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## Incorporating connectivity into conservation planning: A multi-criteria case study from central Mexico

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### ABSTRACT

The interdigitation of the Nearartic and Neotropical biogeographic zones in the Transvolcanic Belt (TVB) of central Mexico provides the region with high faunal richness and endemism. Biodiversity conservation in the TVB must accommodate the region's human population of more than 40 million. The current study presents conservation plans for the TVB intended to protect 99 non-volant mammal species while minimizing the impact on the human population. A rarity-complementarity algorithm was used to select a conservation area network (CAN) from sites with untransformed vegetation to represent 10% of each species' habitat. In addition, a new method was developed for augmenting the connectivity of CANs using graph theory. External sites were assigned quality scores based on the frequency with which they were selected at different targets of representation for species. Graph algorithms identified the highest-quality sites needed to link all conservation areas in an economical manner. These connectivity areas can facilitate migration or egress of biota in the event of local environmental stress. The network initialized with existing protected areas occupied 9.13% of the TVB, whereas the network built from scratch occupied 6.02%. In both cases, an additional area of only about 1.5% of the region was required to link all conservation areas in the network. Finally, a multiple criterion synchronization technique was used to select those connected networks which minimized both total area and human population impact.

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## 1. Introduction

A central tenet of conservation planning is that fragmented and isolated conservation areas are inadequate for the long term persistence of biodiversity, especially if turnover in the conservation areas is high (Margules et al., 1994; Virolainen et al., 1999). Place prioritization algorithms have attempted to address this by minimizing the perimeter length of the net-

work of conservation areas (McDonnell et al., 2002; Nalle et al., 2002; Onal and Briers, 2002) or the total distance between the areas (Fischer and Church, 2003; Onal and Briers, 2003). However, such a strategy does not ensure that a contiguous stretch of protected sites links the conservation areas. Several methods have been proposed for selecting such stretches, which are intended to serve primarily as dispersal corridors for animals (Williams, 1998; Van Langevelde et al.,

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2000; Cerdeira et al., 2005; Onal and Briers, 2005). A shortcoming of these methods is that they are intractable for the large biodiversity data sets being made available through species' ecological niche modeling (Soberón and Peterson, 2004). In addition to incorporating connectivity, conservation plans

for populous regions must address the needs of the human population using multi-criteria analysis (reviewed in Moffett and Sarkar, 2006).

The objective of this study is to develop a framework for conservation planning that integrates ecological niche modeling, the selection of conservation areas, connectivity establishment, and multi-criteria analysis. What is novel about the approach presented here is the combination of these four techniques (Fig. 1) and the connectivity establishment procedure, which is able to handle much larger data sets than previous algorithms (Fuller and Sarkar, 2006). The framework is illustrated by developing a conservation plan for the Transvolcanic Belt (TVB) of central Mexico.

The TVB is particularly suited for a multi-criteria analysis because it has a high population but also high faunal endemism. In particular, the TVB contains all of the known endemic non-volant mammalian genera in Mexico and half of known endemic non-volant mammal species, most of which are small mammals (Fa and Morales, 1993; Escalante et al., 2004). Significant threats to biodiversity in the TVB include high deforestation and other forms of habitat transformation to satisfy the needs of a human population of nearly 40 million (Instituto Nacional de Geografía, Estadística e Informática, 2000; Velázquez et al., 2001). The TVB contains a large number of decreed natural protected areas (NPAs) most of which are small, with areas less than 10 km<sup>2</sup> (Fig. 2). Some of these NPAs were among the first decreed in the country but most were selected on the basis of political or scenic criteria rather than biological content (Alcérreca-Aguirre et al., 1988). For example, even vascular plant inventories are available for less than one-third of the NPAs, suggesting that they were not designated based on known biodiversity content (Villaseñor et al., 2005).

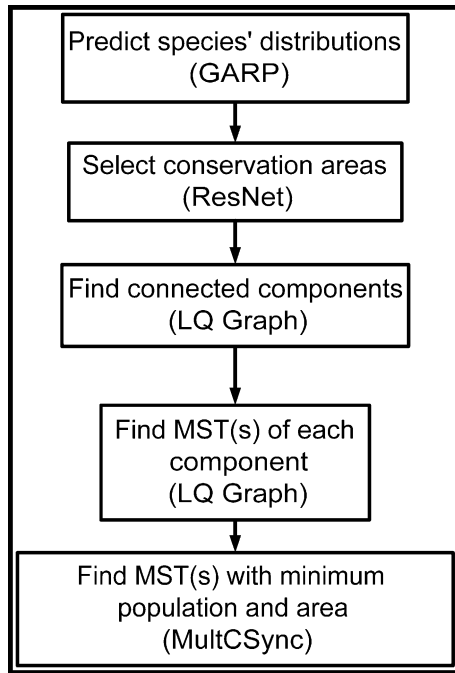


Fig. 1 – Flowchart of the conservation planning framework for the Transvolcanic Belt.

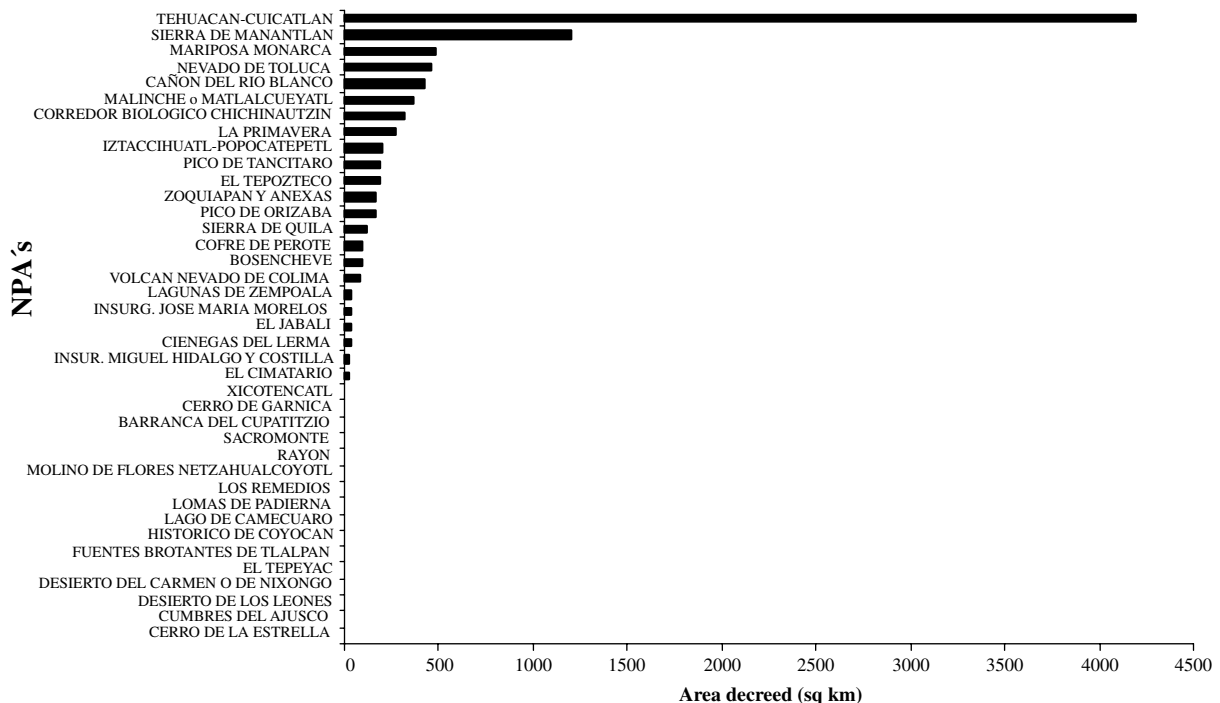


Fig. 2 – Main natural protected areas (NPAs) ranked by decreed area located in the Transvolcanic Belt and included in this study. The smallest NPAs, including Lago de Camécuaro and José María Morelos, are less than 10 km<sup>2</sup>.

As a result, these NPAs are known to be collectively inadequate for conserving the TVB's high biodiversity (Sánchez-Cordero et al., 2004). One option to address these problems would be to increase the size of the NPAs. However, due to the high deforestation, development, and consequent habitat fragmentation in the TVB, almost all the NPAs cannot be enlarged to include more relatively intact biological habitat (see Fig. 3; Munguía, 2004; Sánchez-Cordero et al., 2005a,b).

An alternative strategy to avoid the negative effects of the small size of individual protected areas is to use relatively intact or restorable habitat to establish connectivity between units of a conservation area network (CAN). A CAN is defined as a set of areas managed for the persistence of biodiversity into the future (Sarkar, 2003). The term "conservation area" is preferred over the more traditional "reserve" because the latter term has the connotation that almost all human activity is banned in the protected areas (Sarkar, 2003). While conservation areas should consist of habitat already suited for the long-term persistence of biodiversity features, the connectivity areas may consist of less "high quality" areas. The connectivity areas may have some degree of human-induced transformation but may retain secondary vegetation and may be suitable for the migration of mammal species or as a temporary refuge. Connectivity areas may also comprise areas that are degraded but potentially restorable; restoration to reasonably adequate habitat is much more easily achievable (both in terms of scientific knowledge and economic resources) than restoration into the high quality habitat required for a conservation area (Daily et al., 2003; Gove et al., 2005). Existing protected areas in the TVB have small human populations engaged in agriculture, forestry, and mineral extraction (Bocco et al., 2005; Méndez-Larios et al., 2005). The appropriate policy for each conservation or connectivity area must be determined by local context. It can include human exclusion, habitat restoration, sustainable resource extraction, or even some types of agricultural production (Sarkar, 2005).

The aim of this study is to propose a regional landscape-scale plan for the TVB using all 99 non-volant mammals that occur in the region. Potential users of the plan include the Mexican governmental agencies, Comisión Nacional Para el Conocimiento y Uso de la Biodiversidad (CONABIO) and Comisión Nacional de Áreas Naturales Protegidas (CONANP) or non-governmental organizations in Mexico such as PRONATURA. Non-volant mammals are used because of their high regional extinction risk in the TVB (Sánchez-Cordero et al., 2005a,b), high endemicity, high species richness, and their role as important seed-dispersers in the ecosystem (Sánchez-Cordero and Martínez-Gallardo, 1998; Sánchez-Rojas et al., 2004; Briones-Salas et al., 2006). In Mexico, non-volant mammals are also one of the best known biological groups nationwide, and the species' distributions are well documented (Fa and Morales, 1993; Arita et al., 1997; Villa and Cervantes, 2003).

The specific protocol developed here for integrating connectivity into conservation planning appears to be new. However, as this analysis of the TVB shows, this protocol can be used for any region for which minimal information on species' biogeographic distributions is available.

## 2. Methods

### 2.1. Biogeographic region

The TVB was partitioned into sites with (i) primary vegetation, (ii) secondary vegetation or (iii) neither; sites of type (iii) were considered anthropogenically transformed beyond restoration and excluded from the analysis. The first stage of the plan, that is, place prioritization for biodiversity representation in CANs, used standard techniques of site selection to represent a specified proportion of the habitat of each species in the network in as few sites as possible. During this stage, only type (i) sites were used. Previous work has shown that these areas, as determined using remote-sensed data, formed the most suitable habitat for the mammal species of Mexico (Sánchez-Cordero et al., 2004, 2005a,b).

The TVB was divided into 106,026 sites at a  $0.01^\circ \times 0.01^\circ$  resolution of longitude  $\times$  latitude. Site area varied between 1.153 and 1.179 km<sup>2</sup>, with an average of 1.163 km<sup>2</sup> (SD = 0.00496). The total area was 123,355 km<sup>2</sup>. Remote-sensed data were used to identify sites with relatively intact primary vegetation [type (i)], sites with secondary vegetation [type (ii)], and sites with neither [type (iii)] (Mas et al., 2004). Sites from the last category (38,274 sites with a total area of 44,511 km<sup>2</sup> or 36.08% of the TVB) were excluded from this analysis because they do not belong to the modeled ecological niches of the non-volant mammals considered here (Sánchez-Cordero et al., 2005a,b). Species appear to show niche conservatism over long time scales, and invasion of newly formed ecological niches may not result in persistent populations without recurrent immigration from adjacent untransformed habitats (Peterson et al., 1999; Peterson and Holt, 2003).

### 2.2. Modeling species' distributions

The geographical distribution of 99 non-volant mammal species (see Villa and Cervantes, 2003, for taxonomic nomenclature), were modeled using point occurrence data and environmental layers. The former were obtained from museum voucher specimens from national and international scientific collections (see Acknowledgments). The latter consisted of 10 environmental coverages at  $0.04^\circ \times 0.04^\circ$  pixel resolution, which summarized potential vegetation types, elevation, slope, and aspect, according to the Hydro 1K methodology (United States Geological Survey, 1998), and climatic parameters including mean annual precipitation, mean daily precipitation, maximum daily precipitation, minimum and maximum daily temperature, and mean annual temperature obtained from CONABIO (2002).

Modeled species' distributions were constructed with the Genetic Algorithm for Rule-set Prediction software package (GARP; Stockwell and Peters, 1999). GARP uses ecological-environmental abiotic and biotic variables of known species' occurrence points to produce coarse-grained species' ecological niche models ("Grinnelian" models; Grinnell, 1917) projected as potential distributions. In GARP, occurrence points are divided evenly into training and testing data sets. An iterative algorithm consisting of rule selection, evaluation, testing, and subsequent incorporation or rejection is used to "evolve" a most predictively accurate set of rules from an

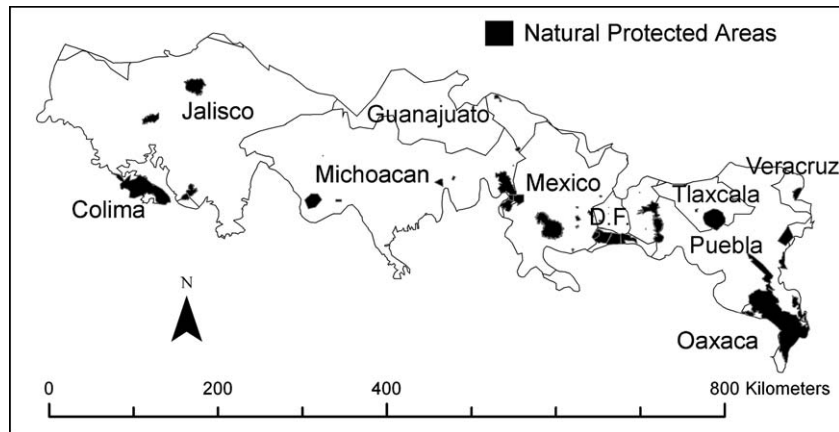


Fig. 3 – Natural protected areas of the Transvolcanic Belt (black) with state names. “D.F.: Distrito Federal”.

original set of possibilities (e.g., logistic regression, bioclimatic rules). The algorithm runs for 1000 iterations or until convergence (see Stockwell and Peterson, 2002). The final rules are then used to predict the total distribution for each species.

GARP has proven a robust tool for predicting species' geographic distributions for mammals (Iloldi-Rangel et al., 2004) and other taxa in Mexico (Garcia, 2006). Because GARP does not produce a unique solution, its use here followed published recommendations for the construction of optimal subsets of replicate models (Anderson et al., 2003). For each analysis, 100 replicate models at a  $0.01^\circ \times 0.01^\circ$  resolution were produced, the 20 models with lowest omission error were initially retained, and the 10 models with commission errors close to the median finally adopted for subsequent use. Further modeling refinement consisted of rejecting obvious over-predictions for microendemics (for example, disjunction distributions) based on Hall (1981). Species' extant distributions were then calculated by overlaying the Inventario Nacional Forestal 2000 map (Mas et al., 2004) and excluding only areas holding highly transformed habitat (type (iii) sites). The extant distribution models were used for the connectivity analyses (see below).

### 2.3. Place prioritization protocols

Two CANs were selected using the rarity-complementarity algorithm in the ResNet software package to represent 10% of the modeled distribution of each species restricted to type (i) sites (Garson et al., 2002). The algorithm included an adjacency criterion that breaks ties by selecting new sites physically adjacent to previously selected sites. This results in a spatially-aggregated CAN. In the first CAN, the algorithm was initialized with the 39 existing natural protected areas (the “NPA” solution) (Fig. 3). The second CAN was designed while ignoring the existing protected areas and initializing the algorithm with the site containing the rarest species (the “rarity” solution). It has been suggested that heuristics such as those implemented in ResNet provide significantly sub-optimal solutions (Rodrigues and Gaston, 2002). To test this, the conservation area selection problem was represented as an integer program in the GAMS modeling language

(Brooke et al., 1998) and the optimal solution was obtained using a branch-and-bound algorithm in the CPLEX 9.1 integer programming solver (ILOG, 2003).

### 2.4. Landscape quality score

Suppose planners wish to protect an at-risk species subject to the following constraints: at most 1% of the habitat of each species can be protected or at most 99% of the habitat can be protected. A site first selected when the first constraint is in effect is more critical for the species' persistence than one first selected under the latter constraint. This assumption was used to score sites in the TVB such that sites first selected at low targets of representation earned higher quality scores than those first selected at higher targets. ResNet was used to prioritize sites to represent species' habitat in the TVB at 20 target levels (5–100% at increments of 5%). One hundred replicates of each of the 20 place prioritizations were generated. Each replicate used a different random reshuffling of the rows of input file. Since ResNet uses a heuristic algorithm in which ties are broken by selecting a site at random, this could result in different solutions in each replicate. The final site quality scores were weighted by the frequency of selection at a given target level so that sites selected frequently at low targets had the highest scores.

### 2.5. Graph-theoretical connectivity protocols

The second stage, that is, the establishment of connectivity in the networks by linking conservation areas, required the development of some new techniques. The connectivity areas were selected with graph algorithms, which select paths that directly link conservation areas via high-quality sites that are not currently part of the conservation areas. This permits organisms, particularly mobile animals, in one conservation area to disperse to another using a path of contiguously protected sites. Graphs have previously been used for conservation planning but only for one or two species at a time (Bunn et al., 2000; Urban and Keitt, 2001). This analysis extends these techniques to an arbitrary number of species and other biodiversity surrogates. Both type (i) and type (ii) sites were used for selecting the connectivity areas. Type (ii) sites are less intact

than those of type (i) but still potentially restorable to adequate habitat for the relevant species. Thus, type (ii) sites were considered suitable for connecting conservation areas, but not adequate as sites for conservation areas themselves.

The LQGraph software package (Fuller and Sarkar, 2005) was used to find all least-cost paths between the conservation areas in both the NPA and rarity solutions. Costs were assigned so that a path consisting of many sites with high landscape quality scores had a low cost (Fuller and Sarkar, 2006). In addition, LQGraph filtered the least cost paths to find a minimum spanning tree (MST), the minimum number of paths required to link all conservation areas via high-quality sites. MSTs should be given priority for conservation because they represent the minimal connectivity-maintaining regions between conservation areas (Urban and Keitt, 2001).

In the TVB, a mammal in one conservation area may be able to disperse to nearby conservation areas but not to more distant conservation areas in the network due to the large percentage of type (iii) sites in the landscape. To quantify this, “connected components” of the NPA and rarity solutions were identified. These connected components are sets of conservation areas such that an individual in one conservation area within the set could reach any other conservation area within it by traversing only paths consisting of selected high-quality sites. A conservation area with a large number of components is highly fragmented from the perspective of an individual attempting to disperse among the conservation areas.

Random graphs ( $n = 1000$ ; Siek et al., 2002) were generated to provide a null model for comparing connectivity properties of the graphs corresponding to the NPA and rarity solutions. In the random graphs, the number of vertices equaled the number of conservation areas in the NPA and rarity solutions but edges were assigned at random between the vertices. Finally, spatial statistics (Syrjala, 1996) were used to assess whether the NPA and rarity solutions had the same configurations and whether their MSTs were spatially similar.

## 2.6. Multi-criteria analysis

The third stage used multi-criteria analysis to select the conservation plan with the minimal area and human impact (measured as the human population of sites in the plan). LQGraph finds all MSTs of a CAN. Alternative MSTs are interchangeable with respect to their connectivity properties but may differ in other criteria relevant for biodiversity conservation. All the MSTs were ordered by their area and human population. Population data were obtained from CONABIO (2002, www.conabio.gob.mx) and Instituto Nacional de Geografía, Estadística e Informática (2000, www.inegi.gob.mx). The GIS model provided data on areas ( $\text{km}^2$ ).

Each MST is a “solution” to the multiple-criterion decision problem of how to minimize the human impact of the conservation plan while representing the non-volant mammals in a connected network of conservation areas. The “best” solutions were the non-dominated ones, which were identified using the methodology of Sarkar and Garson (2004) with the MultCSync 1.0 software package (Moffett et al., 2004). One solution is said to “dominate” another if it is better than the other by at least one criterion (e.g., area or human population), and no worse by any criterion. A solution is called “non-dom-

inated” if it is not dominated by any other solution. In the present study, a “non-dominated solution” is a set of conservation areas and connectivity areas such that the geographical area and human population are as small as possible.

## 3. Results

### 3.1. Species

The species used in this study were 99 non-volant mammal species consisting of 14 species endemic to the TVB, 24 species endemic to Mexico, and 61 non-endemic species. Extant species’ distributions ranged from 50 to 52,770  $\text{km}^2$  (0.04–42.77% of the total area) for the endemics to the TVB, 1290–69,000  $\text{km}^2$  (1.05–55.93% of the total area) for the endemics to Mexico, and 1070–54,970  $\text{km}^2$  (0.87–44.56% of the total area) for the non-endemics (Table 1).

### 3.2. Conservation areas and landscape quality analyses

The 39 existing protected areas had a total area of 9179  $\text{km}^2$  or 7.4% of the TVB. More than half of the decreed NPAs have areas less than 100  $\text{km}^2$  and only two are larger than 1000  $\text{km}^2$ . The NPA-initialized solution contained 9658 sites with a total area of 11,264.4  $\text{km}^2$  or 9.13% of the TVB, whereas the rarity-initialized solution contained 6382 sites with an area of 7431.32  $\text{km}^2$  or 6.02% of the TVB. Both solutions were at most 0.04% suboptimal. In the conservation planning literature, a solution within 1% of the optimum is generally considered optimal (Onal, 2004). These results confirm previous findings that the rarity-complementarity algorithm implemented in ResNet is competitive with optimal solution methods (Sarkar et al., 2004). The graph-based representation of the NPA solution had 442 conservation areas, 4823 paths between conservation areas, and 25 components (Table 2). The graph corresponding to the rarity solution had 409 conservation areas, 4030 paths, and 39 components.

### 3.3. Connectivity analyses

The least cost paths between the conservation areas occupied 20.76% of the TVB in the NPA solution and 22.66% in the rarity solution, which is too large a portion of the landscape to be included in a conservation plan in such a populous region (Table 2). Thus, the least cost paths were filtered to find MSTs. The MSTs established connectivity among conservation areas using only 6.9% and 1.02% of the area of the least cost paths in the respective solutions. Thus, connectivity can be established via MSTs more economically than via least-cost paths.

In the comparison to random graphs, the graph corresponding to the NPA solution had fewer ( $p = 0.042$ ) and the graph corresponding to the rarity solution ( $p \gg 0.05$ ) had more components (randomization test, Manly, 1997). The number of components of the graph can be thought of as a measure of connectivity in the following sense. If the graph has few components, an animal in one conservation area is likely to be able to disperse to almost any other conservation area in the network. Based on this measure, the NPA solution is better connected and better facilitates dispersal than the rarity solution.

**Table 1 – List of non-volant mammals in the Transvolcanic Belt (TVB) of central Mexico, consisting of 61 non-endemics to Mexico (NE), 24 endemics to Mexico (E), and 14 microendemics to the TVB (M)**

Species	Actual distribution (km <sup>2</sup> )	Geographic position
Rodentia		
<i>Glaucomys volans</i>	52,350	NE
<i>Sciurus aureogaster</i>	50,320	NE
<i>Sciurus colliaei</i>	25,940	E
<i>Sciurus deppei</i>	37,560	NE
<i>Sciurus nayaritensis</i>	43,750	NE
<i>Sciurus oculatus</i>	17,310	E
<i>Spermophilus adocetus</i>	19,270	E
<i>Spermophilus mexicanus</i>	41,110	NE
<i>Spermophilus perotensis</i>	11,030	M
<i>Spermophilus variegatus</i>	48,910	NE
<i>Spermophilus spilosoma</i>	12,190	NE
<i>Cratogeomys gymnurus</i>	44,440	M
<i>Cratogeomys merriami</i>	53,050	E
<i>Cratogeomys tylorhynchus</i>	52,770	M
<i>Pappogeomys alcorni</i>	130	M
<i>Pappogeomys bulleri</i>	24,140	E
<i>Thomomys umbrinus</i>	52,870	NE
<i>Zygogeomys trichopus</i>	7740	M
<i>Dipodomys phillipsii</i>	53,350	E
<i>Liomys pictus</i>	41,740	NE
<i>Liomys irroratus</i>	53,300	NE
<i>Liomys spectabilis</i>	17,030	M
<i>Perognathus flavus</i>	1070	NE
<i>Baiomys musculus</i>	43,560	NE
<i>Baiomys taylori</i>	44,280	NE
<i>Habromys simulatus</i>	12,410	E
<i>Hodomys alleni</i>	25,000	E
<i>Nelsonia neotomodon</i>	18,590	M
<i>Neotoma albigula</i>	14,070	NE
<i>Neotoma mexicana</i>	47,900	NE
<i>Neotoma nelsoni</i>	50	M
<i>Neotomodon alstoni</i>	47,900	E
<i>Nyctomys sumichrasti</i>	47,180	NE
<i>Oligoryzomys fulvescens</i>	49,260	NE
<i>Oryzomys couesi</i>	43,030	NE
<i>Oryzomys alfaroi</i>	50,170	NE
<i>Oryzomys melanotis</i>	30,090	E
<i>Osgoodomys banderanus</i>	40,620	E
<i>Peromyscus aztecus</i>	49,200	NE
<i>Peromyscus bullatus</i>	280	M
<i>Peromyscus difficilis</i>	69,000	E
<i>Peromyscus furvus</i>	40,910	E
<i>Peromyscus leucopus</i>	23,830	NE
<i>Peromyscus maniculatus</i>	39,310	NE
<i>Peromyscus mekisturus</i>	1290	E
<i>Peromyscus melanophrys</i>	24,390	E
<i>Peromyscus melanotis</i>	52,880	NE
<i>Peromyscus mexicanus</i>	42,940	NE
<i>Peromyscus pectoralis</i>	39,060	NE
<i>Peromyscus spicilegus</i>	38,370	E
<i>Peromyscus truei</i>	50,910	NE
<i>Reithrodontomys chrysopsis</i>	50,670	M
<i>Reithrodontomys fulvescens</i>	35,690	NE
<i>Reithrodontomys hirsutus</i>	14,700	M
<i>Reithrodontomys megalotis</i>	52,400	NE
<i>Reithrodontomys mexicanus</i>	39,540	NE
<i>Reithrodontomys microdon</i>	32,330	NE
<i>Reithrodontomys sumichrasti</i>	50,640	NE
<i>Sigmodon alleni</i>	37,680	E
<i>Sigmodon fulviventer</i>	37,020	NE

**Table 1 – continued**

Species	Actual distribution (km <sup>2</sup> )	Geographic position
<i>Sigmodon hispidus</i>	45,110	NE
<i>Sigmodon leucotis</i>	43,270	E
<i>Sigmodon mascotensis</i>	43,190	E
<i>Microtus mexicanus</i>	51,680	NE
<i>Microtus quasiater</i>	48,750	M
Carnivora		
<i>Urocyon cinereoargenteus</i>	52,870	NE
<i>Canis latrans</i>	30,090	NE
<i>Bassariscus astutus</i>	54,970	NE
<i>Nasua narica</i>	42,410	NE
<i>Procyon lotor</i>	40,400	NE
<i>Conepatus mesoleucus</i>	37,640	NE
<i>Mephitis macroura</i>	47,050	NE
<i>Spilogale putorius</i>	42,040	NE
<i>Spilogale pygmaea</i>	13,870	E
<i>Mustela frenata</i>	53,440	NE
<i>Lontra longicaudis</i>	37,210	NE
<i>Taxidea taxus</i>	9810	NE
<i>Puma concolor</i>	35,780	NE
<i>Leopardus wiedii</i>	23,340	NE
<i>Lynx rufus</i>	42,460	NE
Insectivora		
<i>Cryptotis goldmani</i>	53,140	NE
<i>Cryptotis mexicana</i>	53,060	E
<i>Cryptotis parva</i>	50,300	NE
<i>Megasorex gigas</i>	35,580	E
<i>Notiosorex crawfordi</i>	27,490	NE
<i>Sorex emarginatus</i>	5480	E
<i>Sorex macrodon</i>	12,330	M
<i>Sorex saussurei</i>	50,510	NE
	5930	NE
Lagomorpha		
<i>Lepus californicus</i>		
<i>Lepus callotis</i>	42,320	NE
<i>Sylvilagus audubonii</i>	8950	NE
<i>Sylvilagus cucularis</i>	49,180	E
<i>Sylvilagus floridianus</i>	50,500	NE
<i>Romerolagus diazii</i>	20,350	M
Didelphimorphia		
<i>Didelphis marsupialis</i>	49,730	NE
<i>Didelphis virginianus</i>	43,670	NE
Artiodactyla		
<i>Odocoileus virginianus</i>	42,090	NE
<i>Tayassu tajacu</i>	38,040	NE
Xenathra		
<i>Dasypus novemcinctus</i>	42,260	NE

Actual distribution predictions were produced by including only remnant untransformed habitat based on the Inventario Nacional Forestal 2000 within the species' potential distributions (see Section 2 for details).

In the MSTs based on the NPA solution, on average an additional 1520.97 (SD = 905.49) sites (in addition to the CAN sites) with an average area of 1766.64 km<sup>2</sup> (SD = 1051.54) or 1.43% of the area of the TVB are prioritized (Fig. 4). In the MSTs based on the rarity solution, on average an additional 247 (SD = 485.46) sites (in addition to the CAN sites) with an

**Table 2 – Statistics of graph models for establishing conservation area networks (CAN) in the Transvolcanic Belt**

	NPA solution	Rarity solution
CAN area (km <sup>2</sup> )	11,264.4	7431.32
Percentage of TVB in CAN	9.13	6.02
Number of conservation areas	442	409
Number of connected components	25	39
Number of least-cost paths	4283	4030
Area of least-cost paths (km <sup>2</sup> )	25,606.97	27,983.98
Total number of minimum spanning trees (MSTs)	48	32
Area of MSTs (km <sup>2</sup> ): mean (SD)	1766.64 (1051.54)	287.47 (563.85)

Note that when the place prioritization algorithm is initialized with the existing NPAs (“NPA solution”), more land is required to represent 10% of each species’ habitat and establish connectivity between conservation areas.

average area of 287.47 km<sup>2</sup> (SD = 563.85) or 0.23% of the area of the TVB are prioritized. This means that the amount of land required to construct paths to connect the conservation areas

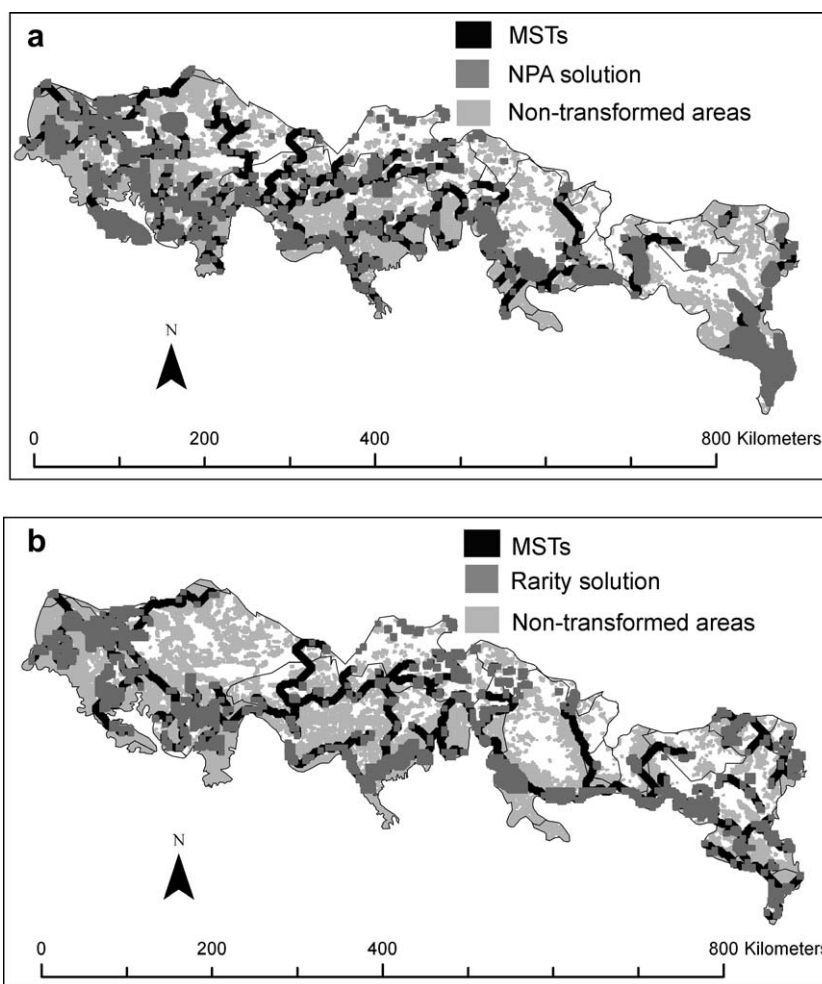
in the rarity solution is less than the land required for the NPA solution. The large standard deviation associated with each average MST area is due to the large variance in the number of conservation areas among components. The spatial configurations of the MSTs based on the rarity and NPA solutions were significantly different (Syrjala test, *p* = 0.01). For both the NPA and rarity solution, the median length of the sets of connectivity areas linking conservation areas was 4.24 km.

### 3.4. Multi-criteria analysis

The set of MSTs based on the NPA solution had three non-dominated solutions and the set of MSTs based on the rarity solution had four.

## 4. Discussion

Like previous studies (Alcérreca-Aguirre et al., 1988; Sánchez-Cordero et al., 2004; Villaseñor et al., 2005), this analysis demonstrates that the existing protected areas in the TVB do not represent biodiversity economically. When the site selection algorithm was initialized with the existing NPAs, 3833 km<sup>2</sup> more land was required to represent 10% of the distribution of each non-volant mammal than if the CAN was not so



**Fig. 4 – Conservation plans for the Transvolcanic Belt: (a) the NPA solution; (b) the rarity solution. Both plans are non-dominated solutions identified by the multi-criteria analysis.**

initialized (Table 2). Among the first locations selected in both the NPA and rarity solution was a site in northern Veracruz containing more than 30 non-volant mammals. A conservation plan for the northeastern TVB using the same mammal database as the present plan (Ortega-Huerta and Peterson, 2004) also prioritized this site. This area should be an immediate priority for regional conservation.

The NPA solution is better connected than the rarity solution to the extent that the latter has more connected components. Human population may account for this difference in connectivity. The connectivity establishment procedure presented here constructs paths between conservation areas via sites with primary or secondary vegetation. It is plausible that a site with a high human population will lack such vegetation or be adjacent to sites without vegetation. The rarity solution contains about eight million more people than the NPA solution. Due to the high population of the rarity solution, many of its conservation areas may be surrounded by sites without vegetation, making it impossible to establish connectivity areas between them. Only when the MST based on the NPA solution was compared with the MST based on the rarity solution did the Syrjala detect significant differences in spatial configuration. In general, rejecting the null hypothesis of identical configurations is quite difficult with the Syrjala test (Sarkar et al., 2005). Therefore, the spatial differences between the MSTs must be quite strong. The MST for the NPA solution has extensive connectivity areas in central Jalisco that are not present in the MST for the rarity solution.

Though the biological importance of establishing connectivity between individual units of a CAN remains controversial (Noss, 1987; Simberloff et al., 1992), connectivity is known to be important for non-volant mammals in the TVB such as those in the genera *Peromyscus* and *Microtus*. In the case of *Peromyscus*, landscape connectivity influences population persistence to the extent that individuals are known to have better access to food in connected habitat patches (Orrock et al., 2003). In the case of *Microtus*, connectivity, rather than climatic fluctuations, affects population size and synchrony (Huitu et al., 2003). *Peromyscus* species are known to use linear landscape features such as strips of remnant habitat as corridors (Bolger et al., 2001). Of the 99 non-volant mammal species considered here, data on maximum dispersal distances were available for only 10 (Sutherland et al., 2000; Bowman et al., 2002). The dispersal distances for nine of these species exceeded the median length of the connectivity areas selected by the graph algorithms. This suggests that these small mammals would use the connectivity areas as dispersal corridors between conservation areas in the TVB. However, future studies should test the utility of these connectivity areas for mammals and other biological groups. In addition to their function as dispersal corridors, the connectivity areas could serve as sites for habitat restoration.

Were taxa other than non-volant mammals used to design the CAN, different places might be prioritized (though it is unlikely that sites selected here would not be selected at all). For example, the Tehuacán-Cuicatlán valley in southern Puebla has 365 endemic plants but its mammal species are both less diverse and less documented (Davila et al., 2002). Thus, when sites were selected to protect mammal habitat and the algo-

rithm was not initialized with the existing natural protected areas, fewer sites in southern Puebla were selected. Quantifying the extent to which the plans presented here represent non-mammalian diversity requires formal surrogacy analysis (Sarkar et al., 2005), which is beyond the scope of this study. Irrespective of this, non-volant mammals are an important component of biodiversity that merit protection. The biodiversity value of a site can be defined as the number of features of the site that are not adequately protected elsewhere (Sarkar and Margules, 2002). By this definition, the biodiversity value of mammal habitat in the TVB is extremely high because the TVB has more endangered mammals than any other region of Mexico (Ceballos et al., 1998) and the existing protected areas do not represent this fauna adequately.

This conservation plan prioritizes many of the same sites as earlier plans for the TVB. A national plan for several hundred bird, mammal, and amphibian species in Mexico at the 0.25° scale prioritized northern Puebla and northern Michoacán (Brandon et al., 2005). The rarity solution (Fig. 4b) selects many sites in these areas. However, Brandon et al. (2005) also prioritize the western half of the state of Mexico. Most sites in the state of Mexico were excluded from the present plan because they lack primary or secondary vegetation. Pérez-Arteaga et al. (2005) designed a CAN for Mexican wildfowl that includes 12 conservation areas in the central highlands of the TVB, where the states of Guanajuato, Jalisco, and Michoacán meet. The NPA solution (Fig. 4a) proposes only 6 conservation areas in this region, but selects extensive connectivity areas there. However, the plans differ in scale since the wildfowl plan was carried out at the national scale. Velázquez et al. (2003) designed a CAN to protect 122 species of threatened and endangered amphibians, reptiles, birds, mammals, and vascular plants in Distrito Federal. They proposed sites along the southern and western borders of the state as “core areas” of the CAN. Although the NPA and rarity solutions (Figs. 4a and b) prioritize some of these same core areas, conservation and connectivity areas in Distrito Federal make up less than 1% of the present plan (Table 3); differences between the plans can be explained by scale to the extent that the present plan is for a region 1440 times larger (Velázquez et al., 2003). In addition, the plan presented here selects sites with high biodiversity content by means of an iterative selection procedure (Garson et al., 2002), whereas Velázquez et al. (2003) employed correspondence analysis and ordination.

Mammal species assemblages in the eastern TVB are dissimilar from the rest of the region, probably because the east has moist forests and cloud forests whereas the forests elsewhere in the TVB are mostly dry (Fa, 1989). The unique mammal fauna of the eastern TVB is represented in both of the CAN's presented here. The plan initialized with the existing natural protected areas selects sites around the Tehuacán-Cuicatlán biosphere reserve in southern Puebla (Fig. 4a). The plan not initialized with the NPAs selected fewer sites in southern Puebla but more sites in the northern part of the state (Fig. 4b).

The planning method described here could be refined in several ways. Here, a two-stage method was used to select contiguity areas. First, the graph algorithms identified many sets of contiguity areas. Each set consisted of sites with high landscape quality that established connectivity between the

**Table 3 – List of states and percent of conservation areas and connectivity areas included in the place prioritization algorithms for the Transvolcanic Belt**

State	Conservation areas (%)	Connectivity areas (%)
Colima	0.0157	0.277
	1.149	0.0376
Distrito Federal	0.141	0.99
	0.238	0.827
Guanajuato	6.142	7.013
	2.879	6.126
Hidalgo	0.768	0.04
	0.311	0.113
Jalisco	37.59	28.922
	32.101	38.858
Mexico	14.478	6.022
	10.438	10.447
Michoacán	18.192	29.319
	14.87	34.987
Morelos	1.802	2.219
	4.483	0.789
Nayarit	0.517	0.713
	0.632	0.827
Oaxaca	2.209	3.011
	8.74	0.526
Puebla	15.544	17.789
	19.0328	3.908
Querataro	1.254	0.436
	0.611	0
Tlaxcala	0.329	1.466
	2.444	1.203
Veracruz	1.0184	1.783
	1.957	1.278
Zacatecas	0	0
	0.114	0.0752

The lower (upper) percentage is for the NPA (rarity) solution.

conservation areas. Second, the multiple-criteria synchronization procedure identified the sets with the smallest geographical areas and human populations. The landscape quality score served as an indicator of habitat suitability. Population served as a measure site vulnerability insofar as mammal habitat is more likely to be disturbed when the human population is high (Carroll et al., 2003). As an alternative to the two-stage method, a single utility function could be used to prioritize contiguity areas based on suitability and vulnerability simultaneously. However, such a function requires assigning arbitrary weights to the two criteria and assumes that they have a common quantitative scale (Sarkar and Garson, 2004). The multiple-criterion synchronization procedure presented here avoids the problems of arbitrariness and incommensurability because it generates an ordinal ranking of the sets of contiguity areas (based on area and population) rather than assigning numerical values to the two criteria.

Second, though the GIS model in this analysis used the same site sizes for the CANs and the connectivity areas, the graph algorithms described above permit different scales to be used. In Mexico, many NPAs are adjacent to expanding cities (Cantú et al., 2004). In this context, conservation planners may wish to use a fine spatial scale to model sites outside the NPAs in order to ensure that the connectivity areas that they select do not intersect with infrastructure such as roads. Moreover, the administrative boundaries of NPAs in Mexico are sometimes poorly defined (Bojórquez-Tapia et al., 2004) such that there is no clear delineation between a park and private lands. In such cases, it would be suitable to represent the CANs with a coarse spatial scale while using a fine spatial scale when selecting connectivity areas. In addition, though the analysis presented here did not calculate the cost of restoring transformed habitat in the TVB, conservation plans from other regions estimate that this can double the cost of the plan (Frazee et al., 2003). Calculating this cost would require data on the cost of buying and administering sites adjacent to conservation areas and the cost of incentive-based agreements between land owners and CONABIO, such as tax breaks. Finally, the methodology presented establishes connectivity between conservation areas via MSTs using as few sites as possible so as to minimize the impact on the human population. However, planners may wish to establish multiple, redundant connections between conservation areas as a safeguard against future disturbances, such as changes in forest and life zone types in the TVB due to climate change (Villers-Ruiz and Trejo-Vázquez, 1998). This could be accomplished by placing all of the least-cost paths between conservation areas under protection rather than filtering the paths to find the MST(s). An alternative method to protect the CAN against future disturbance is to select sites here-and-now so as to minimize the expected cost of protecting species adequately in the future using stochastic optimization (Snyder et al., 2004).

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## REFERENCES

- Alcérreca-Aguirre, C., Consejo, J., Flores, O., Gutiérrez, D., Hentschel, E., Herzig, M., Pérez-Gil, R., Reyes, J.M., Sánchez-Cordero, V., 1988. Fauna Silvestre y Areas Naturales Protegidas. Fundación Universo Veintiuno, México D.F.
- Anderson, R.P., Lew, D., Peterson, A.T., 2003. Evaluating predictive models of species' distributions: criteria for selecting optimal models. *Ecological Modelling* 162, 211–232.
- Arita, H.T., Figueroa, F., Frisch, A., Rodríguez, P., Santos del Prado, K., 1997. Geographical range size and the conservation of Mexican mammals. *Conservation Biology* 11, 92–100.
- Bocco, G., Velázquez, A., Siebe, C., 2005. Using geomorphological mapping to strengthen resource management in developing countries: the case of rural indigenous communities in Michoacán, Mexico. *Catena* 60, 239–253.
- Bojórquez-Tapia, L.A., Cueva, H., Díaz, S., Melgarejo, D., Alcantar, G., Solares, M.J., Grobet, G., Cruz-Bello, G., 2004. Environmental conflicts and nature reserves: redesigning the Sierra San Pedro Mártir national park, Mexico. *Biological Conservation* 117, 111–126.
- Bolger, D.T., Scott, T.A., Rotenberry, J.T., 2001. Use of corridor-like structures by bird and small mammal species. *Biological Conservation* 102, 213–224.
- Bowman, J., Jaeger, J.A.G., Fahrig, L., 2002. Dispersal distance of mammals is proportional to home range size. *Ecology* 83, 2049–2055.
- Brandon, K., Gorenflo, L., Rodrigues, A., Waller, R., 2005. Reconciling conservation, people, protected areas, and agricultural suitability in Mexico. *World Development* 33, 1403–1418.
- Briones-Salas, M., Sánchez-Cordero, V., Sánchez-Rojas, G., 2006. Multi-species fruit and seed removal in a tropical deciduous forest in Mexico. *Canadian Journal of Botany* 84, 433–442.
- Brooke, A., Kendrick, D., Meeraus, A., Raman, R., 1998. GAMS: A User's Guide. GAMS Development Corporation, Washington, DC.
- Bunn, A.G., Urban, D.L., Keitt, T.H., 2000. Landscape connectivity: a conservation application of graph theory. *Journal of Environmental Management* 59, 265–278.
- Cantú, C., Wright, R.G., Scott, J.M., Strand, E., 2004. Assessment of current and proposed nature reserves of Mexico based on their capacity to protect geophysical features and biodiversity. *Biological Conservation* 115, 411–417.
- Carroll, C., Noss, R.F., Paquet, P.C., Schumaker, N.H., 2003. Use of population viability analysis and reserve selection algorithms in regional conservation plans. *Ecological Applications* 13, 1773–1789.
- Ceballos, G., Rodríguez, P., Medellín, R.A., 1998. Assessing conservation priorities in megadiverse Mexico: mammalian diversity, endemicity, and endangerment. *Ecological Applications* 8, 8–17.
- Cerdeira, J.O., Gaston, K.J., Pinto, L.S., 2005. Connectivity in priority area selection for conservation. *Environmental Modeling and Assessment* 10, 183–192.
- Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. 2002. Metadata and Digital Map Library. [http://conabioweb.conabio.gob.mx/metacarto/metadatos\\_ing.pl](http://conabioweb.conabio.gob.mx/metacarto/metadatos_ing.pl) (last accessed 9.12.05).
- Daily, G., Ceballos, G., Pacheco, J., Suzán, G., Sánchez-Azofeifa, A., 2003. Countryside biogeography of neotropical mammals: conservation opportunities in agricultural landscapes of Costa Rica. *Conservation Biology* 17, 1814–1826.
- Davila, P., del Coro Arizmendi, M., Valiente-Banuet, A., Villaseñor, J.L., Casas, A., Lira, R., 2002. Biological diversity of the Tehuacán-Cuicatlán valley, Mexico. *Biodiversity and Conservation* 11, 421–442.
- Escalante, T., Rodríguez, G., Morrone, J.J., 2004. The diversification of Nearctic mammals in the Mexican transition zone. *Biological Journal of the Linnean Society* 83, 327–339.
- Fa, J., 1989. Conservation-motivated analysis of mammalian biogeography in the Trans-Mexican Neovolcanic belt. *National Geographic Research* 5, 296–316.
- Fa, J., Morales, L., 1993. Patterns of mammalian diversity in Mexico. In: Ramamoorthy, T., Bye, R., Lot, A., Fa, J. (Eds.), *Biological Diversity of Mexico: Origins and Distribution*. Oxford University Press, Oxford, pp. 319–364.
- Fischer, D.T., Church, R.L., 2003. Clustering and compactness in reserve site selection: an extension of the biodiversity management area selection model. *Forestry Science* 49, 555–565.
- Frazer, S., Cowling, R., Pressey, R., Turkipie, J., Lindenbergh, N., 2003. Estimating the cost of conserving a biodiversity hotspot. *Biological Conservation* 112, 275–290.
- Fuller, T., Sarkar, S., 2005. LQGraph Version 1.0 Manual. University of Texas Biodiversity and Biocultural Conservation Laboratory, Austin, Texas. <http://uts.cc.utexas.edu/~consbio/Cons/ResNet.html> (last accessed 9.12.05).
- Fuller, T., Sarkar, S., 2006. LQGraph: a software package for optimizing connectivity in conservation planning. *Environmental Modeling and Software* 21, 750–755.
- García, A., 2006. Using ecological niche modelling to identify diversity hotspots for the herpetofauna of Pacific lowlands and adjacent interior valleys of Mexico. *Biological Conservation* 130, 25–46.
- Garson, J., Aggarwal, A., Sarkar, S., 2002. ResNet Ver 1.2 Manual. University of Texas Biodiversity and Biocultural Conservation Laboratory, Austin, Texas. Available from: <http://uts.cc.utexas.edu/~consbio/Cons/ResNet.html>.
- Gove, A., Majer, J., Rico-Gray, V., 2005. Methods for conservation outside of formal reserve systems: the case of ants in the seasonal dry tropics of Veracruz, Mexico. *Biological Conservation* 126, 328–338.
- Grinnell, J., 1917. The niche-relationship of the Californian thrasher. *Auk* 43, 427–433.
- Hall, E.R., 1981. *The Mammals of North America*, vols. 1 and 2. Ronald Press, New York.
- Huitu, O., Norrdahl, K., Korpimäki, E., 2003. Landscape effects on temporal and spatial properties of vole population fluctuations. *Oecologia* 135, 209–220.
- Illoldi-Rangel, P., Sánchez-Cordero, V., Peterson, A.T., 2004. Predicting distributions of Mexican mammals using ecological niche modeling. *Journal of Mammalogy* 85, 658–662.
- ILOG, 2003. ILOG CPLEX 9.1. Gentilly Cedex, France.
- Instituto Nacional de Geografía, Estadística e Informática, 2000. XII Censo General de Población y Vivienda 2000. <http://www.inegi.gob.mx/est> (last accessed 9.12.05).
- Manly, B.F.J., 1997. *Randomization, Bootstrap, and Monte Carlo Methods in Biology*. 2nd ed. Chapman & Hall, London.
- Margules, C.R., Nicholls, A.O., Usher, M.B., 1994. Apparent species turnover, probability of extinction and the selection of nature reserves: a case study of the Ingleborough limestone pavements. *Conservation Biology* 8, 398–409.
- Mas, J.-F., Velázquez, A., Diaz-Gallegos, J.-R., Mayorga-Saucedo, R., Alcantara, C., Bocco, G., Castro, R., Fernandez, T., Pérez-Vega, A., 2004. Assessing land use/cover changes: a nationwide multivariate spatial database for Mexico. *International Journal of Applied Earth Observation and Geoinformation* 5, 249–261.
- McDonnell, M.D., Possingham, H.P., Ball, I.R., Cousins, E.A., 2002. Mathematical methods for spatially cohesive reserve design. *Environmental Modeling and Assessment* 7, 107–114.
- Méndez-Larios, I., Villaseñor, J.L., Lira, R., Morrone, J.J., Dávila, P., Ortiz, E., 2005. Toward the identification of a core zone in the Tehuacán-Cuicatlán biosphere reserve, Mexico, based on

- parsimony analysis of endemism of flowering plant species. *Interciencia* 30, 267–274.
- Moffett, A., Garson, J., Sarkar, S., 2004. MultCSync: a software package for incorporating multiple criteria in conservation planning. *Environmental Modelling and Software* 20, 1315–1322.
- Moffett, A., Sarkar, S., 2006. Incorporating multiple criteria into the design of conservation area networks: a minireview with recommendations. *Diversity and Distributions* 12, 125–137.
- Munguía, M., 2004. Representatividad Mastofaunística en Áreas Naturales Protegidas y Regiones Terrestres Prioritarias en el Eje Neovolcánico: un Modelo de Conservación. Tesis de licenciatura, Facultad de Ciencias, Universidad Nacional Autónoma de México, México, D.F.
- Nalle, D., Arthur, J.L., Sessions, J., 2002. Designing compact and contiguous reserve networks with a hybrid heuristic algorithm. *Forestry Science* 48, 59–68.
- Noss, R.F., 1987. Corridors in real landscapes: a reply to Simberloff and Cox. *Conservation Biology* 1, 159–164.
- Onal, H., 2004. First-best, second-best, and heuristic solutions in conservation reserve site selection. *Biological Conservation* 115, 55–62.
- Onal, H., Briers, R.A., 2002. Incorporating spatial criteria in optimum reserve network selection. *Proceedings of the Royal Society of London B* 269, 2437–2441.
- Onal, H., Briers, R.A., 2003. Selection of a minimum-boundary reserve network using integer programming. *Proceedings of the Royal Society of London B* 270, 1487–1491.
- Onal, H., Briers, R.A., 2005. Designing a conservation reserve network with minimal fragmentation: a linear integer programming approach. *Environmental Modeling and Assessment* 10, 193–202.
- Orrock, J.L., Danielson, B.J., Burns, M.J., Levey, D.J., 2003. Spatial ecology of predator–prey interactions: corridors and patch shape influence seed predation. *Ecology* 84, 2589–2599.
- Ortega-Huerta, M.A., Peterson, A.T., 2004. Modelling spatial patterns of biodiversity for conservation prioritization in North-eastern Mexico. *Diversity and Distributions* 10, 39–54.
- Pérez-Arteaga, A., Jackson, S., Carrera, E., Gaston, K.J., 2005. Priority sites for wildfowl conservation in Mexico. *Animal Conservation* 8, 41–50.
- Peterson, A.T., Holt, R.D., 2003. Niche differentiation in Mexican birds: using point occurrences to detect ecological innovation. *Ecology Letters* 6, 774–782.
- Peterson, A.T., Soberón, J., Sánchez-Cordero, V., 1999. Conservatism of ecological niches in evolutionary time. *Science* 285, 1265–1267.
- Rodrigues, A.S., Gaston, K.J., 2002. Optimisation in reserve selection procedures – why not? *Biological Conservation* 107, 123–129.
- Sánchez-Cordero, V., Martínez-Gallardo, R., 1998. Postdispersal fruit and seed removal by forest-dwelling rodents in a lowland rainforest in Mexico. *Journal of Tropical Ecology* 14, 139–151.
- Sánchez-Cordero, V., Munguía, M., Peterson, A.T., 2004. GIS-based predictive biogeography in the context of conservation. In: Lomolino, M., Heaney, L. (Eds.), *Frontiers in Biogeography*. Sinauer Press, Sunderland, MA, pp. 311–323.
- Sánchez-Cordero, V., Cirelli, V., Munguía, M., Sarkar, S., 2005a. Place prioritization for biodiversity representation using species' ecological niche modelling. *Biodiversity Informatics* 2, 11–23.
- Sánchez-Cordero, V., Illoldi-Rangel, P., Linaje, M., Sarkar, S., Peterson, A.T., 2005b. Deforestation and extant distributions of Mexican endemic mammals. *Biological Conservation* 126, 465–473.
- Sánchez-Rojas, G., Sánchez-Cordero, V., Briones, M., 2004. Effect of plant species, fruit density, and habitat on post-dispersal fruit and seed removal by spiny pocket mice (*Liomys pictus*, Heteromyidae) in a tropical dry forest in Mexico. *Studies on Neotropical Fauna and Environment* 39, 1–6.
- Sarkar, S., Margules, C., 2002. Operationalizing biodiversity for conservation planning. *Journal of Biosciences* 27, S299–S308.
- Sarkar, S., 2003. Conservation area networks. *Conservation and Society* 1, v–vii.
- Sarkar, S., 2005. *Biodiversity and Environmental Philosophy: An Introduction*. Cambridge University Press, New York.
- Sarkar, S., Garson, J., 2004. Multiple criterion synchronization (MCS) for conservation area network design: the use of non-dominated alternative sets. *Conservation and Society* 2, 433–448.
- Sarkar, S., Pappas, C., Garson, J., Aggarwal, A., Cameron, S., 2004. Place prioritization for biodiversity conservation using probabilistic surrogate distribution data. *Diversity and Distributions* 10, 125–133.
- Sarkar, S., Justus, J., Fuller, T., Kelley, C., Garson, J., Mayfield, M., 2005. Effectiveness of environmental surrogates for the selection of conservation area networks. *Conservation Biology* 19, 815–825.
- Siek, J., Lee, L.-Q., Lumsdaine, A., 2002. *The Boost Graph Library: User Guide and Reference Manual*. Addison-Wesley, Boston.
- Simberloff, D., Farr, J., Cox, J., Melman, D., 1992. Movement corridors – conservation bargains or poor investments? *Conservation Biology* 6, 493–504.
- Snyder, S.A., Haight, R.G., ReVelle, C.S., 2004. A scenario optimization model for dynamic reserve site selection. *Environmental Modeling and Assessment* 9, 179–187.
- Soberón, J., Peterson, A.T., 2004. Biodiversity informatics: managing and applying primary biodiversity data. *Philosophical Transactions of the Royal Society of London B* 359, 689–698.
- Stockwell, D.R.B., Peters, D., 1999. The GARP modelling system: problems and solutions to automated spatial prediction. *International Journal of Geographical Information Science* 13, 143–158.
- Stockwell, D.R.B., Peterson, A.T., 2002. Controlling bias in biodiversity data. In: Scott, J.M., Heglund, P.J., Morrison, M.L. (Eds.), *Predicting Species Occurrences: Issues of Scale and Accuracy*. Island Press, Washington, DC, pp. 537–546.
- Sutherland, G.D., Harestad, A.S., Price, K., Lertzman, K.P., 2000. Scaling of natal dispersal distances in terrestrial birds and mammals. *Conservation Ecology* 4, 16 [online] URL: <http://www.consecol.org/vol4/iss1/art16>.
- Syrjala, S.E., 1996. A statistical test for a difference between the spatial distributions of two populations. *Ecology* 77, 75–80.
- United States Geological Survey, 1998. GTOPO30 Global 30 Arc-second Digital Elevation Model. Reston: USGS. <http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html> (last accessed 9.12.05).
- Urban, D., Keitt, T., 2001. Landscape connectivity: a graph-theoretical perspective. *Ecology* 82, 1205–1218.
- Van Langevelde, F., Schotman, A., Claasen, F., Sparenburg, G., 2000. Competing land use in the reserve site selection problem. *Landscape Ecology* 15, 243–256.
- Velazquez, A., Mas, J.F., Diaz-Gallegos, J.R., Mayorga-Saucedo, R., Alcantara, P.C., Castro, R., Fernandez, T., Bocco, G., Escurra, E., Palacios, J.L., 2001. Patrones y tasas de cambio de uso de suelo en México. *Gaceta Ecológica Nueva Época* No. 62. Instituto Nacional de Ecología y Secretaría del Medio Ambiente y Recursos Naturales, México D.F., México.
- Velázquez, A., Bocco, G., Romero, F.J., Pérez-Vega, A., 2003. A landscape perspective on biodiversity conservation: the case of central Mexico. *Mountain Research and Development* 23, 240–246.
- Villa, B., Cervantes, F.A., 2003. *Los mamíferos de México*. Instituto de Biología, UNAM- Grupo Editorial Iberoamericana, México, D.F.
- Villaseñor, J.L., Ibarra-Manríquez, G., Meave, J.A., Ortiz, E., 2005. Higher taxa as surrogates for plant biodiversity in a megadiverse country. *Conservation Biology* 19, 232–238.

- Villers-Ruíz, L., Trejo-Vázquez, I., 1998. Climate change on Mexican forests and natural protected areas. *Global Environmental Change* 8, 141–157.
- Viirolainen, K.M., Virola, T., Suhonen, J., Kuitunen, M., Lammi, A., Siikamäki, P., 1999. Selecting networks of nature reserves: methods do affect the long-term outcome. *Proceedings of the Royal Society of London Series B-Biological Sciences* 266, 1141–1146.
- Williams, J.C., 1998. Delineating wildlife corridors with multiobjective programming. *Environmental Modeling and Assessment* 3, 77–86.