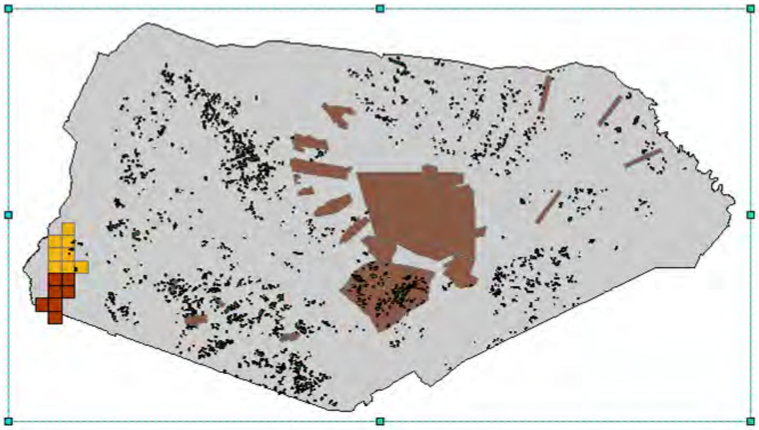
Figure 5. Results for one cluster of GT with total carrying capacity of 5,000.

The optimal solution with one large conservation area and 10 GF sites (Figure 5b) shows that this area would, as in other solutions, be located at the southeast corner of the installation, and is identical to the solution without GF considerations. This is because, as depicted in Figure 5d, there are 10 sites in that area that are within 2 km of a pond in that solution. When the number of GF sites is increased to 20 sites, the selected sites are still in the southwest corner of the installation, but the locations change because the model now has to add more sites that are located within 2 km of a pond.

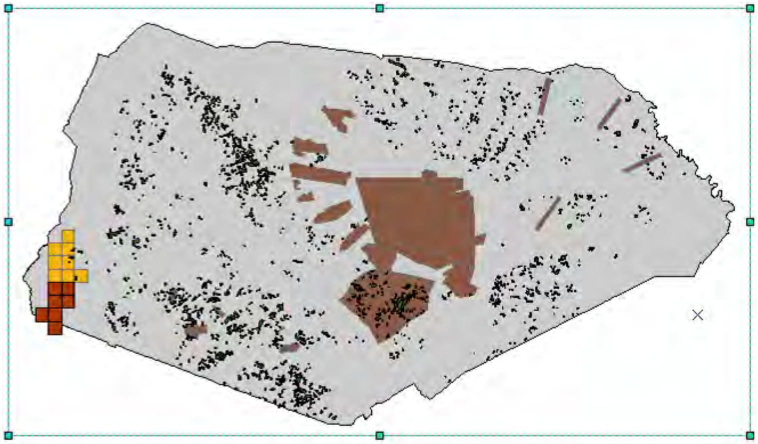
The results for two CMAs are shown in Figure 6. For 10 GF sites, the optimal configuration is similar to the base model solution. When 20 GF sites are required, the results change dramatically, as the model selects one compact CMA with 9 sites and another with 11 sites that are located away from each other and close to the locations of the ponds.

The results for three CMAs are shown in Figure 7. In the base model solution one CMA was located in the north-central region away from ponds. The case with 10 GF sites (Figure 7b) now moves that CMA located away from the ponds to a region with nearby ponds without increasing the total number of selected sites. The case with 20 GF sites (Figure 7c) again selects more sites and has three CMAs that are located in different regions of the base.

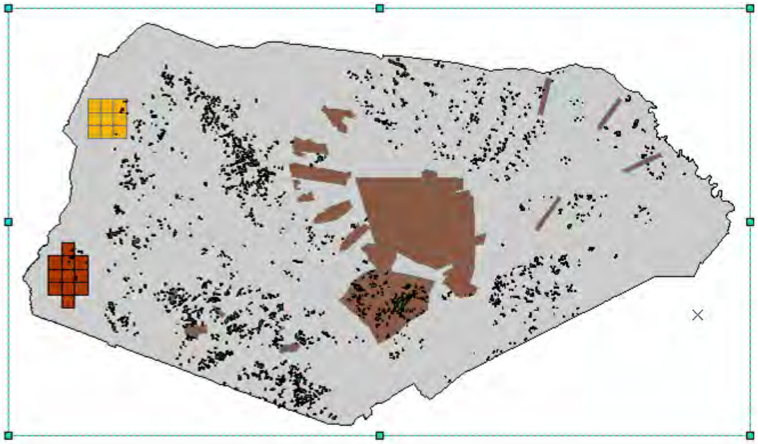
The solution including four CMAs (Figure 8)shows that it is possible to meet the 5,000 GT population and the 10 GF site goals with only 13 sites, just one more site than the set-covering solution and same as the GT-only solution. When requiring 20 GF sites, the optimal selection includes more sites that are located in the west side of the installation and part of the well grouped compact GT clusters. Clearly this is a much-preferred configuration, as opposed to the spatially unrestricted (and thus scattered) configuration shown in Figure 1b. In general, allowing for four CMAs results in more compact CMAs since the model is able to place the smaller CMAs in the most suitable areas while allowing for large enough individual CMAs to support a minimum viable population of GTs assumed in the analysis.



a. No Gopher Frog.

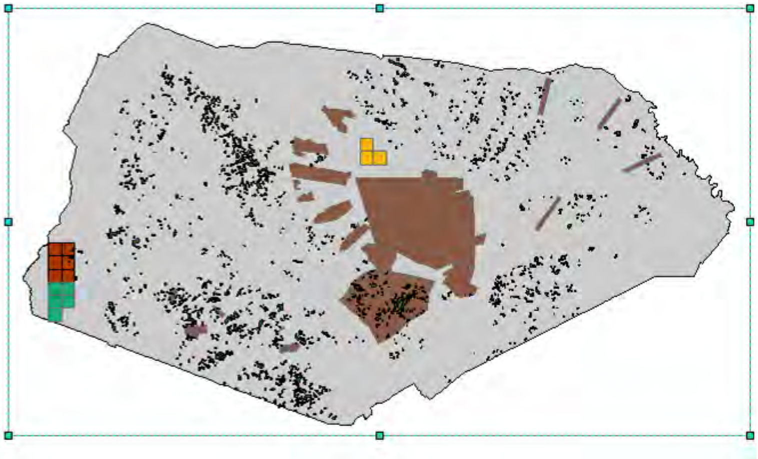


b. 10 Parcels of Gopher Frog.

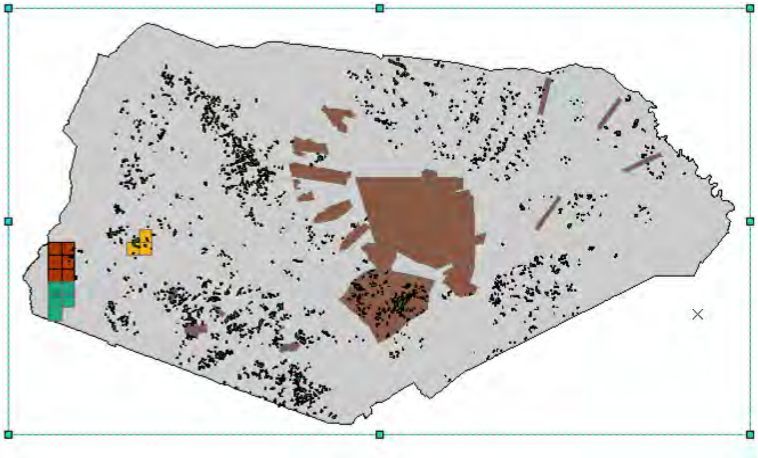


c. 20 Parcels of Gopher Frog.

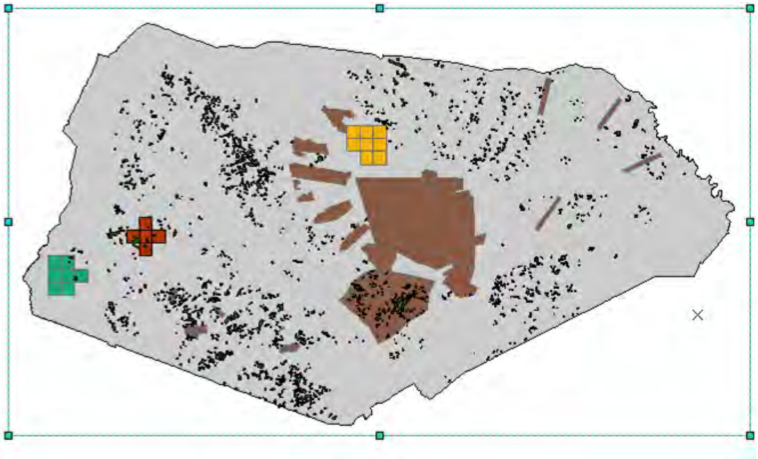
Figure 6. Results for two clusters of GT with total carrying capacity of 5,000.



a. No Gopher Frog.

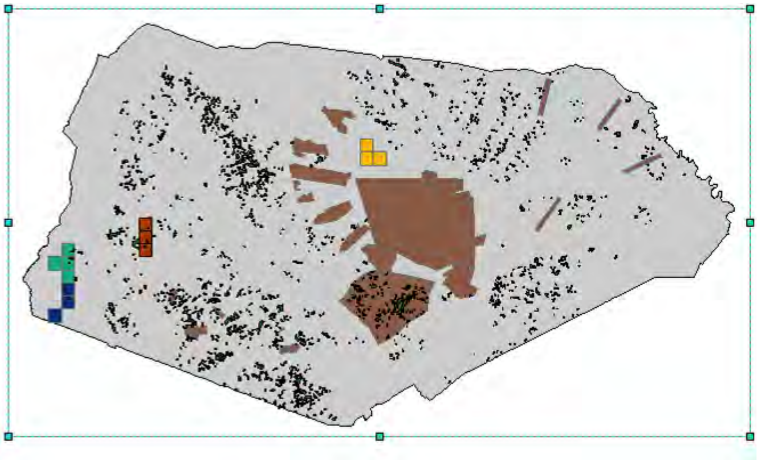


b. 10 Parcels of Gopher Frog.

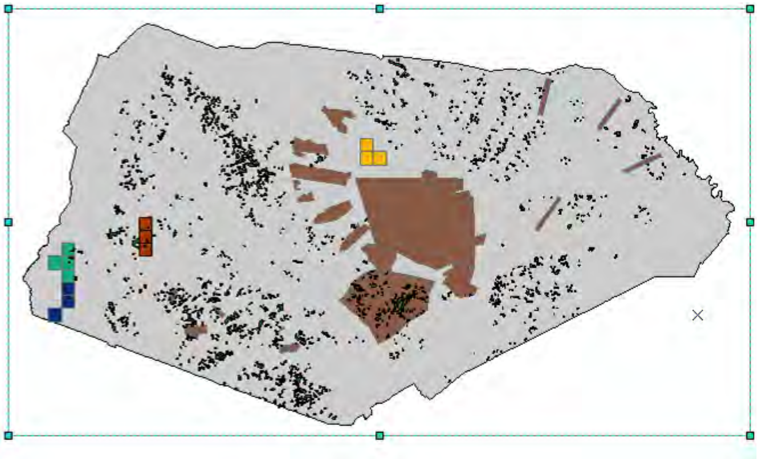


c. 20 Parcels of Gopher Frog.

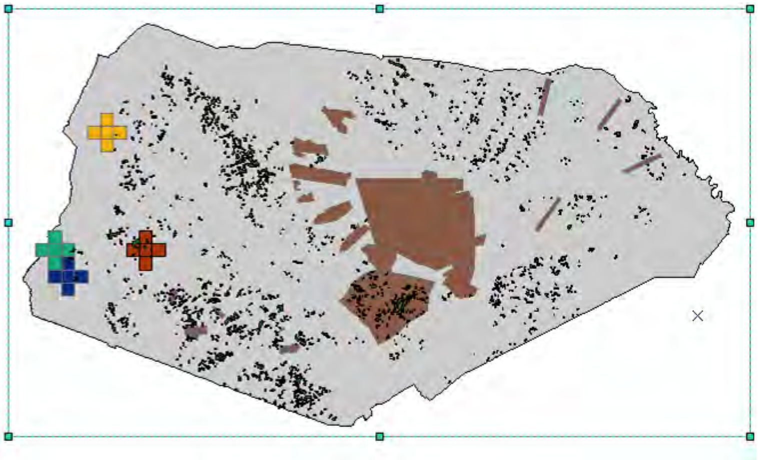
Figure 7. Results for three clusters of GT with total carrying capacity of 5,000.



a. No Gopher Frog.



b. 10 Parcels of Gopher Frog.



c. 20 Parcels of Gopher Frog.

Figure 8. Results for four clusters of GT with total carrying capacity of 5,000.

4 Conclusions

This report has presented an application of linear integer programming to determine compact and ecologically valuable conservation management areas (CMAs) on a military installation with populations of species at risk. Two models were developed and applied to conservation efforts at Fort Stewart, GA, involving the Gopher Tortoise and Gopher Frog. The Gopher Frog depends on Gopher Tortoise presence in protected areas, and also requires proximity to ponds for breeding purposes.

The models identified CMAs that meet Fort Stewart's military and ecological land management criteria by:

- selecting compact GT site clusters to comprise each CMA
- identifying possibilities for establishing multiple CMAs, instead of a single large one, which improves sustainable habitat quality while reducing the amount of military training land dedicated to CMAs

Additionally, incorporating GF habitat requirements into the GT analysis did not change the results when a small number of GF sites were assumed, but the results changed considerably in runs where a large number of GF sites were required.

The single and joint species conservation management models were solvable in a short amount of computation time, which suggests that the formulations presented here may be applied to much larger data sets without concern about data processing requirements. In all cases, the optimum solutions were obtained after only a few minutes of processing time.

Adding extra requirements to the model, such as a need for additional GF conservation requirements, can force the model to select a number less-suitable parcels when the best available parcels do not meet criteria for location, compactness, or other parameters. This can lead to the selection of larger CMAs or poorer compactness. Predictably, then, there is a tradeoff between incorporating additional requirements and the economic efficiency in optimal selection of conservation CMAs.

The sites, represented by grid cells in the model, are rather large (1,000 x 1,000 m). In many practical CMA design problems, much smaller areas may have to be considered as decision units, depending on factors such as data accuracy, site costs, and uniformity of individual sites in terms of their habitat characteristics. That requirement could increase model size considerably and lead to computational difficulties. However, for conservation analyses that require higher resolution, this model would support a multistep modeling approach in which low-resolution data can be used first to locate the general area, then successively higher-resolution data can be used for the surrounding areas 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 subdivided into sufficiently small spatial decision units to identify the specific conservation areas at desired resolution.

The results presented here demonstrate that it is possible to optimally select compact sites that form up to four centrally placed CMAs within the boundaries of a specific military installation. The CMAs become smaller and more compact, and comprise higher-quality sites, as the allowed number of CMAs increases. However, those CMAs may be dispersed throughout the installation. When GF considerations are included, the model identifies CMAs that simultaneously serve as good GT habitats and also GF habitats, which indicates that ecological considerations for multiple species can be incorporated jointly within a unified framework.

A significant empirical finding of this study was that Fort Stewart’s GT habitat conservation objective can be served by designating only a small amount of land, thus avoiding significant sacrifice in the availability of military training land for current and future requirements.

With appropriate modifications, the methods introduced here can be applicable to many other conservation problems involving different at-risk species and multiple land uses.

References

[1]. Balbach H. E., Keane E. L. and Meyer W. D. (2006). Strategy for Better Management of At-Risk Species: A Proposed Interagency Initiative. U. S. Army Corps of Engineers, Engineer Research Development Center. http://www.cecer.army.mil/techreports/ERDC-CERL_TN-06-04/ERDC-CERL_TN-06-04.pdf

[2]. GAMS Development Corporation. (2007). General Algebraic Modeling Software (GAMS) Release 21.6. Washington, DC.

[3]. Benton, N., J.D. Ripley, and F. Powledge, eds. Conserving Biodiversity on Military Lands: A Guide for Natural Resources Managers. 2008 edition. Arlington, Virginia: NatureServe. Available at http://www.dodbiodiversity.org.

[4]. Cocks, K.D., and I.A. Baird. (1989). Using mathematical programming to address the multiple reserve selection problem: an example from the Eyre Peninsula, South Australia. *Biological Conservation* 49: 113–30.

[5]. Margules, C. R., Nicholls, A. O. and Pressey, R. L. (1988). Selecting networks of reserves to maximize biological diversity. Biol. Conserv. 43, 63–76.

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

[7]. Nicholls, A. O. and Margules, C. R. (1993). An upgraded reserve selection algorithm. *Biological Conservation*. 64, 165–169.

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

[9]. Pressey, R.L., Possingham, H.P., and Day, J.R. (1997). Effectiveness of alternative heuristic algorithms for identifying indicative minimum requirements for conservation reserves. *Biological Conservation* 80: 207–19.

[10]. Church, R. L., Stoms, D. M. and Davis, F. W. (1996). Reserve selection as a maximal covering location problem. *Biological Conservation*. 76, 105–112.

[11]. Rodrigues, A.S.L. and Gaston, K.J. (2002). Optimization in reserve selection procedures – why not? *Biological Conservation* 107, 123-129.

[12]. Önal, H. (2004). First-best, second-best, and heuristic solution in conservation reserve site selection, *Biological Conservation* 115, 55–62.

[13]. Toregas C. and ReVelle C. (1973). Binary logic solutions to a class of location problems, *Geographical Analysis*, 5(2), 145–155.

[14]. Church, R. L. and ReVelle, C. (1974). The maximum covering location problem. *Papers in Regional Science Association*. 32, 101-118.

[15]. Underhill L. G. (1994). Optimal and suboptimal reserve selection algorithms, *Biological Conservation*. 70, 85–87.

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

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

[18]. Williams, J. C. and ReVelle C.S. (1997). Applying mathematical programming to reserve selection. *Environmental Modeling & Assessment* 2 167-175.

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

[20]. Cova, T. J., and Church, R. L. (2000). Contiguity constraints for single-region site search problems. *Geographical Analysis*, 32, 306–329.

[21]. Williams, J. C. (1998). Delineating protected wildlife corridors with multiple-objective programming. *Environmental Modeling & Assessment* 3:77-86.

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

[23]. Önal, H., and Briers, R.A. (2005). Designing a conservation reserve network with minimal fragmentation: a linear integer programming approach. *Environmental Modeling & Assessment* 10, 193–202.

[24]. Önal, H. and Wang, Y. (2008). A Graph theory approach for designing conservation reserve networks with minimal fragmentation. *Networks* 52, 142-152.

[25]. Cerdeira, J.O. and Pinto, L.S. (2005). Requiring connectivity in the set covering problem. *Journal of Combinatorial Optimization* 9, 35-47.

[26]. Cerdeira, J.O., Gaston, K.J., Pinto, L.S. (2005). Connectivity in priority area selection for conservation. *Environmental Modeling & Assessment* 10, 183-192.

[27]. Cabeza, M., Araujo, M.B., Wilson, R.J., Thomas, C.D., Cowley, M.J.R. Moilanen, A. (2003). Combining probabilities of occurrence with spatial reserve design. *Journal of Applied Ecology* 41, 252–262.

[28]. Nalle, D. J., Arthur J. L., C. A. Montgomery, J. Sessions. (2002). Economic and spatial impacts of an existing reserve network on future augmentation. *Environmental Modeling & Assessment* 7, 99–105.

[29]. Williams, J. C., ReVelle, C. S., and Levin, S. A. (2005). Spatial attributes and reserve design models: a review. *Environmental Modeling & Assessment* 10, 163–181.

[30]. Garfinkel, R.S., Neebe, A.W., Rao, M.R. (1974). An algorithm for the m-median plant location problem. *Transportation Science*, 25 , 183–187.

[31]. Elliott M., Anderson L., Bumback B., Schmidt J. P., Kramer L. (2003). Georgia GAP reptile models. *Gap Analysis Project*. http://gapanalysis.nbii.gov/. Last accessed on 06-25-2008.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
October 2011

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Optimal Selection of Conservation Lands at Fort Stewart Using Integer Programming

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
A896

6. AUTHOR(S)
Sahan T. M. Dissanayake, Hayri Önal, James D. Westervelt, and Harold E. Balbach

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Research and Development Center
Construction Engineering Research Laboratory
P.O. Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CERL TR-11-39

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology
1400 Defense Pentagon
Washington DC 20301-1400

10. SPONSOR/MONITOR'S ACRONYM(S)
ASA(ALT)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report documents an application of linear integer programming for determining compact and ecologically valuable conservation management areas (CMAs) on a military installation with populations of at-risk animal species. Two models were developed and applied to the conservation efforts Fort Stewart, GA, involving the at-risk Gopher Tortoise (GT) and the tortoise-dependent Gopher Frog (GF).

The models produced solutions that are consistent with the species conservation and military training land-use objectives at Fort Stewart. They identified suitable, compact GT habitat clusters and were able to minimize the total amount of managed areas by selecting fewer and better sites. In runs that incorporated GF requirements into the GT analysis, the model was able to determine that the optimized GT CMAs also will support a small number of GF sites. However, on runs that assumed a large required number of GF sites, the GT results changed considerably in order to incorporate the GF sites. Both the single and joint species conservation management models were solvable in a short computation time, suggesting that these models may be applied to much larger data sets without significant data processing problems. The methods introduced here may be modified for application to other species, locations, and land uses.

15. SUBJECT TERMS
Gopher Tortoise (*Gopherus polyphemus*), Gopher Frog (*Rana capito*), threatened and endangered species, habitat, land-use planning, modeling, integer programming, Fort Stewart, Georgia, military installations

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER *(include area code)***
Unclassified	Unclassified	Unclassified		29	