

Chapter 10

NATURE RESERVE SELECTION FOR ENDANGERED SPECIES CONSIDERING HABITAT NEEDS : THE CASE OF THAILAND

Bertrand Hamaide^{*1}, Jack Sheerin² and Charit Tingsabadh³

¹. Faculté des Sciences Economiques, Sociales et Politiques,
Facultés Universitaires Saint-Louis, 1000 Brussels, BELGIUM

². Smithsonian Institution, Washington, DC, 20560, USA

³. Centre for Ecological Economics, Faculty of Economics,
Chulalongkorn University, Bangkok, 10330, THAILAND

ABSTRACT

Creating or enlarging nature reserves to preserve key habitats and species living within those reserves is one of the important strategies to conserve biodiversity. This paper uses 0-1 programming models originating from the location science and termed SSCP (or Species Set Covering Problems), requiring representation of each and every species in the system within a minimum number of land parcels. The species under consideration in this study are the 68 mammals, reptiles and amphibians listed as threatened species in Thailand by the International Union for Conservation of Nature and Natural Reserves (IUCN), and the sites under consideration are known in Thailand as “amphoes”, or small administrative districts. Since habitat requirements rarely have been introduced explicitly in reserve selection methods, this paper aims at identifying strategies to protect each threatened species while taking into account the habitat range of each particular terrestrial vertebrate of the data set. Results of the model are compared with the standard SSCP model and differences in outcomes are evaluated. Estimating the opportunity costs of converting countryside and forested areas for conservation purposes in terms of loss in economic output and incorporating them in the formulations further refines the model. Reserve networks that protect all threatened species and also that

* Corresponding author: Tel. +32.2.211.78.75 ; fax : +32.2.211.79.97. E-mail address: hamaide@fusl.ac.be

consider habitat needs are then selected at minimum opportunity costs. Results are compared with the former models to evaluate conservation policy options.

1. INTRODUCTION

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

One of the most important strategies for conserving biodiversity is the creation or enlargement of nature reserves. Since Thailand ratified the Convention on Biological Diversity, it expanded, among other conservation actions, its national nature reserve system.

The aim of this study is to assemble a data set and build quantitative models to theoretically determine the minimum number of districts to be set aside as nature reserves or the minimal cost of the reserve so as to protect all threatened and endangered species. This is a theoretical exercise, applied on a real data set. Hence, it does not explicitly consider existing reserves in Thailand but proposes academic exercises in conservation policies.

The method of analysis for selecting nature reserves parallels that of location science aimed at selecting sites for locating economic activities (see ReVelle et al., 2002, for an extensive comparison between reserve selection and location covering models). The theoretical corpus used in this study is based on a location science problem termed LSCP, or Location Set Covering Problem. It was first proposed by Toregas et al. (1971) and Toregas and ReVelle (1973). The problem was to locate the least number of facilities (say, fire stations) so that all demand nodes (say, households) are covered by stations within a certain distance or time standard.

More than a decade later, Kirkpatrick (1983) and later Margules (1989) developed heuristic formulations, selecting sites by iterative methods, for protecting species (by attractivity of habitat for example). But it was only a decade again after the publication of Kirkpatrick's paper that Possingham et al. (1993) and Underhill (1994) independently recognized that the problem at stake was in fact a bioscience counterpart of the LSCP. This new problem of nature reserve selection, called SSCP, or Species Set Covering Problem, aims at selecting the smallest number of eligible land sites for a nature reserve so that all species are present in at least one selected site.

Over the years, models have been refined by including spatial characteristics (see Williams et al., 2005 for a review of such spatially-oriented models), probabilistic formulations (see for example, Polasky et al., 2001 and Haight et al., 2000), redundant coverage (see for example Malcolm and ReVelle, 2005 and Hamaide et al., 2006) or dynamic formulations (e.g. Costello and Polasky, 2004), among others. Very recently, Marianov et al. (2007) considered the importance of habitat needs in formulating a theoretical reserve selection problem.

This paper starts from the idea, like Marianov et al. (2007), that habitat range, differentially articulated for individual species, is important and should be taken into account when establishing a reserve network. New models are thus proposed here in which the aim is to identify methods that protect all threatened and endangered species either at minimum cost

or with a minimal number of sites. They are applied to species presence-absence data constructed for the whole Kingdom of Thailand while requiring that all species enjoy at least their individual maximal home ranges.

The remainder of the paper is organized as follows. Section 2 details the theoretical models. The next section exercises the models on random data for determining their use and the potential differences between the proposed models. Section 4 reviews the data set for Thailand, that is, the presence-absence matrix, the list of eligible sites and the surface area of each site, the list of threatened and endangered species, the maximal individual home range for each of these species and the opportunity cost, for each district, if it is part of the reserve network. Section 5 presents the results of the models based on the elaborated data and compares the outputs of the models. The paper concludes with some summary observation and caveats in interpretation of the findings.

2. THE MODELS

The original SSCP requires representation of each species in at least one parcel in the system and seeks the minimum number of parcels in the reserve system to achieve this requirement.

Let there be n parcels of land eligible for selection and indexed j and represented by the set of sites J ($J = \{1, 2, \dots, n\}$) and m species that all need to be represented in the system, indexed i , and represented by the set of species I ($I = \{1, 2, \dots, m\}$). The problem is formulated as the following integer program:

$$\text{Min } Z_1 = \sum_{j=1}^n x_j \quad (1)$$

$$\text{s.t. } \sum_{j=1}^n a_{ij} x_j \geq 1 \quad \forall i \in I \quad (2)$$

$$x_j \in \{0, 1\}, a_{ij} \in \{0, 1\} \quad \forall j \in J, \forall i \in I \quad (3)$$

$$\text{where } x_j = \begin{cases} 1 & \text{if site } j \text{ is selected for the reserve system} \\ 0 & \text{otherwise} \end{cases}$$

$$\text{and } a_{ij} = \begin{cases} 1 & \text{if site } j \text{ belongs to the set of sites that contains species } i \\ 0 & \text{otherwise} \end{cases}$$

Objective (1) seeks to minimize the number of land parcels required for species protection. Constraint (2) requires that for each species i , the sum of parcels containing that species must be greater or equal to 1, that is, at least one parcel x_j where species i is present ($a_{ij}=1$) must be equal to 1, or equivalently, species i must be contained in the system.

The solution to this integer program gives a number Z_1 representing the number of sites necessary to represent all species. Replacing the objective by equation (4) and defining c_j as the opportunity cost of acquiring site j would result, after solving the integer program, in finding a number representing the minimum cost for preserving all species:

$$\text{Min } \sum_{j=1}^n c_j x_j \quad (4)$$

Among terrestrial vertebrate species represented in this study, some may be considered, in surface-area terms, as short range while others can be qualified as long range. This home range consists of a more or less restricted area within which an animal moves in the course of its daily activities (Harris et al., 1990). For example, a squirrel does not need a large territory to be able to sustain itself, find food and reproduce if it is living in a suitable habitat. On the contrary, carnivorous species such as tiger need a much larger area for its hunting, breeding and other daily activities.

As sites generally represent large patches of land, let us suppose that all species can sustain themselves in either one or two contiguous parcels; said differently, home-range can either be included in a single site or needs to spread over two sites. Let us further suppose that all sites have the same area. The second model can thus be written as such:

$$\text{Min } Z_2 = \sum_{j=1}^n x_j \quad (5)$$

$$\text{s.t. } \sum_{j=1}^n l_{ij} x_j \geq 1 \quad \forall i \in I_1 \quad (6)$$

$$\sum_{j=1}^n f_{ij} v_j \geq 2 \quad \forall i \in I_2 \quad (7)$$

$$v_j \leq \sum_{k \in H_j} f_{ik} x_k \quad \forall j \in J, \quad \forall i \in I_2 \quad (8)$$

$$v_j \leq x_j \quad \forall j \in J \quad (9)$$

$$x_j \in \{0,1\}, v_j \in \{0,1\}, l_{ij} \in \{0,1\}, f_{ij} \in \{0,1\} \quad \forall j \in J, \forall i \in I \quad (10)$$

where the set of new variables is defined as such:

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

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

$$v_j = \begin{cases} 1 & \text{if site } j \text{ is selected for the reserve system as one of the two adjacent sites in which } i \text{ breeds} \\ 0 & \text{otherwise} \end{cases}$$

H_j = set of adjacent sites 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

Objective (5) aims at finding the minimum number of sites while requiring, with equation (6), that, for each shorter range species i ($i \in I_1$), at least one parcel x_j where species i is present ($l_{ij}=1$) must be preserved, hence is greater or equal to 1. Constraint (7) requires that, for each longer-range species i ($i \in I_2$), at least two parcels v_j where species i is present ($f_{ij}=1$) must be part of the nature reserve as well. However, since these longer range species need two

adjacent sites for being protected, constraint (8) ensures that, for each species i ($i \in I_2$), if v_j is selected ($v_j=1$), then at least one contiguous cell to j among which the species in question is present ($f_{ik}=1$ for species i) is also part of the reserve ($\sum_{k \in H_j} f_{ik} x_k \geq 1$). Additionally,

constraint (9) makes sure that x_j is considered as part of the reserve once v_j is equal to 1 ($v_j \leq x_j$).

The solution to this integer program gives a number Z_2 representing the minimal quantity of sites that is necessary to protect all species taking home ranges into account.

In reality, sites rarely, if ever, have identical areas. Regular geometric areas can be specified when the species presence-absence data set is constructed for conservation purposes. A widely used example of such a data set is the Oregon terrestrial vertebrates data. Since the mid 1990's, many selection models have been implemented with various versions of the Oregon data set (see for example, Csuti et al., 1997; Haight et al., 2000, Polasky et al., 2001, Arthur et al., 2004, Hamaide et al., 2008 and others). But 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.

When parcels do not have identical areas, it remains theoretically possible that a long-range species would need the equivalent of 4 or 5 sites if it were to select the smallest contiguous parcels. In order to avoid this more costly choice – it is often the case that when longer borders are included in a reserve network, the cost of managing the reserve is higher – the models described hereafter are formulated so as to choose the smallest number of parcels (for example two large sites for wide ranging species) and not the smallest surface (for example five small sites with the same surface as the previous two large sites). The third model outlined below does so while requiring that habitat range is met for all eligible species:

$$\text{Min } Z_3 = \sum_{j=1}^n x_j \quad (11)$$

$$\text{s.t. } \sum_{j=1}^n s_j l_{ij} x_j \geq R_i \quad \forall i \in I_1 \quad (12)$$

$$\sum_{j=1}^n s_j f_{ij} v_j \geq R_i \quad \forall i \in I_2 \quad (13)$$

$$v_j \leq \sum_{k \in H_j} f_{ik} x_k \quad \forall j \in J, \quad \forall i \in I_2 \quad (14)$$

$$v_j \leq x_j \quad \forall j \in J \quad (15)$$

$$x_j \in \{0,1\} \quad v_j \in \{0,1\} \quad l_{ij} \in \{0,1\} \quad f_{ij} \in \{0,1\} \quad \forall j \in J, \quad \forall i \in I \quad (16)$$

where the new variables are defined as such:

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

R_i = home range (in km^2) for each species i

Taking the hypothesis that two contiguous sites of different areas can cover all longer range species¹, the problem is very similar to the previous one since it aims at minimizing the total number of sites (and not total area for preventing possible selection of many small sites) selected while taking habitat range into account. The only difference lies in equations (12) and (13). These equations stipulate that for each short and long-range species i , the surface of each parcel j selected, as part of the reserve network, must at least cover the species' home range (R_i). And for the longer-range species, when more than one site is selected, the model, via equations (14) and (15), ensures that selected sites are contiguous as site x_k is required to have a common border with site v_j (since $k \in H_j$) and hence x_j (since $v_j \leq x_j$).

The outcome of the model is another integer Z_3 identifying the minimum number of sites in the reserve network with contiguous sites for longer-range species that need more than one parcel for performing their daily activities.

Another version of this third model would be to select those sites that are the cheapest (lowest opportunity cost) while respecting constraints (12) to (16). As stated above for the third model, objective (11) is then simply replaced by objective (4).

3. CLASSROOM EXAMPLE

Prior to the application of the models described above on a real data set, it may be interesting to test them on more limited, made-up data.

Suppose that an independent region can be divided up into 36 square sites ($J=36$). Suppose further that there are 20 species of interest ($I=20$). Presence and absence data of the 20 species in the 36 sites are generated randomly².

The models in this section and in Section 5 are coded with Mosel language and run on Xpress MP (Xpress MP, 2006).

The SSCP model is applied first (equations 1 to 3). One optimal scenario among the various alternate optima is illustrated in Figure 1 and shows a selection of 3 sites for protecting all species.

¹ The application on Thailand data, as detailed later in Sections 4 and 5, shows that all long range threatened or endangered terrestrial mammals may be preserved within two contiguous sites at the most, which is the reason why two adjacent sites are proposed here. The same analysis can nevertheless be done with three or more contiguous sites. Equation (14) would then need to be modified accordingly. Note that it would even be possible to require that long range species be protected in one site only. However, as this would limit the site selection, mostly for the Asian elephant, this restrictive hypothesis is not considered

² Data can be made available upon request

X_1	X_2	X_3	X_4	X_5	X_6
X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}
X_{19}	X_{20}	X_{21}	X_{22}	X_{23}	X_{24}
X_{25}	X_{26}	X_{27}	X_{28}	X_{29}	X_{30}
X_{31}	X_{32}	X_{33}	X_{34}	X_{35}	X_{36}

Figure 1: SSCP Model 1 – Output of the classroom example

X_1	X_2	X_3	X_4	X_5	X_6
X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}
X_{19}	X_{20}	X_{21}	X_{22}	X_{23}	X_{24}
X_{25}	X_{26}	X_{27}	X_{28}	X_{29}	X_{30}
X_{31}	X_{32}	X_{33}	X_{34}	X_{35}	X_{36}

Figure 2: Model 2 – Output of the classroom example

X_1	X_2	X_3	X_4	X_5	X_6
X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}
X_{19}	X_{20}	X_{21}	X_{22}	X_{23}	X_{24}
X_{25}	X_{26}	X_{27}	X_{28}	X_{29}	X_{30}
X_{31}	X_{32}	X_{33}	X_{34}	X_{35}	X_{36}

Figure 3: Model 3 – Output of the classroom example

The second model includes the importance of home range for selecting sites (equations 5 to 10). It takes the hypothesis that all sites have identical areas and that 3 of the 20 species considered are longer-range species ($I_1=17$ and $I_2=3$). Hence, they need at least two parcels of land for being considered as protected while the others are covered within one site. Nine sites are now selected. The contiguous sites aimed at protecting long-range species are depicted in dark grey while the sites protecting short-range species are in light grey (see Figure 2). This selection means that the three long-range species cannot be protected on similar sites (this is due to the random data set) and none of these contiguous sites are able to protect as many species as the three original sites from the SSCP. Hence, no economies in sites can be found and the model needs to choose six additional parcels, compared with the SSCP, for respecting the home range constraint of equations (7) to (9).

The last model lifts the strong hypothesis of identical site sizes. Suppose that the 12 northern sites have a surface of 2 km^2 , the 12 central sites, of 4 km^2 and the remaining cells have a surface equivalent to 6 km^2 . This is depicted in Figure 3. Running Model 3 (equations 11 to 16) with these additional data gives a minimum number of 10 sites. This is one more site than if all parcels are of equivalent size. Analyzing the results a bit more shows that two of the three long range species select the same sites as before (x_{14} and x_{15} for one x_{34} and x_{35} for the other) while protection of the last long range species is no longer possible on the previous sites (x_4 and x_5). The reason is that the combined surface of these two parcels is too small to be able to protect the species. Therefore, the model needs to select other contiguous sites, such as x_{24} and x_{30} , meeting the minimum surface (10) required for that long-range species. The two other long-range species keep the same sites as before as they respect their home range of 8 km^2 for the former and 12 km^2 for the latter.

The next section details data computation for the Kingdom of Thailand and the three models will then be re-run on those data.

4. DATA SET

4.1. Species, Sites and Presence-Absence Data

The 68 species included as candidates for the Thailand study, and detailed in Table I, are those 57 mammals, 9 reptile and 2 amphibian species that appears in the International Union for the Conservation of Nature and Natural Resources (IUCN) Red Lists for any year(s) from 1990 through 2006 (IUCN, 2006). Included are those taxa that are classified as any of the IUCN categories – rare, threatened and endangered. Some species about which the preponderance of evidence suggests that this animal has been extirpated in the wild in Thailand are excluded. Examples include *Cervus eldi* (Eld's deer) and *Rhinoceros sondaicus* (Javan rhinoceros). Also, note that all of these 68 species are considered to be terrestrial vertebrates. As a matter of fact, otters are considered terrestrial, although they occupy aquatic and shoreline habitat. Similarly, *Macaca fascicularis* (long-tailed macaque) is a mammal occupying a habitat such as lagoons, mangroves, etc. Cetaceans or marine mammals are likewise excluded.

Table I: IUCN Redlisted Species for Thailand

Source: IUCN

Scientific Name	Common Name	Taxon
<i>Craseonycteris thonglongyai</i>	Kitti's Hog-Nosed Bat	mammal
<i>Macaca nemestrina</i>	Pig-tailed Macaque	mammal
<i>Macaca assamensis</i>	Assamese Macaque	mammal
<i>Macaca arctoides</i>	Stump-tailed Macaque	mammal
<i>Macaca mulatta</i>	Rhesus Macaque	mammal
<i>Macaca fascicularis</i>	Long-tailed Macaque	mammal
<i>Presbytis melalophus</i>	Banded Langur	mammal
<i>Presbytis obscura</i>	Dusky Langur	mammal
<i>Presbytis cristata</i>	Silvered Langur	mammal
<i>Presbytis phayrei</i>	Phayre's Langur	mammal
<i>Hylobates lar</i>	White-handed Gibbon	mammal
<i>Hylobates pileatus</i>	Pileated Gibbon	mammal
<i>Hylobates agilis</i>	Agile Gibbon	mammal
<i>Manis javanica</i>	Malayan Pangolin	mammal
<i>Manis pentadactyla</i>	Chinese Pangolin	mammal
<i>Ratufa affinis</i>	Cream-colored giant squirrel	mammal
<i>Ratufa bicolor</i>	Black giant squirrel	mammal
<i>Petuarista elegans</i>	Lesser giant flying squirrel	mammal
<i>Aeromys tephromelas</i>	Large black flying squirrel	mammal
<i>Petinomys setosus</i>	White-bellied flying squirrel	mammal
<i>Belomys pearsoni</i>	Hairy-footed flying squirrel	mammal
<i>Eothenomys melanogaster</i>	Pere David's vole	mammal
<i>Hapalomys longicaudatus</i>	Marmoset rat	mammal
<i>Rattus sillimensis remotus</i>	Island rat	mammal
<i>Rattus neilli</i>	Neill's rat	mammal
<i>Rattus hinpoon</i>	Limestone rat	mammal
<i>Canis aureus</i>	Golden Jackal	mammal
<i>Cuon alpinus</i>	Dhole	mammal
<i>Ursus thibetanus</i>	Asiatic black bear	mammal
<i>Helarctos malayanus</i>	Sun bear	mammal
<i>Mustela strigidorsa</i>	Black-striped weasel	mammal
<i>Lutra lutra</i>	Common Otter	mammal
<i>Lutra (Lutrogale) perspicillata</i>	Smooth-coated Otter	mammal
<i>Lutra sumatrana</i>	Hairy-nosed Otter	mammal

<i>Amblonyx (Aonyx) cinera</i>	Small-clawed otter	mammal
<i>Prionodon pardicolor</i>	Spotted linsang	mammal
<i>Prionodon linsang</i>	Banded linsang	mammal
<i>Arctictus derbyanus</i>	Binturong	mammal
<i>Hemigalus derbyanus</i>	Banded palm civet	mammal
<i>Felis marmorata</i>	Marbled cat	mammal
<i>Prionailurus viverrinus</i>	Fishing Cat	mammal
<i>Felis bengalis</i>	Leopard Cat	mammal
<i>Felis chaus</i>	Jungle Cat	mammal
<i>Catopuma temmincki</i>	Asian golden Cat	mammal
<i>Neofelis nebulosa</i>	Clouded Leopard	mammal
<i>Panthera pardus</i>	Leopard, Panther	mammal
<i>Panthera tigris</i>	Tiger	mammal
<i>Elephas maximus</i>	Asian Elephant	mammal
<i>Tapirus indicus</i>	Malayan Tapir	mammal
<i>Dicerohinus sumatrensis</i>	Sumatran Rhino	mammal
<i>Muntiacus feae</i>	Fea's Barking Deer	mammal
<i>Cervus porcinus annamiticus</i>	Indochina Hog Deer	mammal
<i>Bubalus bubalis</i>	Wild Water Buffalo	mammal
<i>Bos javanicus</i>	Banteng	mammal
<i>Bos Gaurus</i>	Guar	mammal
<i>Capricornis sumatraensis</i>	Serow	mammal
<i>Naemorhedus goral</i>	Goral	mammal
<i>Tylototriton verrucosus</i>	Crocodile salamander	amphibian
<i>Rana fasciculispina</i>	Spine-breasted giant frog	amphibian
<i>Platysternon megecephalum</i>	Chinese big-headed turtle	reptile
<i>Batagur baska</i>	River terrapin	reptile
<i>Heosemys spinosa</i>	Spiny terrapin	reptile
<i>Testudo emys</i>	Chinese land tortoise	reptile
<i>Varanus bengalensis</i>	Bengal monitor	reptile
<i>Varanus rudicollis</i>	Red-headed monitor	reptile
<i>Varanus dumerilii</i>	Black jungle monitor	reptile
<i>Python molurus bivattatus</i>	Burmese python	reptile
<i>Python curtus</i>	Blood python	reptile

Thailand, in the geographic configuration considered, is comprised of 76 provinces; each province is divided into “amphoes”, the nation’s smallest administrative districts. In this study, we consider 567 amphoes. All amphoes for the Bangkok metropolitan area have been excluded because of their highly urbanized and disturbed environments, as well as the presence of few of the species of interest there. Also, there have been recent boundary changes in the provinces in central and northeastern Thailand. Hence, for the purpose of our analysis, amphoes in that area have been classified back into their original set of amphoes so that all data remain comparable and at the same scale.

The species set for Thailand is elaborated in Sheerin (2007). The main compendium of recent information on endangered species is that of Humphrey and Bain (1990), which updates and extends Legakul and McNeely's seminal study (1977) on mammals in the country. Specific locational references to species occurrences are coded into a presence-absence matrix of all amphoes, followed by amphoe reference for species presence from distribution maps from agencies of the Royal Thai Government. Where multiple estimates of distribution are available, the more conservative or restrictive alternative is used. In the cases where more recent species-specific studies are available, that source is used, as in Sompoad and Varavudh (1995) for *Bos javanicus* (banteng) and *Bos gaurus* (guar). Also, constructed data can be crosschecked with the electronic Bioinventories of the World (2006), which applies to protected areas and can be readily mapped to amphoes. The correspondence between this source and the others (Humphrey and Bain, 1990 and Legakul and McNeely, 1977) is extremely close; in only one case is there a reference found in which the Bioinventories cited an occurrence in an amphoe which does not occur in the other sources.

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 amphoes are best considered as historical ranges. This may be considered as 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 in Thailand.

4.2. Species Frequency

After completing the elaboration of the presence-absence matrix, it is interesting to examine the difference in occurrences among all threatened and endangered species in Thailand. Indeed, a limited number of species is very frequent – communities of Malayan pangolin, smooth coated otter, leopard cat, clouded leopard and leopard were reported at some period in most of the parcels³ – while others are very rare – the island rat, Pere David's vole, black-striped weasel and Bengal monitor were reported in two or three districts only. Three species are only present in one single amphoe: Neill's rat, limestone rat and Kitt's hog-nosed bat. Moreover, that last species is endemic to Thailand. The frequency distribution of species' areas of occupancy is shown in Figure 4.

³ It is important to remember that the presence of these species in most of the parcels does not mean that these species are not in danger. Even though they are widely present, their numbers may be low and their reproductive habitat may be altered. So, these species remain at risk; they are either rare, threatened or endangered.

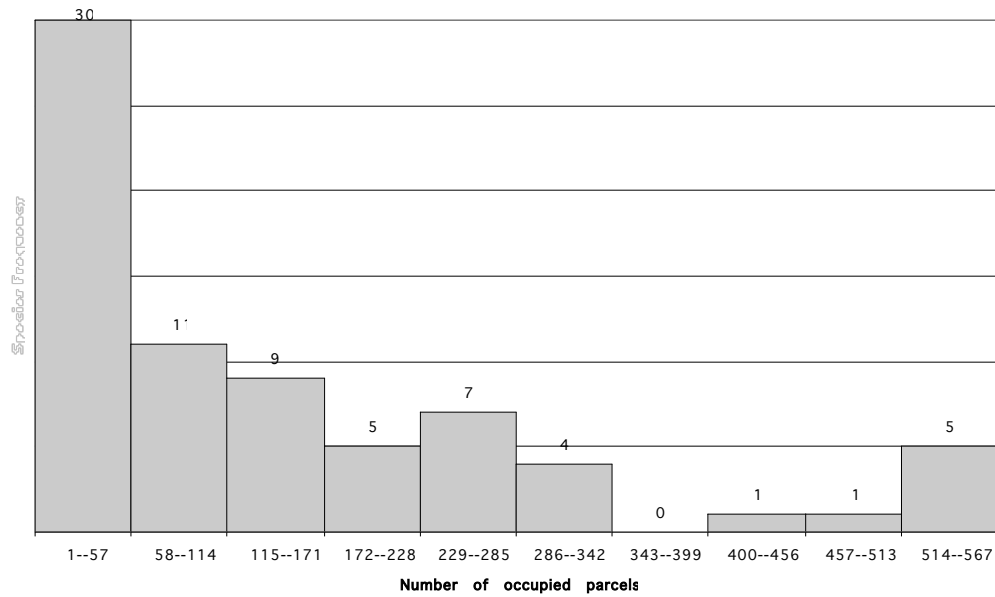


Figure 4: Frequency distribution of species' area of occupancy

Church et al. (1996) and Storch and Sizling (2002) found out that, in general, most species are either relatively infrequent or very common in terms of the number of occupied sites, that is, the frequency distribution of species occurrences often is bimodal. It is confirmed by Hamaide et al. (2006) for the Oregon data set but it is not the case with the Thailand data set. This is not surprising because in this study, we have included only threatened and endangered species that is, the statistical tail of one mode of a general distribution of species occurrences by location. Therefore, it is expected that most of these species are present in a small number of parcels: about 45% of the species occupy less than 10% of the parcels of Thailand (the first bar of the graph) and about 75% of them (50 out of 68) are present in 30% of the parcels at the most (the first three bars of Figure 4). Said differently, many threatened species are present in few amphoes, as expected, and hence, quite a few sites need to be selected if all listed species are to be protected.

4.3. Surface Data

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 (1) the listing by province (<http://www.moi.go.th/province.htm#3>) and (2) www.amphoe.com/menu.php. These websites allow the user to search for information for the districts in each province.

The current data source refers to districts as configured in 2007. In some cases, their geographic boundaries differ from boundaries used in assembling the species presence-absence data, whose amphoes are based on an earlier set of province and district boundaries. As mentioned above, this is the result of the creation of new districts from former sub-district

area units. It is mainly relevant to provinces established in the recent periods, since the 1980s. In one case, the province of Sakaew was formerly part of the province of Prachinburi, and was created in the year 1993.

For the purpose of the paper, we have compiled the data in two steps. Firstly the current districts are listed by province, and the information on the surface area is obtained from the district information website (www.amphoe.com). The second step is to match these to the district list used for the species data. At this step, where it is found that the district names do not match, implying that new districts have been created for the province, we examine the “history” section of the district database, where usually there is information on how the new district has been formed from parts of a former district. Once this is done, we reclassify the new district back to the old district. The total number of such reclassification is less than 10% of the number of districts used in the analysis.

4.4. Home Ranges

The Thai Wildlife Research Division, Department of National Parks and Wildlife, in the Ministry of Natural resources and Environment of the Thai Government, have estimated home ranges for about 20 large mammals. These estimations come 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 the other species, home ranges are collected from existing literature. For example, Humphrey and Bain (1990) and Mason and McDonald (1986) provide estimates for various types of otters⁴. Habitat range for gibbons comes from Leighton (1987) and Rowe (1996). And Grassman et al. (2005), Grassman (2001), Odden et al. (2005), Nowak (1999) and De Lisle (1996) provide data for binturong, various cat species, the hog deer, the wild water buffalo and monitors 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 upper bound is used as a safety criterion. Also, when male and female data differ, the larger of the two – typically the male home range – is considered in the analysis.

When data are not available, range descriptions for the nearest taxonomic relative are used. Said differently, the problem-species parent Genus range, or failing that, taxonomic Family range is used. And as a further safety criterion, the inferred species range is set at the largest found in that family.

4.5. Opportunity Costs

Conservation of rare species entails costs, at least in the form of short-run costs. The scale of such costs might be approximated by estimates of the economic opportunities foregone in conversion to conservation uses: economists’ measure known as opportunity cost.

⁴ Note that otters’ home ranges are often computed in river length, that is, in kilometers, instead of km². The value is used as if it were a km² value for considering the complete length of the home range. Not doing so might underestimate the length of the otters’ daily activities.

We estimate a worst-case scenario of opportunity cost for each site under consideration as the annual loss of economic output, Gross Product Originating (GPO), at the amphoe level⁵. New data on rural population and income at the amphoe (and smaller) levels recently has been derived by Healy and Jitsuchon (2007). Numerical extension of amphoe rural population by mean annual income per capita and expressing GPO as an index number permits the comparison of this measure of economic sacrifice among sites as well as the ability to compare it with regional and national aggregates. Source population and income data used are public data from the Thailand National Statistical Office (Royal Thai Government, 2000).

The Jitsuchon-Healy data sets are the result of an extensive econometric exercise in which the authors derive annual income and consumption data at the amphoe and tambon level from the 2000 Thai population census and Thai 2000 Socioeconomic Survey. While most of their paper consists of assessing the accuracy of the method by multiple means and the identification of small-area poverty-alleviation targets for domestic policy purposes, it also yields four very large data sets, one for income in urban places in each province, and one for consumption in urban places in each province, then two more for income and consumption for rural places (amphoe) in each province. At the authors' suggestion, the consumption series for rural places was used here, although the data for income and consumption were quite similar. The consumption series exhibited greater stability over time and location. Further, the two measures sum to a similar value over time.

5. APPLYING THE MODELS ON THE THAILAND DATA SET

The set covering model seeks the minimum number of sites so that all species are represented at least in one of these selected sites. Running that first model (equations 1 to 3) on the Thailand data set with Xpress-MP (2006) gives a solution $Z_1=11$. This means that, under the hypothesis that each species can be considered as protected once it appears in one single site, all of them can be covered with the selection of 11 amphoes as nature reserves. Figure 5 shows the location of such parcels on a map of Thailand.

⁵ 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 is therefore acceptable.

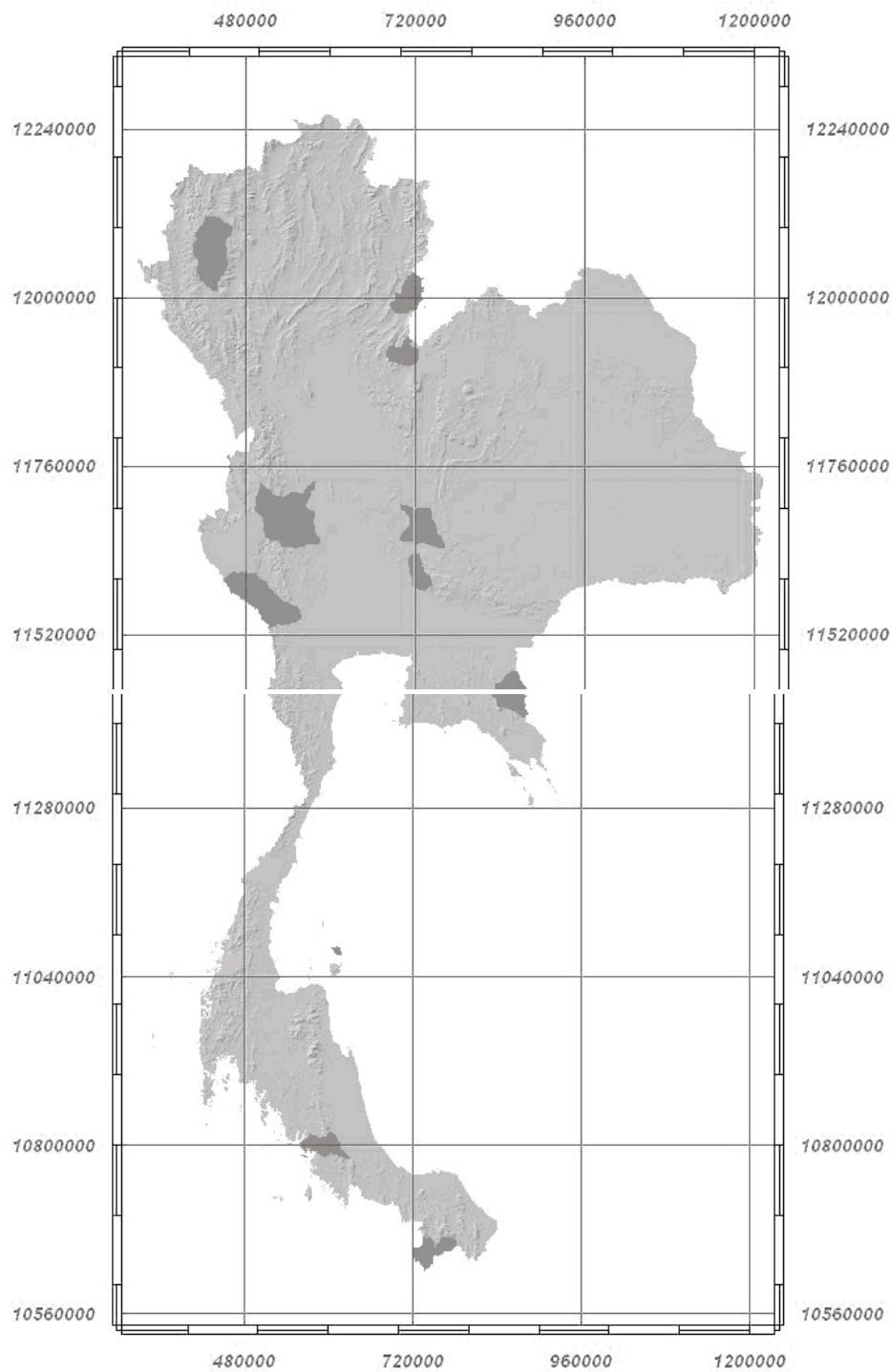


Figure 5⁶: Districts selected, SSCP solution

⁶ Base map source for Figures 5 to 7: Souris (2007).

The outcome displayed in Figure 5 is one of the many alternate optima that can be found for this integer program. Said differently, other sites are able to protect all species as well but it is not possible to cover all species with a smaller number of sites.

For choosing the smallest number of sites, the model selects those parcels that are either species-rich (that is, they include many different species) as well as those that are the only natural habitat for the rarest of the species (as three species are only present in one single amphoe).

The second model described in section 2 (equations (5) to (10)) takes home ranges into consideration but does not account for differences in site areas – which means that the model implicitly assumes that all sites have the same surface areas. This is obviously not the case when applied to the Thailand data set. Hence, we should rather concentrate on Model 3, represented by equations (11) to (16), whose aim is to select the smallest number of sites while representing all species in the reserve network and requiring that each shorter range and longer range species enjoy a habitat whose area is at least equivalent to that of its respective maximal home range. Besides, the model also ensures that longer-range species benefit from contiguous sites when protected.

Most of the 68 vertebrate species used in this study are animals of small body size that typically have a very small home range (from less than 1 km² to a few km²). Some species have a larger home range (from 5 to 60 km²) and only two species, the Asian elephant and the tiger, are considered for this paper as longer-range species as they may respectively cover a maximum of 300 and 100 km² for their activities. Comparing these two home ranges with district surface areas may lead us to overcome the problem of selecting contiguous sites. As a matter of fact, many sites have a larger area than 300 km². Equation (14), requiring 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 simply select a sufficiently large amphoe in which each longer range species is able to enjoy at least its own home range. The purpose for not deleting that equation and for requiring selection of at least two contiguous sites for longer-range species is to account for edge effects. As a matter of fact, it may be possible that the species occurs close to the border of one amphoe. If this is the case, it might be advisable to select its neighboring site as well as species do not know amphoes' borders⁷. Obviously, this is less true for shorter-range species, as by definition, their daily activities are much more limited in terms of area.

The third model (equations (11) to (16)) selects 13 sites, 11 of which protect shorter-range species and two contiguous sites protecting both longer-range species. The site selection is displayed in Figure 6.

⁷ One may oppose to this argument that the species in question may live at the other side of the amphoe and therefore, say if the second site selected is the one at the right border of the first site and if the species lives close to the left border, the contiguous site selection will be mis-placed. To overcome this problem, while running the model, we took this element into consideration and selected those contiguous sites for longer range species where either contiguous site could be selected, that is where the long range species is present in both contiguous sites.

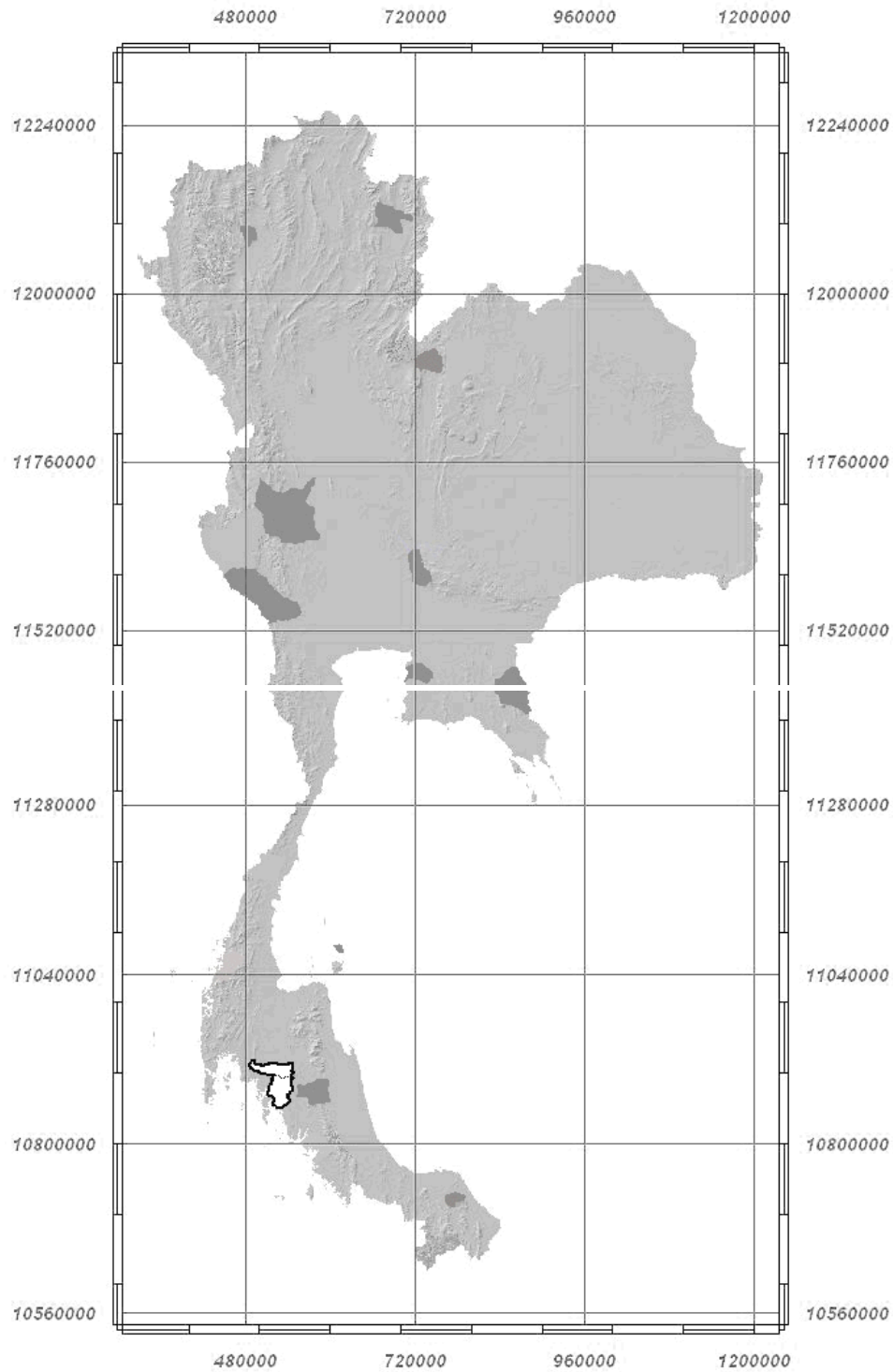


Figure 6: Districts selected, Model 3 solution without cost consideration

Compared with the SSCP model's solution, two additional sites are selected. Because all shorter range species (that is all species but two) need only a single site for protection (since all their home ranges are smaller than the area of each parcel selected), the model would not find any of these species-rich area or area where the rarest of the species occur for selection as natural habitat for longer range species. Hence, two additional contiguous sites are selected for longer-range species – they are depicted in white while the other sites selected for shorter-range species are in dark grey. Also, because of the site minimization objective, the model has chosen only two additional sites instead of three or four sites because both Asian elephant and tiger occur in the same two sites that are shown in white⁸.

The model has selected areas ranging from 166 km² to 5126 km² for short-range species while the two contiguous sites have a combined surface area of 1832 km². Compared with the SSCP solution, five sites are identical in both models and two other ones are very close (selection of either a contiguous or a very nearby site – often with similar species frequency characteristics) while the others are different. Three sites must of course be identical as they are the single site available for the three rarest species but it is not so for the fourth and fifth sites. Furthermore, one of these sites is present in all runs and in all alternate optima that can be found for all of the three models detailed in Section 2. That very site might have the irreplaceability characteristic, as determined by Jacobi et al. (2007).

Finally, considering cost elements can refine the model. As a matter of fact, setting land aside for nature reserve entails an opportunity cost in terms of output foregone, as explained above in Section 4.5. Replacing objective (11) by equation (4) in Model 3 gives a minimum cost value of 606 Million Baht⁹ for 13 sites selected, as depicted in Figure 7.

⁸ For comparison purposes, running model 2 (equation (5) to (10)) brings about the selection of 13 sites as well among which the same four sites as the SSCP and model 3 are selected and the same two contiguous sites for longer range species are selected as well.

⁹ This number should not be viewed as a cost figure for purchasing the site as it represents the annual income of that amphoe, as explained in Section 4. All subsequent opportunity cost data will be expressed in Million Baht as well.

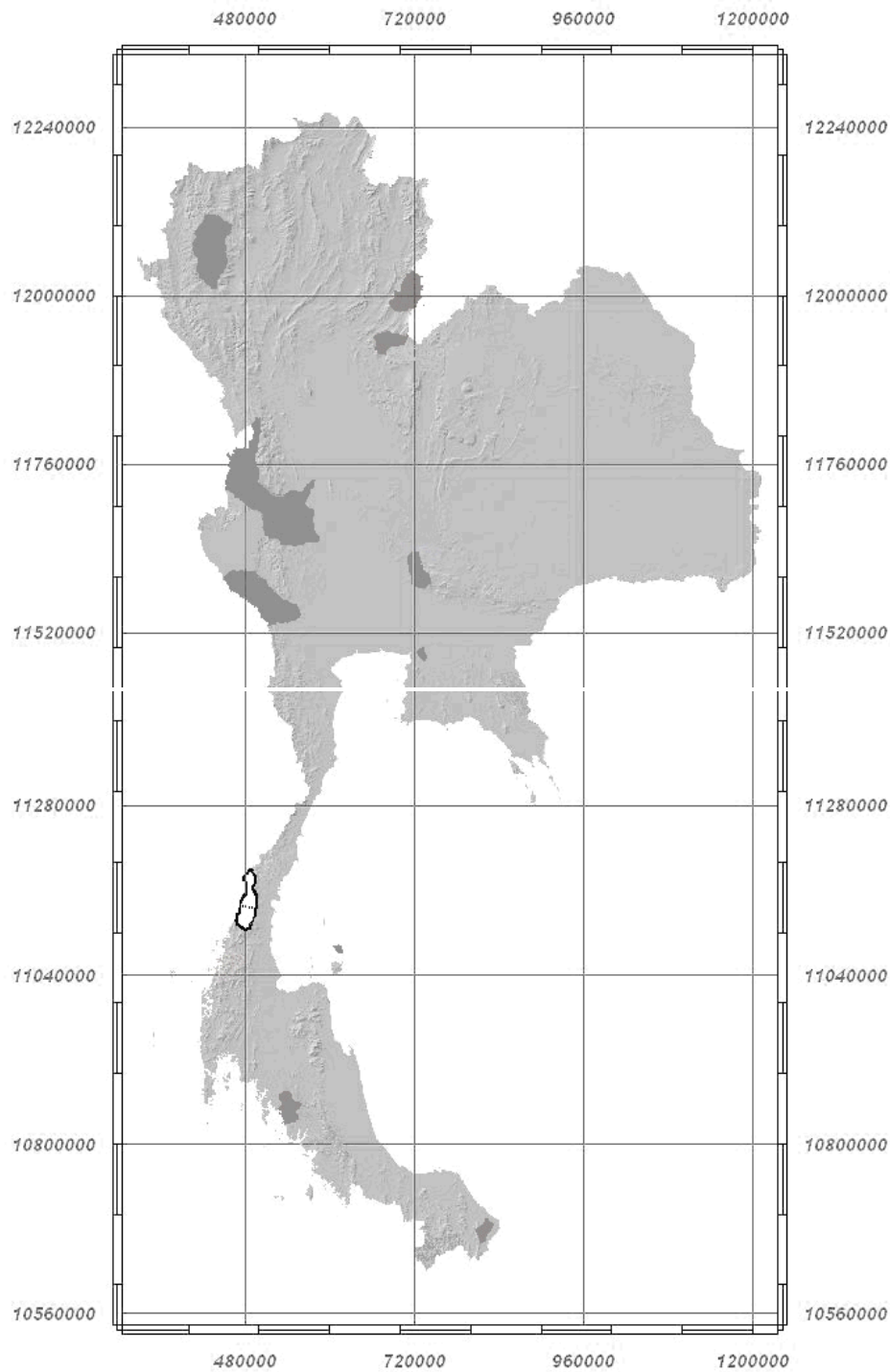


Figure 7: Districts selected, Model 3 solution with cost consideration

The model now chooses the least expensive sites for protecting all species within a suitable area range meeting habitat requirements for each and every species. The opportunity

cost of defining an amphoe as a nature reserve varies from 21 to 489 for the complete data set and selected districts' costs range from 21 to 125 – the highest cost being reserved for selecting the only site in which one of the species is present. This is obviously a more cost efficient alternative as the optimal solution of the site-minimizing Model 3 (the same model without cost consideration), amounts to a cost value of 1285, which is more than twice that of the cost-minimizing solution of Model 3. The gain is very important even though the site selection was fairly limited for various reasons. First, 3 sites out of 13 must be selected whatever their cost because 3 species are reported in a single site in Thailand. Second, four additional species are present only in two or three districts, which also severely limits the choice for a lower-cost parcel selection. Third, the number of species in this study is limited to threatened and endangered species, which prevents the bi-modal species frequency pattern often observed in studies that involve a large number of both common and rare species. Notwithstanding these remarks, the cost-efficient model is by far less costly than the site-minimizing problem.

Only the three sites that contain the three rarest species are common to the site-minimizing Model 3 and the cost-minimizing Model 3. However, six sites are common to the cost-minimizing Model 3 and the SSCP. This difference has the effect of moderating the irreplaceability characteristic mentioned above. In fact, it seems that, aside from the three sites that must be selected, as they are the only option for the three “site-endemic” species, no other site is totally irreplaceable but some areas (sites that are close-by) are nevertheless selected in most of the computer runs.

Moreover, concerning the longer-range species, the two contiguous sites selected for the cost-minimization problem (white color in Figure 7) are different from those selected with the site-minimization problem (white color in Figure 6). The reason is of course the lower opportunity costs of having these two sites in a reserve network. In this modified model, the new costs for contiguous sites correspond to a total of 84 compared with the higher amount of 155 for the site-minimization solution.

6. CONCLUSION

A classical method for protecting species is to set aside pieces of land to be part of a nature reserve. This paper formulates various set covering models aimed at protecting all those vertebrate species considered as threatened and/or endangered by the IUCN in Thailand. Species presence/absence data are assembled from the results of previous studies, area of amphoes, the nations' smallest districts are considered, home-ranges of each of the 68 species under consideration are gathered from various sources, and opportunity costs in terms of output foregone when a district is selected as part of the reserve are computed.

Starting with the well-known set covering problem, protecting each and every species in at least one district, the model is further refined to account for home ranges and for opportunity costs of creating reserves.

This paper should be considered as a theoretical exercise since it does not incorporate existing nature reserves in Thailand. Rather, it starts from the theoretical hypothesis that no reserve exists in the country and hence, it selects those districts best suited to provide natural

and large enough habitat for preserving all species at stake. The geographic sites selected, which are the various outcomes of the models, are displayed on maps in Figures 5 to 7.

Clearly, these results are not the only possible results. There are in general many alternate optima for such integer programs. In this particular case, there may be fewer optima than in other reserve site selection models applied on other large data such as the Oregon data set because three sites (that is more than 20 percent of all sites needed to protect all species with home range requirements) contain single species and must therefore be selected. Moreover, other species also occur in very few sites, which limits the selection procedure and the quantity of alternate optima.

Another important point to consider in the interpretation of the above results is that, as in Williams et al. (2003), a selected amphoe can be thought of, not as a site to acquire or a reserve, but as a general locale in which specific parcels for acquisition could be identified by local planners and decision makers. These smaller specific parcels are nevertheless expected to be large enough to respect the home-range constraints.

Finally, this paper does not consider competition among species and problems of co-location of habitat. 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.

REFERENCES

- Arthur, J., Camm, J., Haight, R., Montgomery, C., Polasky, S. (2004). Weighing conservation objectives: maximum expected coverage versus endangered species protection. *Ecological Applications*, 14, 1936-1945.
- Bioinventories of the world (2006). *Biological inventories of the world's protected areas*. International center for the environment, University of California, Davis. www.ice.ucdavis.edu/bioinventory/bioinventory.html
- Church, R., Stoms, D., Davis, F. (1996). Reserve selection as maximal covering location problem. *Biological Conservation* 76, 105-112.
- Costello, C. and Polasky, S. (2004). Dynamic Reserve Site Selection. *Resource and Energy Economics*, 26, 157-174.
- Csuti, B., Polasky, S., Williams, P., Pressey, R., Camm, J., Kershaw, M., Keisler, A., Downs, B.,
- Hamilton, R., Huso, M., Sahr, K (1997). A comparison of reserve site selection algorithms using data on terrestrial vertebrates in Oregon. *Biological Conservation*, 80, 83-97.
- De Lisle, H. (1996). *Natural History of Monitor Lizards*. Krieger Publishing Company, Florida.
- Eisenberg, F. (1997). Tapirs, status survey and conservation action plan. In Brooks, D. (Ed.). *IUCN Tapir Specialist Group*. IUCN. Switzerland.
- Grassman, L., Tewes, M., Silvy, N. (2005). Ranging, habitat use and activity patterns of binturong 'arctictis binturong' and yellow-throated marten 'mates flavigula' in north-central Thailand. *Wildlife Biology*, 11, 49-57.

- Grassman, L. (2001). *Spatial ecology and conservation of the felid community in Phu Khien wildlife sanctuary*. Progress report to CAT.
- Haight, R., ReVelle, C., Snyder, S. (2000). An integer optimization approach to a probabilistic reserve site selection problem. *Operations Research* 48, 697-708.
- Hamaide, B., ReVelle, C.S. and Malcolm, S (2006). Biological Reserves, Rare Species and the Trade-off between Species Abundance and Species Diversity. *Ecological Economics*, 56, 570-583.
- Hamaide, B., Williams, C., ReVelle, C. (2008). Cost-efficient reserve site selection favoring persistence of threatened and endangered species. *Geographical Analysis*, accepted for publication.
- Harris, S., Cresswell, W., Forde, P., Trehwella, W., Woollard, T., Wray, S. (1990). Home range analysis using radio tracking data: a review of problems and techniques particularly as applied to the study of mammals. *Mammal Review*, 20, 97-123.
- Healy, A. J., & Jitsuchon, S., (2007). Finding the Poor in Thailand, *Journal of Asian Economics* In print.
- Humphrey, S., Bain, J. (1990). *Endangered animals of Thailand*. Sandhill Crane Press, 468p.
- IUCN (2006). *Summary statistics for globally threatened species*. 1990, 1994, 1995, 2002, 2006. Gland, Switzerland. www.iucnredlist.org
- Jacobi, S., ReVelle, C., Pressey, R., Williams, J. (2007). Novel operations research methods for efficiently determining irreplaceable sites for conservation. *Environmental Modeling and Assessment*, 12, 91-103.
- Kahn, M. (1967). Movement of a herd of elephants in the upper Perak area. *Malay Nat. Journal*, 20, 18-23.
- Kaplan, H. (2007). Primate database. www.unm.edu/~hkaplan/pnas/primatedatabase.xls
- Kirkpatrick, J. (1983). An iterative method for establishing priorities for the selection of natural reserves: an example from Tasmania. *Biological Conservation* 25, 127-134.
- Legakul, ., McNeely, A. (1977). *Mammals of Thailand*. Association Conservation Wildlife, Bangkok, 758p.
- Leighton, S. (1987). Gibbons: territoriality and monogamy. In Smuts, B., Cheney, D., Seyfarth, R., Wrangham, R. and Struhsaker, T. (Ed.). *Primate societies*. University of Chicago Press, Chicago, 135-145.
- Malcolm, S., ReVelle, C., (2005). Preserving species diversity with backup coverage. *Environmental Modeling and Assessment*, 10, 99-105.
- Margules, C., Nichols, A., Pressey, R. (1988). Selecting networks of reserves to maximize biological diversity. *Biological Conservation* 43, 63-76.
- Marianov, V., ReVelle, C., Snyder, S. (2007). Selecting compact habitat reserves for species with differential habitat size needs. *Computers and Operations Research*, in print.
- Mason, C., McDonald, S. (1986). *Otters: ecology and conservation*. Cambridge University Press, Cambridge.
- Ministry of Interior. Royal Thai Government. www.moi.go.th www.amphoe.com
- Novak, R. (1999). *Walker's mammals of the world*. 6th edition. The Johns Hopkins University Press, Baltimore.

- Nunn, C., Altizer, S., Sechrest, W., Jones, K., Barton, R., Gittleman, J. (2004). Parasite species richness and evolutionary diversity of primates. *American Naturalist*, 164, S90-S103.
- Odden, M., Wegge, P., Storaas, T. (2005). Hog-deer 'axis procinus' need threatened tallgrass floodplains. *Animal Conservation*, 8, 99-104.
- Polasky, S., Camm, J., Garber-Yonts, B. (2001). Selecting biological reserves cost-effectively: an application to terrestrial vertebrate conservation in Oregon. *Land Economics*, 77, 68-78.
- Possingham, H., Day, J., Goldfinch, M., Salzborn, F. (1993). The mathematics of designing a network of protected areas for conservation. In: Sutton, D., Cousins, E., Pierce, C. (Eds.), *Decision sciences, tolls for today*, Proceedings of the ASOR Conference, Adelaide, Australia.
- ReVelle, C., Williams, J., Boland, J. (2002). Counterpart models in facility location science and reserve selection science. *Environmental modeling and assessment* 7, 71-80.
- Rowe, N. (1996). *The pictorial guide to the living primates*. Pogoneas Press, East Hampton, NY.
- Royal Thai Government (2000). *Socio-economic survey: 2000*. Thailand Population and housing census.
- Sheerin, J. (2007). *Protecting Endangered Species in Thailand*. Manuscript.
- Sompoad, S., Vadavudh, S. (1995). Populations of gaur and banteng and their management in Thailand. *Natural History Bulletin Siam Society*, 43, 55-83.
- Souris, M. (2007). *Thailand DEMS. 400m Resolution Maps of Thailand*. IRD, Asian Institute of Technology, Pathum Thani, Thailand. www.star.ait.ac.th/~souris/thailand.htm.
- Storch, D., Sizling, A. (2002). Patterns of commonness and rarity in Central European birds: reliability of the core-satellite hypothesis within a large scale. *Ecology* 25, 405-416.
- Snyder, S., ReVelle, C., Haight, R. (2004). One and two objective approaches to an area-constrained habitat reserve site selection problem. *Biological Conservation*, 119, 565-574.
- Toregas, C., Swain, R., ReVelle, C., Bergman, L. (1971). The location of emergency service facilities. *Operations Research* 19, 1363-1373.
- Toregas, C., ReVelle, C. (1973). Binary logic solutions to a class of location problems. *Geographical Analysis*, 5, 145-155.
- Underhill, L. (1994). Optimal and suboptimal reserve selection algorithms. *Biological Conservation* 35, 85-87.
- Williams, J.C., ReVelle, C.S., Bain, D. (2003). A decision model for selecting protected habitat areas within migratory flyways, *Socio-Economic Planning Sciences* 37, 239-268.
- Williams, J., ReVelle, C., Levin, S. (2005). Spatial attributes and reserve design models: a review. *Environmental Modeling and Assessment*, 10, 163-181.
- Xpress MP, (2006). Xpress MP software development, Dash optimization, Release 2006, Englewood Cliffs, NJ, USA.