Species Protection From Current Reserves : Economic and Biological Considerations, Spatial Issues and Policy Evaluation

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Abstract

The expansion of nature reserves is an important public policy strategy for the protection of biological diversity. In this paper, the authors use integer programming model structures derived from Location Set Covering Problem and Maximal Covering Location Problem approaches of location science as tools for selectively augmenting nature reserve sites for special status species protection. The linear programming models presented incorporate the following: biological constraints in the form of species' area needs; economic constraints in the form of opportunity costs of converting smaller administrative districts into nature reserves; and spatial constraints in the form of required connectivity among districts in site selection. The construction of a taxonomic data set for Thailand enables the implementation of the models, the comparison of results and evaluation of the differences in outcomes. The models build upon the existing nature reserve network in Thailand and suggest various public policy options that would augment the reserves for enhancing species protection and for possibly improving national conservation efforts at lowest costs.

1. Introduction

One of the goals of the Convention on Biological Diversity, opened for signature at the United Nations Conference on Environment and Development, held in Rio de Janeiro in 1992, and ratified by a large number of countries, including Thailand, was to achieve a significant reduction in the current rate of biodiversity loss by 2010.

The establishment and enhancement of nature reserves is a highly important strategy for the conservation of biological biodiversity. Since Thailand ratified the Convention, the Government expanded, among other conservation actions, the country's national nature reserve network.

The first national park in Thailand, Khao Yai National Park, was established in 1962 and has been managed by the Royal Forestry Department since it became a protected area (Albers and Robinson, 2007). Thailand was one of the first developing countries to implement an ambitious system of protected areas, currently composed of 31 wildlife sanctuaries and 57 national parks. Over the years, protected areas were not selected at random but were more likely to be considered if they had higher historical forest cover, were located further from high quality agricultural land, further from mineral and timber resources, were close to national borders due to security reasons and included endemic species (Sims, 2010).

For more than twenty years, ecologists, economists and others have formulated mathematical models whose broad aim is to support efficient methods to protect special status animal and plant species in such nature reserves. Some analytical models have examined strategies aimed at protecting as many species as possible, while others have been directed at only the most critically endangered species.

Most such modeling efforts implicitly incorporate biological, economical or spatial parameters and generally have been constructed using available data to show their potential use to public officials charged with effective protection of biodiversity. This paper explicitly considers biological, economic and spatial constraints, applied to a large data set from the Kingdom of Thailand, as these three parameters seem critical in protecting species and hence, contribute to a reduction in biodiversity loss. More precisely, area needs of each species under consideration, heterogeneous land costs, and spatial restrictions such that sites added to reserves must be adjacent to existing reserves, will all be taken into account.

Furthermore, the analysis begins using the existing national nature reserve network in Thailand, then moves to identify an enhanced level of protection for the set of endangered vertebrate species through the selective addition of land in a cost-efficient way, so as to preserve additional species, previously unprotected in the current reserve network.

All component parts of the models have been analyzed and described in previous studies, but they have not all appeared together in a similar context featuring a large data set in a developing country application.

2. Methodology and Scope of Analysis

2.1. EARLY LITERATURE REVIEW AND SCOPE OF ANALYSIS

The analytic methods in which a nature reserve system is formulated parallels that of location science, which seeks to identify a set of geographic sites for locating economic activities (ReVelle et al., 2002) in some optimal way. Two such location science techniques, the Location

Set Covering Problem (LSCP) and the Maximal Covering Location Problem (MCLP), developed in the 1970s, seek to locate the fewest number of facilities in such a way that all demand nodes are covered within a certain distance or time standard (Toregas et al., 1971; Toregas and ReVelle, 1973), or alternatively, to cover as many demand nodes as possible with a limited number of facilities (Church and ReVelle, 1974). Over the subsequent three decades, analysts began to apply these location science models to nature reserve problems. In nature reserve applications, the parallel objective is either: (1) to choose the smallest number of land sites from a population of sites for a nature reserve such that each species of interest is present in at least one selected site (Possingham et al., 1993; Underhill, 1994), or (2) to identify a nature reserve system in which the habitats of the largest number of species is preserved, even if the system of sites may not be sufficient to preserve every species of interest (Church et al., 1996; Camm et al., 1996).

More recently, several authors developed probabilistic (e.g., Haight et al., 2000) and dynamic models (e.g., Costello and Polasky, 2004) for selecting nature reserves. Examples of other interesting research directions included the introduction of cost-efficient reserve selection, the introduction of individual habitat range for every species under consideration, and spatial issues in designing a reserve network. The purpose of this paper is to enrich the deterministic literature by incorporating these elements together and by applying them to a developing country data set, taking existing reserves into account.

2.2. METHODOLOGY

This paper uses 0-1 programming models of the Location Covering Problem types. Following Marianov et al. (2008) and Polasky et al. (2008), it explicitly takes into account geographic range, differentially articulated for individual species, in establishing a reserve network.

The paper also incorporates cost-efficient site selection as in Ando et al. (1998) and Polasky et al. (2001), because, for a given level of species protection, selecting sites based on the total surface or on the quantity of land parcels is always more expensive than selecting them based on the opportunity cost of converting a site to a nature reserve.

Based on these earlier studies, a first model starts with the set of nationally endangered species that already can be considered as protected, that is, those that are part of an existing reserve system. Then, using area needs for each remaining species, it mathematically attempts to determine in an iterative process the most cost efficient method to protect each additional species, until all species are included in the augmented reserve system. Further, this computation makes possible the derivation of the marginal cost of additional species protection.

Adding requirements for spatial coherence has been shown to enhance further the protection of critical species. Williams et al. (2005) reviewed various spatial attributes in reserve design, while Moilanen et al. (2009) reviewed current theory and methodologies that deal with spatial aspects of species conservation. This latter review considered basic methodological structures, optimization methods for solving spatial problems and biological applications that include habitat modeling, metapopulations, spatial population viability, conservation planning issues and software packages developed for planning needs.

In the biological literature, species persistence is often modeled as a function of spatial pattern of protection, and is employed to justify spatially explicit requirements such as compact reserves or reserves otherwise located close together. As a matter of fact, such reserves may increase local persistence by reducing edge effects and by facilitating dispersal and allowing recolonization of unoccupied but suitable sites (i.e. Cabeza and Moilanen, 2001; Cabeza et al., 2004, Araujo and Williams, 2000).

Spatially explicit reserve selection models over the years have considered the delineation of core areas and buffer zones (i.e. Williams and ReVelle, 1998), proximity and compactness (i.e. Önal and Briers, 2002), connectivity (i.e. Nalle et al., 2002, Önal and Briers, 2006) and boundary shape or convexity (i.e. Williams, 2003). All of these spatial questions may be addressed using integer programming tools and are reviewed in detail in Haight and Snyder (2009) who also underscore the difference between structural and functional connectivity. Another paper by Nalle et al. (2004) proposes a sophisticated economic and ecological model combining a spatial and dynamic analysis in a single species study. Using the Haight and Nalle studies as a basis, we propose two further models that utilize spatial analysis in that only "connected" parcels of current reserves are considered as eligible sites. Thus they seek to protect as many (if not all) additional species by selecting the least-costly connected land sites.

This paper uses an existing reserve network as a starting point. Typically, models are applied to a data set with the presumption that no species protection exists, even though, in reality, countries and sub-national jurisdictions set aside land as nature reserves and devote manpower and other resources to conservation goals. Thus, it is more realistic, for policy purposes, to take the existing reserve network into consideration and to evaluate whether the current network is satisfactory and also whether it should be amended to better protect species. Haight et al (2004) concentrate on a reserve expansion for protecting one single species while Nalle et al (2002) explore a reserve augmentation having spatial characteristics in which all habitat types, used as a proxy measure for species coverage, are sufficiently represented. Another technique, not used in this paper, is GAP analysis (Jennings, 2000). This method identifies 'gaps' in the conservation network: biodiversity elements in the existing conservation areas that are poorly represented or not represented at all. It then considers methods to expand the network by setting priorities for subsequent conservation actions. In this paper, the current reserve system is augmented in a cost-effective way, taking into consideration spatial needs of each protected species, to cover those species that are not represented in the original network.

3. Species Data for Thailand

Thailand is comprised of 76 provinces; each province is divided into "amphoes", the nation's smallest administrative districts. This study considers 567 amphoes, ranging from a few square kilometres to 2407 square kilometres[i], leaving aside the Bangkok metropolitan area because of its highly urbanized character and disturbed environment with few species of interest[ii]. Henceforth, in this paper, amphoes are referred to by the English term "districts".

A total of 68 terrestrial vertebrates, classified as rare, threatened or endangered by the International Union for the Conservation of Nature and Natural Resources (IUCN, 2006) are considered in this study. Of these, 57 are mammals, 9 are reptiles and 2 are amphibian species.

The species set for Thailand is detailed in Hamaide et al. (2008). The construction of a presence-absence matrix of all species in all districts is based on endangered species information from Humphrey and Bain (1990), which updates and extends Legakul and McNeely's seminal study (1977) on mammals in the country. Where multiple estimates of distribution are available, the more conservative or restrictive alternative is used. Also, constructed data are crosschecked with the electronic Bioinventories of the World (2006), which applies to protected areas and can be readily mapped to districts and the correspondence with the presence-absence matrix is extremely close.

With the passage of time since distribution estimates were made, and subsequent human development and encroachment, it seems clear that the ranges as coded to districts are best considered to be historical ranges. This may be considered a caveat in the analysis. However, these ranges, even if only accurate historically, offer conditions that provide suitable natural habitats, and have been used in this regard for species reintroduction. Hence, we feel that these presence-absence data may be helpful as a tool for conservation management issues in Thailand.

The data on district surface area are collected from the websites of the Ministry of Interior, Royal Thai Government. The sites of the most relevance are the listing by province (http://www.moi.go.th/province.htm#3) and the site www.amphoe.com/menu.php , which allows the user to search for district information in each province.

The Thai Wildlife Research Division, located within the Ministry of Natural Resources and Environment, has estimated home ranges for about 20 large mammal species. The home range consists of a more or less restricted area within which a species typically moves in the course of its normal activity (Harris et al, 1990). These estimates were produced either from their own field research in Thailand or from other researchers' work such as Khan (1967) and Eisenberg (1997) who respectively studied the elephant and the tapir.

For other species, home ranges are taken from existing literature. For example, Humphrey and Bain (1990) and Mason and McDonald (1986) provide estimates for various types of otters[iii]. Area needs for gibbons come from Leighton (1987) and Rowe (1996). In addition, Grassman et al. (2005), Grassman (2001), Odden et al. (2005), Nowak (1999) and De Lisle (1996) provide data for binturong, various cat species, hog deer, wild water buffalo and several species of monitor, respectively. Home range computations for various macaques and langur are also found in Nunn et al. (2004) and in Kaplan (2007). For all these species, when a range is proposed in the literature, the more geographically extensive estimate, or upper bound, is used. Similarly, if male and female range data differ, the larger of the two ranges – typically the male home range – is used. These two considerations lend, if anything, a more cautious bias to the analysis. When data for a particular species are not available, the area need of a similar species (i.e. a member of its taxonomic family) is used.

Conservation of rare species entails costs. As mentioned in Naidoo et al. (2006), these include acquisition costs, transaction costs, potential damage costs and opportunity costs. Acquisition costs often are available in developed countries but generally are not available in developing nations. As spatially explicit cost data across a study region such as Thailand is not available at a resolution appropriate for the analysis undertaken, it is necessary to develop surrogates, such as areas, to represent the cost of conservation (Wilson et al., 2009). This process, however, ignores spatial variation and assumes that costs are homogeneous across space. The surrogate used here is the opportunity cost of conserving land.

A worst-case (or highest cost) scenario of opportunity cost for each site under consideration is estimated as the annual loss of economic output, Gross Product Originating (GPO), at the district level[iv]. Recent data on rural population and income at the district (and smaller) levels recently have been derived by Healy and Jitsuchon (2007). Source population and income data used are public data from the Thailand National Statistical Office (Royal Thai Government, 2000). These data enable the computation of this particular measure of opportunity costs when converting a site into a nature reserve.

A new nature reserve, if selected, must cover the larger part of a district but generally does not include the entire district; some districts are very large and may have significant settlements outside the reserve. Therefore, equating the cost of the selected land parcel with the loss of economic output may be an overestimation. A more fine-tuned proxy for a developing country is used in Naidoo and Adamowicz (2006), who focus on the opportunity cost of acquiring land or otherwise protecting land for conservation, but their analysis considers a much more limited territory (a 2920 square kilometers reserve in Paraguay). This approach is not readily applicable to Thailand. It would require calculations of alternative land uses and/or net rents in all districts[v]. Therefore, even though this rough proxy may overestimate costs in some (large) districts, it may be considered as a credible, yet imperfect, upperbound estimate.

Another question may concern the choice of Thailand as a case study. Strange et al. (2007) evaluated the usefulness of conservation planning in developing countries, such as Cambodia, where data are limited and implementation of institutions are weak. We feel that the construction of this data set for Thailand and its application to the models described in the following section is worthwhile. Not only was it suggested by government officials during our visits on site but more importantly, apart from Malaysia, Thailand seems to be the only country in the Indo-Burma hotspot (Mittermeier et al., 1998) to which a systematic reserve selection model could be applied. Indeed, Vietnam's information seems uneven and incomplete in some respects, barely better than Cambodia's, which is in turn better than that for Burma, which appears to militate against even investigation. This is confirmed by Sims (2010), who underlines the fact that Thailand provides an interesting case study because of its unusually ambitious system of protected areas for a developing country and because of its relatively well-documented selection process. Moreover, Thailand seems willing to improve species protection and augment nature reserves even though its current network is already fairly intensive in comparison to its neighbors.

4. The Models

The starting point of the analysis is the current nature reserve network in Thailand. This network requires the identification of the number of endangered species that are represented in the system, comprised of districts currently set aside as nature reserves.

Among terrestrial vertebrate species represented in this study, some may be considered as short range while others can be qualified as long range. For example, a squirrel needs little territory to sustain itself, find food and reproduce if it is living in a suitable habitat. Some carnivorous species need a much larger area for their hunting, breeding and other daily activities. As sites generally represent large patches of land, it is feasible that each species can breed in one parcel, provided the model finds a parcel large enough for the species' area needs. However, for increasing the breeding option of large mammals such as the tiger and the elephant that need extended range, this study imposes the need to have home-range spread over two connected sites.

Most site selection models in the literature have used regular geometric areas (see for example, Csuti et al., 1997; Haight et al., 2000, Polasky et al., 2001, Arthur et al., 2004, Hamaide et al., 2006 and others). In reality however, sites rarely, if ever, have identical areas and when natural boundaries, like counties, provinces or districts are used to delineate sites, these will vary, often considerably, in surface area. Snyder et al. (2004) imposed limits on the total area of selected sites or minimized the surface of the reserved network while trying to protect as many species as possible while Polasky et al. (2008) do not use regular geometric areas. This analysis also uses site-specific surface.

Model 1 seeks to determine the most cost efficient method to protect species that are not currently represented in a reserve by augmenting the protected area in Thailand.

Let there be n parcels of land indexed by j and represented by the set of sites J ($J = \{1, 2, .., n\}$) and m species, indexed i, and represented by the set of species I ($I = \{1, 2, .., m\}$). The model, considering all of the above elements is formulated as the following integer program:

$$\text{Min } Z_1 = \sum_{j \notin NR} c_j x_j \tag{1}$$

$$\text{s.t.} \quad \sum_{i=1}^{m} y_i \geq \Lambda + \xi \tag{2}$$

$$R_i y_i \leq \sum_{j=1}^{n} s_j l_{ij} x_j \qquad \forall i \in I_1 \tag{3}$$

$$R_i y_i \leq \sum_{j=1}^{n} s_j f_{ij} v_j \qquad \forall i \in I_2 \tag{4}$$

$$v_j \leq \sum_{k \in H_j} f_{ik} x_k \quad \forall j \in J, \quad \forall i \in I_2 \tag{5}$$

$$v_j \leq x_j \quad \forall j \in J \tag{6}$$

$$x_j = 1 \quad \forall j \in NR \tag{7}$$

$$x_j \in \{0,1\}, v_j \in \{0,1\}, y_i \in \{0,1\}, l_{ij} \in \{0,1\}, f_{ij} \in \{0,1\} \quad \forall j \in J, \forall i \in I \tag{8}$$

where the following variables are defined as such:

$$x_j = \begin{cases} 1 \text{ if district } j \text{ is selected as part of the reserve network} \\ 0 \text{ otherwise} \end{cases}$$

$$y_i = \begin{cases} 1 \text{ if species } i \text{ is included in at least one district of the reserve system} \\ 0 \text{ otherwise} \end{cases}$$

$$l_{ij} = \begin{cases} 1 \text{ if district } j \text{ belongs to the set of sites that contains a short range species (species needing 1 site)} \\ 0 \text{ otherwise} \end{cases}$$

$$f_{ij} = \begin{cases} 1 \text{ if district } j \text{ belongs to the set of sites that contains a long range species (species needing 2 sites)} \\ 0 \text{ otherwise} \end{cases}$$

$$v_j = \begin{cases} 1 \text{ if } j \text{ is selected as one of the two connected districts} \\ 0 \text{ otherwise} \end{cases}$$

c_j = cost of converting district j to a nature reserve

s_j = surface (in km^2) of each district j

R_i = area need (in km^2) for each species i

H_j = set of adjacent districts to j and excluding j itself

I_1 = set of species whose home range requires one site, referred to as short range species

I_2 = set of species whose home range requires two sites, referred to as long range species

NR = set of districts which together comprise the current nature reserve network

Λ = number of species protected in the current reserve system

The model's objective (1) is to minimize the cost of reserve augmentation, since it considers only those costs to be borne in the course of new district selections. Constraint (2) allows the incremental growth in the number of species protected at each run, beginning at Λ and increasing to full protection (hence, $\xi = [1,.., m - \Lambda]$). This constraint is placed first to show its importance in biodiversity conservation. Indeed, if ξ were equal to zero, the optimal solution would be to spend nothing (Z_1=0). At each additional run of the model, the cost increases. Hence, solving Model 1 until the protection of all species is achieved, with a Linear Programming (LP) software, enables us to derive the marginal cost of successively greater species protection.

Constraint (3) states that a shorter range species $i \in I_1$ is protected if the surface of the current reserve network within a district ($\sum_{j=1}^{n} s_j l_{ij} x_j$) exceeds or meets its area need ($R_i y_i$). Constraint (4) is the counterpart of equation (3) for species having longer range. Since it is assumed that all longer range species should be present in two connected sites in order to be considered protected, constraint (5) ensures that, for each species i ($i \in I_2$), if v_j is selected (v_j=1), then at least one adjacent district k in which the species in question is present (f_{ik}=1 for species i) is also part of the reserve ($\sum_{k \in H_j} f_{ik} x_k \geq 1$). Further, constraint (6) ensures that x_j is considered a part of the reserve once v_j is equal to 1 ($v_j \leq x_j$) and constraint (7) verifies which districts are part of the original reserve system.

Constraints (3) through (7) are used to estimate Λ, the number of species protected in the current reserve system, knowing that a district is considered as part of the network if more than half of its area is covered by protected parks.

The spatial constraint introduced in Model 2 and used thereafter serves to restrict site selection to those districts connected with the current reserve network, while adhering to the species range constraint.

The problem can be formulated in two different ways. On one hand, the model can maximize the number of species protected while selecting one additional district connected to the current reserve network system at each run (Model 2, Z_2). Alternatively, it can minimize the cost of converting additional districts, linked to existing parcels in the reserve, into conservation areas while requiring that one additional species is protected at each run (Model 3, Z_3).

The latter model (Model 3) is in the line of thought of the non-spatial reserve augmentation (Model 1) and is a cost-sensitive spatial model while the former model (Model 2) essentially aims at finding additional sites that, at first, protect the largest number of non-covered species, therefore placing a lower importance on the economic efficiency of site selection. These two new models are formulated below.

$$\text{Max } Z_2 = \sum_{i=1}^{m} y_i \qquad (9)$$

s.t.

$$\sum_{j \in W} w_j \geq S \qquad (10)$$

$$R_i y_i \leq \sum_{j \in W} s_j l_{ij} w_j \qquad \forall i \in I_1 \qquad (11)$$

$$R_i y_i \leq \sum_{j \in W} s_j f_{ij} v_j \qquad \forall i \in I_2 \tag{12}$$

$$v_j \leq \sum_{k \in H_j} f_{ik} w_k \quad \forall j \in W \cup NR, \quad \forall i \in I_2 \tag{13}$$

$$v_j \leq w_j \quad \forall j \in W \tag{14}$$

$$w_j \in \{0,1\}, v_j \in \{0,1\}, y_i \in \{0,1\}, l_{ij} \in \{0,1\}, f_{ij} \in \{0,1\} \quad \forall j \in J, \forall i \in I \tag{15}$$

where the following variables are defined as such:

$$w_j = \begin{cases} 1 \text{ if district } j \text{ is connected to an existing reserve and selected as part of the network} \\ 0 \text{ otherwise} \end{cases}$$

W = set of sites connected to NR (nature reserve) sites

Model 2 maximizes the number of non-covered species (equation 9) for various runs. Indeed, the right hand side of equation (10) increases monotonically by one unit at each run of the model, so that S=1 in the first run (one new district connected to the current reserve is selected by the model). The model stops when the objective function ceases to increase following a steady increase of S in the last few runs. This means that either the model stops when all species are protected or when it is not possible to protect additional species in contiguous parcels of land.

The other constraints are similar to the first model. Each short and long range species must have enough breeding space in the selected district connected to the existing reserve (equations 11 and 12). The model also requires that once a new district is selected for longer range species, a connected parcel in which the species is present and that is either connected to the existing reserve or part of it must be selected as well (equation 13). Finally, constraint (14) ensures that w_j is a newly selected district once v_j is part of the reserve.

$$\text{Min } Z_3 = \sum_{j \in W} c_j w_j \tag{16}$$

$$\text{s.t.} \quad \sum_{i=1}^{m} y_i \geq \Lambda + S \tag{17}$$

(11) to (15)

Model 3 minimizes the opportunity cost of converting additional districts, connected to some portion of the existing reserve network, to nature reserves under the same constraints as before. As shown in constraint (17), Model 3 starts with the existing reserves where Λ species are protected and the number of species protected increases monotonically by one unit (starting from S=0) at each run and the model stops either when all species are protected at minimal cost or when the model is not able to cover the number of species required by equation (17) in sites connected to the existing network. It is in this respect that equation (17) differs from equation (2).

5. Applying the models on the Thailand Data Set

The Thai nature reserve system as reflected in the database above offers protection to 58 of the 68 special status species. This reserve system, comprised of whole districts, includes numerous national parks and wildlife areas, although these protected areas do not exhaust the area of any but a few districts. A district is thus considered to be part of the network if the formally protected areas account for half or more of the district's surface area. Even within a protected park, few commercial activities exist and population is limited, but altogether, Sims (2010) estimates that more than 500,000 people live inside national parks and wildlife sanctuaries; elsewhere in the inclusive district(s), activities and residential settlements may exist. This situation is analogous to published research studies using the Oregon data set (e.g., Csuti et al., 1997, Polasky et al., 2001; Arthur et al., 2004, and others), since the hexagon parcels also exhaust all the area of Oregon, including cities. Hence, when a parcel is selected as a nature reserve in the present study, its complete surface area not only includes national and regional parks and forests, but may also include some residential and rural commercial activities.

Most of the 68 species of interest have small home ranges: from less than 1 km^2 to a few km^2. Some species require larger home ranges (from 5 to 60 km^2) and only two species, the Asian elephant and the tiger, are considered for this paper to be longer-range species, as they may respectively cover a maximum of 300 and 100 km^2 for their activities. Since many available districts are very large, up to 2,407 km^2 in area, equation (5), which requires the selection of at least two contiguous sites for each longer-range species, might be considered as unnecessary. If that equation were deleted, the model would select a sufficiently large district so that each longer-range species is able to utilize at least its own home range within the nature reserve portion of that district. The equation is retained, however, to allow for the selection of two connected sites, and thus to account for edge effects. Species occurrences near a natural district boundary are in fact common and the existence of administrative boundaries in this context is obviously without meaning. Thus, it might be advisable to select its neighboring site as well. Clearly, this is less true for shorter-range species.

Respecting constraints (3) to (7) gives a solution Λ=58; 22 districts are thus defined as biological reserves and they altogether cover 58 of the 68 species in the set. Figure 1 shows the locations, in light grey, of those districts that constitute the current reserves in Thailand.

Figure 1: Current Nature Reserve (Light Grey) and Site Selection for Full Coverage (Dark Grey)

Model 1 is solved as a linear program with branch-and-bound[vi]. This method finds an optimal solution and the objective enables the selection of those districts estimated to be a least-cost solution for protecting at least one additional species at each model iteration. In doing so, the model computes the marginal cost of species protection, starting from the current level of protection provided in the existing reserve network. The results are displayed in Figure 2.

Figure 2: Marginal Costs of Additional Species Protection Relative to the Current Reserve

The coverage of the 10 remaining species[vii] shows the expected exponential marginal cost curve (see Figure 2), as in Polasky et al. (2001) and Hamaide et al. (2009). A total of 8 districts, shown in dark grey color in Figure 1, are needed to cover these 10 species. Six of these 8 districts protect one additional species at each run. The two large mammals are covered in a single site, because the model has selected one parcel in which both the tiger and the elephant breed. Moreover, that district, Phato, located in Chumphon province, the most southern dark grey district in Figure 1, is contiguous with another site, Kapoe, located in Ranong province, belonging to the current nature reserve where both mammals are present as well[viii]. The last site protects the two last species, Neill's rat and Limestone rat. The total cost for protecting all 10 remaining species is 375 Million BHT[ix]. Clearly, costs by districts vary widely. The opportunity costs of reserving each site range from 11 to 489 Million BHT. More than half of this burden is accounted for in the cost of protecting the last three species.

Model 2 takes spatial considerations into account in that it permits the selection of additional districts w_j only from those that are connected to the existing nature reserve districts. In most studies, real connectivity, also called *structural* connectivity in Haight and Snyder

(2009), is applied empirically with small cells: Nalle et al. (2002) use 1km^2 sites and Önal and Briers (2006) divide their data set in 4km^2 cells. Structural connectivity calls for strict adjacency of reserves and effectively is required here for large mammals. Sites available for selection when large mammals are present *must* therefore have a common boundary with an existing reserve. Said differently, the newly acquired area *must* be connected to the portion of the district that is considered reserved. For all other species in this study, the spatial requirement is that of *functional* connectivity, that is, reserves must lie within a certain distance of each other. It is therefore a requirement of reserve proximity, rather than pure connectivity, in the way that Önal and Briers (2002) ,who minimize the sum of pairwise distances between reserves, used.

The successive runs of Model 2 require that the right hand side term of equation (10) increases by one unit at each run. In the first run, the model selects one district in which the two large mammals – tiger and elephant – are present and that has a structural connection with another reserved site containing these species. Hence, the model first selects a somewhat species-rich contiguous district. The other runs result in the protection of but one additional species at a time. In 6 successive runs, the model was able to protect 7 out of the 10 remaining species. These districts are depicted in dark grey color in Figure 3 (light grey cells representing the original nature reserve network). Adding supplementary districts would not change species coverage since the 3 last species are not present in any site with a functional connection to the current reserve system. The model therefore ends with a protection of 65 species (Z_2=65) at a cost of 587.3 Million BHT. Hence, the spatial constraint of Model 2 does not allow the protection of Neill's rat, the Limestone rat and the Island rat. Two additional scattered parcels would have been necessary to reach full protection[x]. Total cost is much higher than in Model 1 even though not all species are protected, mostly because the choice in site selection is much more limited, but, to a lesser extent, also because the objective of the model is not to minimize costs.

Figure 3: Contiguous Site Selection in Model 2 (Dark Grey Cells) and Model 3 (Striped Cell) from Current Reserve (Light Grey Cells)

Very similar results are found with the cost-minimizing spatial model (Model 3). First, the model selects the least costly districts for protecting 7 additional species, but cannot go further because the last three species are not found in parcels with a functional connection to the current reserve. The newly protected districts are depicted in dark grey in Figure 3. Second, Model 3 provides only a very small cost reduction compared with Model 2 because, from the limited number of sites to choose from, the model is able to find only one different and least costly district from Model 2's solution, for the Burmese python – striped cell in Figure 3 replacing the dark grey cell connected to it. All other districts selected are identical in Models 2 and 3. Hence, total cost amounts to 563.5 instead of 587.3 Million BHT. The newly protected species, listed in order of increasing cost are the following: The Giant frog, the Tiger and the Asian elephant, the endemic Kitti's hog-nosed bat, the Black-striped weasel, the Burmese python and Pere David's vole.

6. Conclusion and Caveats

This paper formulates various set covering models aimed at protecting vertebrate species in Thailand that are considered as threatened and/or endangered by the IUCN. Starting with the existing reserve network and those species already protected within the network, the first model minimizes the cost of selecting additional districts to protect the remaining species of interest.

The last two models reduce the range of choice in district selection by considering only those districts that are connected (structural or functional connectivity) to some portion of the existing reserves. Under this spatial requirement, the second model selects additional connecting districts so as to protect as many additional species as possible, while the third model chooses additional non-covered species found in the least costly districts adjacent to the already selected network. The geographic sites selected, which are the various outcomes of these models, are displayed in maps in Figures 1 and 3.

Table I: Protected Area by Province as Share of Province Total Area in the 3 Models

Among the three selection sets identified in the paper, the various reserve networks comprise from 9.9 percent (in Model 1) to 10.9 percent (in Model 2) of the total land area of Thailand, as Table I shows. A total of 26 Thai provinces, or about one-third of the national total, contain areas that enjoy reserve protection. These range from approximately 77 percent each in Kanchanaburi, Uthai Thani, and Petchaburi provinces down to less than 5 percent of the area in Chonburi and Narathiwat provinces.

Nature reserves cover the majority (from 57% to 93%) but not the whole surface area of selected districts. As a matter of fact, as shown in Williams et al. (2003), a selected site may be thought of as a general locale in which specific parcels may be identified as protected land by local planners and decision makers. But population centers and various economic activities may be found in the portion of the district outside of the reserve. Current reserves protect 58 of the 68 threatened species of the study. By standards of most of the developing world, the Thai authorities' aggressive policies of adding new protected areas for several decades has done an enviable job in conserving biodiversity.

Species protection can nevertheless be improved by converting additional districts to nature reserves. Model 1 shows that expansion of reserves can be done at a modest cost, even though protecting the last species is always very costly as these generally are located in few districts and/or in expensive ones, including places where human activities are more important. If spatial protection is favored, both for economic reasons (reduction of management costs) and biological reasons (large connected territory), the cost of additional species protection increases at a higher pace and the connectivity requirement prevents full protection since some species only breed in areas that are not linked to the current reserve network system.

There are obviously caveats in this paper that need to be mentioned. First, competition among species and problems of co-location of habitat are not considered. It is well established in the biology and ecology literature that, for a variety of reasons, some species do not occur in the same area as other species. On the contrary, some species may need to live in the same surroundings as other species. These biological elements are not taken into account here and might somewhat modify the results. Second, the cost computations, which are based on existing studies, and using gross district product as a proxy, in the absence of available land cost data, on converting districts into nature reserves are certainly very rough approximations of direct costs. Moreover, the presence of a village or a town in a district might make it appear as costly even though there may be large tracts of rural land that are not particularly costly. Third, this study does not include any dynamics; the models are therefore once-and-for-all decisions whereas conservation budgets and gross products typically vary over the years. Fourth, the amount of protected area within a district is modelled as 0 or 1 (1 if the majority of the district is covered by protected parks) which may be less accurate than if it was modelled as a continuous variable. Similarly, reserve expansion requires selection of additional whole districts instead of an increase in protected area within a district, if it were a continuous variable. Fifth, the types of models described here take the hypothesis that a species is protected if it is breeding in at least one site; in reality, this may not ensure species survival. Finally, species' area needs considered here are different than species' habitat needs because specific habitat elements, resource needs, carrying capacity, population levels or habitat quality are not taken into account. Notwithstanding these caveats, we feel that such analyses may help decision makers fine tune conservation policies for species protection and survival.

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Figures and Tables

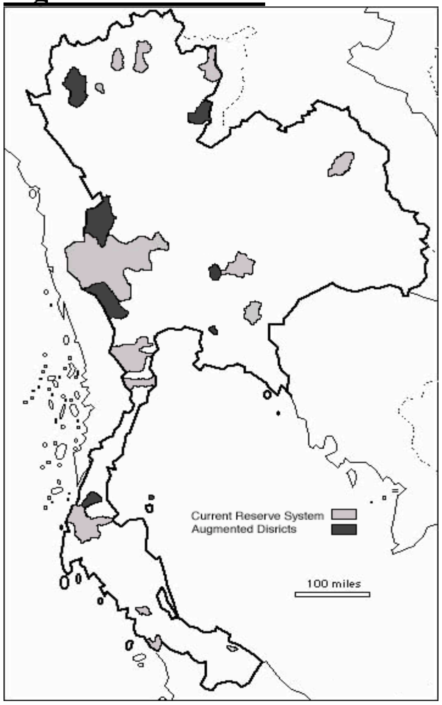

Figure 1: Current nature reserve (light grey) and site selection for full coverage (dark grey)

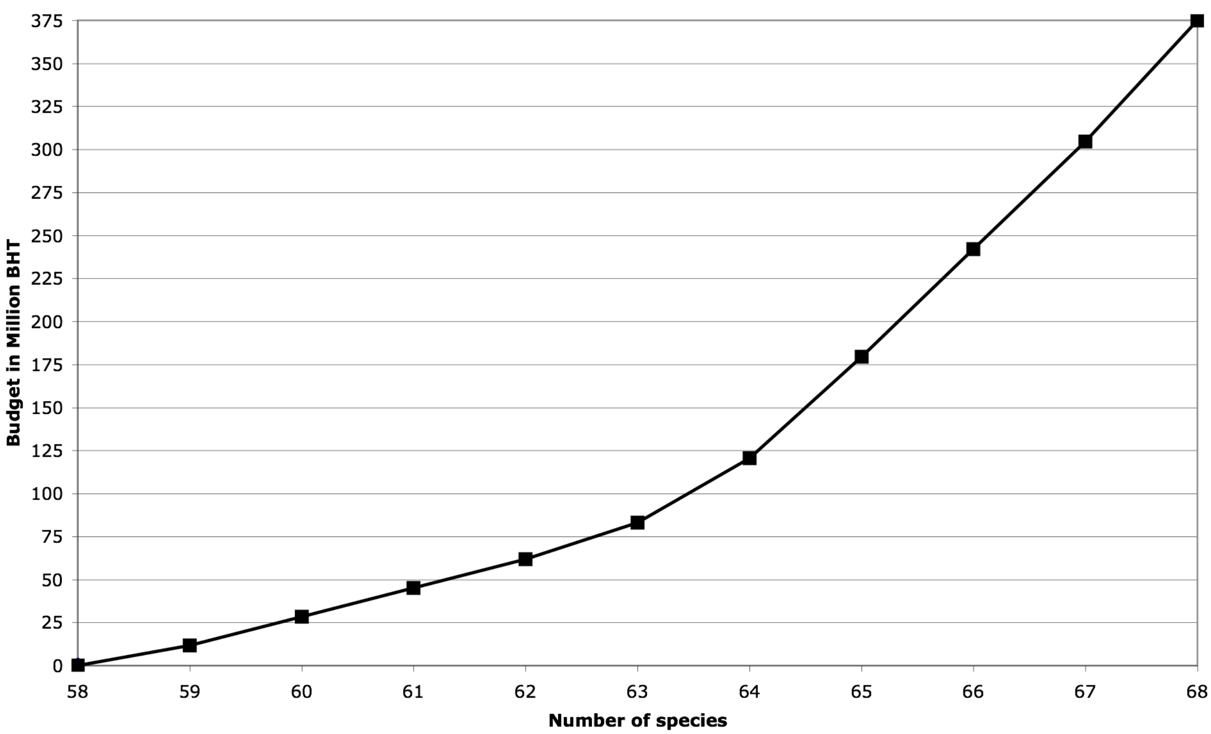

Figure 2: Marginal costs of additional species protection relative to the current reserve

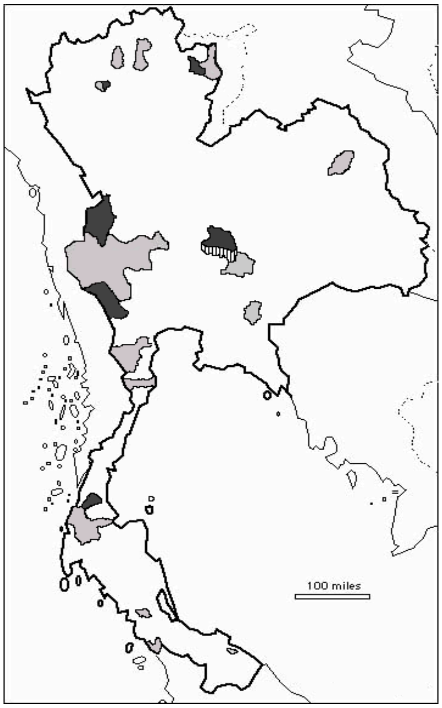

Figure 3: Connected site selection in Model 2 (dark grey cells) and Model 3 (striped cell) from current reserve (light grey cells)

Province	Km.^{2} (000)	Model 1	Model 2	Model 3
Chiang Mai	20.1	0.238	0.365	0.365
Chiang Rai	11.7	0.087	0.087	0.087
Chonburi	4.4	0.039	--	--
Chumphon	6.0	0.170	0.170	0.170
Khon Kaen	10.9	--	--	--
Kanchanaburi	19.5	0.496	0.668	0.668
Lobburi	6.2	--	0.289	0.083
Lampang	12.5	0.082	0.082	0.082
Mae Hong Son	12.7	--	--	--
Nan	11.5	0.153	0.153	0.153
Nakhon Ratchasima	20.5	0.089	0.089	0.089
Narathiwat	4.5	0.038	0.038	0.038
Prachinburi	7.2	0.362	0.362	0.362
Petchabun	12.7	--	--	--
Prachuap Khiri Khan	6.4	0.282	0.282	0.282
Phitsanuloke	10.8	--	--	--
Phetchaburi	6.2	0.773	0.773	0.773
Ranong	3.3	0.319	0.319	0.319
Sakhon Nakhon	9.6	0.106	0.106	0.106
Saraburi	3.6	0.262	--	--
Surat Thani	12.9	0.365	0.352	0.352
Tak	16.4	0.264	0.264	0.264
Trang	4.9	0.088	0.088	0.088
Satun	2.5	0.435	0.435	0.435
Uthai Thani	6.7	0.762	0.762	0.762
Uttaradit	7.8	0.216	--	--
Thailand	513.1	0.099	0.109	0.106

Table I: Protected area by province as share of province total area in the 3 models

[i] The average size of all districts is approximately 906 km^2.

[ii] Since the 1990's, there have been changes in many provincial and districts delineations. Hence, for the purpose of our analysis, all districts have been classified back into the set of district in place in the early 1990's so that all scientific and geospatial data remain comparable and at the same scale.

[iii] Note that otters' area needs are often computed in river length, that is, in kilometers, instead of km^2. The value is used as if it were a km^2 value for considering the complete length of the home range. Failure to do so might underestimate the range of the otters' daily activities.

[iv] If the purpose of the analysis is to determine absolute cost values, it might have been more appropriate to estimate the capital value of income streams over time to get a global discounted cost number for each site. However, in addition to the fact that no dynamics are used in this study, the purpose is not to work with precise cost figures but to have estimates for comparing the various alternatives. Since all data are computed with the same methodology, the comparison therefore seems acceptable.

[v] Another option would be to use agricultural land values as a proxy for conservation costs, as in Polasky et al. (2001) and Naidoo and Iwamura (2007) who produce a global map of economic rents from agricultural land by estimating the flow of economic benefits derived from crops and livestock. This option was not pursued because of the limited availability of land cost data and other data at the districts level and because of the availability of previous work from Healy and Jitsuchon (2007).

[vi] This model and the two subsequent models are solved in less than 9 seconds on a PC dual core.

[vii] The unprotected species are: Craseonycteris thonglongyai (Kitti's hog-nosed bat), Eothenomys melanogaster (Pere David's vole), Rattus sillimensis (island rat), Rattus neilli (Neill's rat), Rattus hinpoon (limestone rat), Mustela strigidorsa (black striped weasel), Panthera tigris (tiger), Elephas maximus (Asian elephant), Rana fasciculispina (spine-breasted giant frog) and Python molurus bivattatus (Burmese python).

[viii] And even though the surface of the district already protected is very large and can contain both mammals as far as area need is concerned, the model nevertheless requires selection of a connected site where these two species are present as well to prevent for potential edge effects.

[ix] BHT stand for Baht, which is the Thai currency. The approximate exchange rate is the following : 1€ ≈ 44 BHT and 1$ ≈ 32 BHT.

[x] The former two species are present in the same single district and cannot be found elsewhere in the system whereas the island rat is present in various districts but not in the same one as the other two.