Area selection for conservation of Mexican mammals

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Abstract
Area selection for conservation of Mexican mammals.— Three sets of priority cells for mammal conservation in Mexico were identified using distributional data. A complementarity approach was implemented through linear integer programming. The minimum set of sites required for the representation of each mammal species varied between 38 (5.4%) grid cells for at least one occurrence, 110 (15.6%) grid cells for at least three occurrences, and 173 (24.5%) grid cells for at least five occurrences. The complementary analyses mainly highlighted three regions of particular concern for mammal conservation in Mexico: (i) the trans–Mexican Volcanic Belt and natural provinces of the Pacific Coast, (ii) Sierra Madre del Sur and the Highlands of Chiapas, and (iii) the northern portion of the Sierra Madre Occidental. The results reported here did not indicate absolute priority locations for conservation activities, but rather identified locations warranting further investigation at finer resolutions more appropriate to such activity.

Key words: Priority areas, Complementarity, Mammal conservation, Mexico.

Resumen
Selección de zonas para la conservación de mamíferos en México.— Mediante el uso de datos de distribución geográfica se pudieron identificar tres series de áreas prioritarias para la conservación de mamíferos en México. Se llevó a cabo un estudio de complementariedad mediante programación lineal entera. La cantidad mínima de series de áreas requeridas para la representación de cada especie de mamífero variaba entre 38 (5,4%) celdas para al menos una presencia, 110 (15,6%) celdas para al menos tres presencias, y 173 (24,5%) celdas para al menos cinco presencias. Los análisis de componentes principales destacaron tres regiones de una particular importancia en la conservación de los mamíferos en México: (i) el Eje Neovolcánico Transversal y las provincias naturales de la costa del Pacífico, (ii) la Sierra Madre del Sur y los Altos de Chiapas y (iii) la parte norte de la Sierra Madre Occidental. Los resultados del presente estudio no señalaron ninguna localidad con prioridad absoluta para las actividades de conservación, sino más bien identificaron las zonas que serían más apropiadas para llevar a cabo investigaciones futuras con una mayor resolución para proyectar acciones más concretas de conservación.

Palabras clave: Complementariedad, Conservación de mamíferos, México, Zonas prioritarias.

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Introduction

While the global protected area network for early 2003 comprises some 102,100 sites, covering 18.8 million km^2 (Chape et al., 2003), there is huge variation in the development in different countries. Of particular concern are the networks in the so–called "megadiversity" countries, in which the vast majority of the world's terrestrial and freshwater species reside (Mittermeier et al., 1999). Taken together, these countries contain over 50% of the global land area under protection. Nonetheless, there remain serious gaps in the protected area networks of megadiverse countries in their representation of ecosystems and for a considerable numbers of species (Mittermeier et al., 1999).

In Mexico, one of the most species–rich countries, more than 500 protected areas have been officially created since 1917, including one of the oldest such areas in the world (Desierto de los Leones National Park; Simonian, 1995). Together, these areas cover more than half the country's land area. Unfortunately, however, most of these areas no longer retain this protection status because of a lack of planning before they were created, unresolved land tenure issues, and lack of funds for management. Although close to 9% of the Mexican territory (154 protected areas) falls within the IUCN management categories only 53 of these 154 protected areas have designated management programs or policies for their use (CONANP, http://www.conanp.gob.mx [accessed May 2005]). Few studies have evaluated the effectiveness or efficiency of the existing national protected area network in terms of biodiversity protection (e.g. Cantú et al., 2004; Vázquez, 2005; Ceballos, 2007). Such studies have indicated that the present Mexican reserve network is inadequate to ensure the conservation of several important species and biodiversity features. Actions to increase the number of protected areas in the country are urgently required. This is particularly problematic because high levels of loss and fragmentation of natural habitat, human population growth, demand for agricultural land, and a scarcity of funding for conservation activities severely reduce opportunities to expand the existing protected area network in Mexico and consequently compromise the long–term maintenance of biodiversity (Vázquez & Gaston, 2006).

Recent efforts have been made to identify areas of high conservation value across Mexico (e.g. Arita et al., 1997; Ceballos et al., 1998; Villaseñor et al., 1998; Perez–Arteaga et al., 2005; Torres & Luna, 2006; Ceballos, 2007). The most important scheme, proposed in 1996 and 1999 by the National Commission for Knowledge and Use of Biodiversity (CONABIO), was a priority–setting initiative for terrestrial and marine regions, identifying conservation priorities based on the biological characteristics of specific areas. One hundred and fifty–one terrestrial and 70 marine regions were recognised throughout the country as priority areas for conservation of biodiversity (Arriaga et al., 2000). The terrestrial regions (covering 504,634 sq km) were defined according to natural features of the landscape, including topography, watersheds, soil, and vegetation types, together with the occurrence of certain key species. However, priorities were established on a site–by–site basis and not selected to function as a network.

To supplement this methodology, in this study we applied a systematic conservation planning approach (Margules & Pressey, 2000) to identify priority areas for mammal conservation in Mexico. To do this we employed principles of representation, complementarity and irreplaceability (Pressey et al., 1993), identifying sets of sites that, in combination, capture a minimal target representation of biodiversity features.

Mexican mammals are one of the best studied groups of organisms in Mexico. They make an interesting case study for several reasons: first, the taxonomy and distribution of Mexican mammals are relatively well known. Mexico is an internationally significant reservoir of mammal biodiversity due to its varied habitats, high species diversity and high degree of endemism (Arita & Ceballos, 1997). There are currently 525 species, of which 30% are endemic (Ceballos et al., 2002). Second, a large number of these species have extremely narrow distributions, 131 (31%) of all species occurring in areas of less than 114,000 sq km (Arita et al., 1997). Third, mammals are important economically and because of their emotional appeal and effects on ecosystems. Fourth, this group could serve as a model system on which to base initial policy and management decisions because some patterns of diversity and many problems of conservation can be generalised to other groups of organisms. Finally, they are the subject of legitimate conservation concern, because many species have gone extinct and many more are endangered.

Methods

Information on mammal distributions was obtained from an established data set on the distribution of 833 mammal species across North America compiled by the Mexican Commission on Biodiversity (Arita & Rodríguez–Tapia, 2004). Details of the method used to build the database are presented elsewhere (Arita et al., 1997), but briefly, range maps were drawn for all species, using as a starting point the maps of Hall (1981); these were scored at a spatial resolution of a half–degree, but information was updated with new taxonomic and distributional data published up to the end of 2002 (Reid, 1997; Wilson & Ruff, 1999; Ceballos et al., 2002). Presence data were referenced onto a grid of 823 half–degree cells. The size of each cells averaged 53.25 km on each side, corresponding to an area of 2,835.8 sq km. To avoid bias in terms of the contribution of coastal land–area to the complementary models, grid cells with less than 25% land–cover were omitted from the final dataset. For the purpose of this study, the analyses were restricted to land mammals, with introduced and insular species excluded. In consequence, a total of 423 mammal species were analysed within a grid of 705 cells (86% of total grid–cells).

Protected area data were obtained from the World Database on Protected Areas (WDPA Consortium,

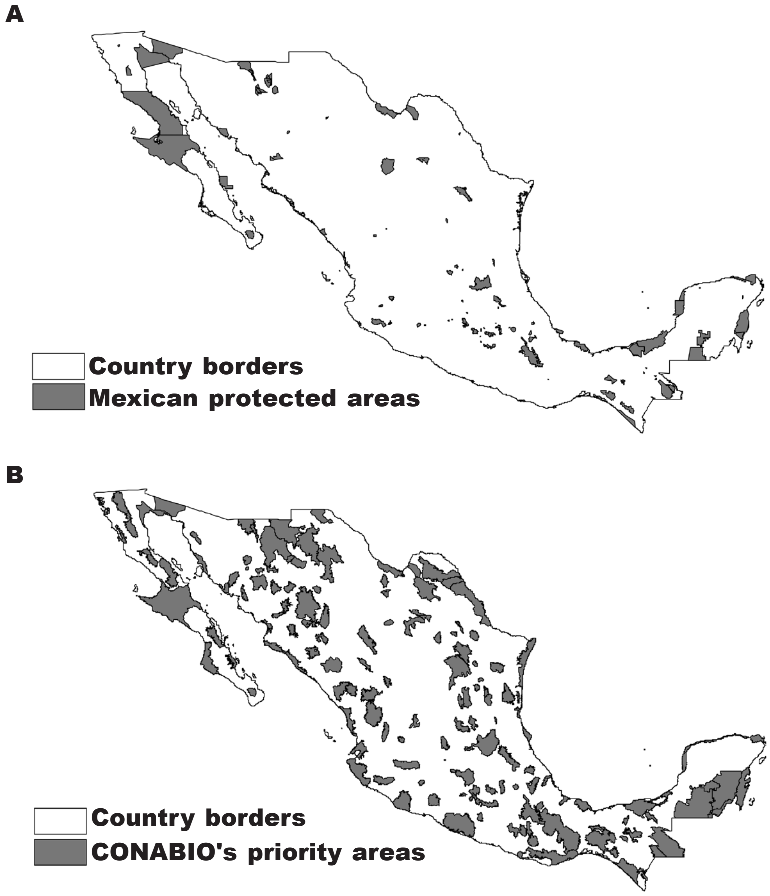

Fig. 1. Maps illustrating: A. Mexican protected areas; B. Priority areas proposed by CONABIO.

Fig. 1. Mapas que ilustran: A. Las zonas protegidas mexicanas ya existentes; B. Las zonas prioritarias propuestas por CONABIO.

2005). The geographical limits of proposed terrestrial protected areas were obtained from CONABIO (available at http://www.conabio.gob.mx). Information on the size and location of all current mainland protected areas and proposed protected areas were obtained throughout the country. All existing protected areas (until 2005) used in the analyses correspond to IUCN management categories I, II, IV and IX, these being strict nature reserves, national parks, managed nature reserve/wildlife sanctuaries, and biosphere reserves, respectively. Although category IX (Biosphere Reserve) is not commonly used in conservation assessments of this kind, because of the inclusion of human settlement and activities within such areas, we included this category because it has been shown that these areas play a role in the conservation of important biodiversity features in Mexico (Gómez–Pompa & Dirzo, 1995). Indeed, more than 60% of the protected land in the country falls under this category. We used protected area polygon data to calculate the percentage of each half–degree grid cell covered by these areas, using ArcView 3.2a (ESRI, 2000). Although protected areas are almost invariably smaller in extent than entire half–degree grid cells, this resolution can be useful to seek out areas in need of conservation attention (Larsen & Rahbek, 2003).

Data for 113 mainland protected areas and 151 proposed protected areas were available (fig. 1). The protected areas were located within 169 half–degree grid cells, each covering 0.2–100% of the respective grid cell area. Proposed protected areas were located within 416 grid cells. For the purpose of this study we considered that a cell was protected only if their surface covered ≥ 10% of its total area. For these grid cells, we assumed the protected area to have the same characteristics as the entire grid cell in which they reside.

Complementarity exercises usually use species ranges, often in grid–based spatial data, in their analyses (see Williams et al., 1996; Williams, 1996). Species ranges, however, are abstractions of where specimens are actually collected, often considering ecological continuity or its surrogates to extrapolate from known localities to unsampled areas (Brown et al., 1996). The data available for generating species ranges, and hence for conservation analyses, are necessarily incomplete (Kodric–Brown & Brown, 1993; Winker, 1996). Despite such limitations (see Rodrigues et al. 2003 for a discussion), we consider they do not reduce the importance of our study.

The principle of complementarity (Pressey et al., 1993) is an efficient way of representing particular biodiversity features in a set of sites. The complementarity approach used in this paper is a modified minimum set cover problem (Pressey et al., 1997; Pressey & Taffs, 2001). Originally developed for operations research, this mathematical priority area selection method aims to represent all natural features (e.g. species or habitats) a given number of times in the smallest possible area, fewest numbers of sites, or with the lowest overall cost (Rodrigues et al., 2000). The conservation importance of any individual area is, therefore, the extent to which it complements the others in a network of such areas, by contributing to the attainment of the conservation goals predefined for that network (Williams, 2001). Typically, analyses of this type have concentrated on the identification of the minimum set of sites required to represent all species at least once (e.g. Margules et al., 1988; Saetersdal et al., 1993; Pressey et al., 1997; Howard et al., 1998). However, for the present analysis, complementary networks were obtained to meet representation targets of 1, 3 and 5 grid cell occurrences of each species (where possible).

Throughout the study, optimal solutions were obtained using C–PLEX Linear Optimiser 7.1 software (ILOG, 2001). Given the numbers of species and areas included in the site–selection algorithms, multiple optimal solutions are inevitable (Arthur et al., 1997); we obtained 100 optimal solutions for each representation target. For each specific target, each time a solution was sought an additional constraint was added to the problem that excluded the solution previously found (Rodrigues et al., 2000). In this way, the optimisation algorithm finds another optimum solution (if it exists).

As an indicator of the overall contribution of a grid cell in achieving a desired conservation target, we calculated a measure of irreplaceability (Ferrier et al., 2000). We considered irreplaceability as the likelihood that the cell will be required as part of a conservation system that achieves the representation target (Pressey et al., 1994). The irreplaceability of a cell was measured as the percentage of all representative combinations of cells in which that cell occurs (Pressey et al., 1994), based on the frequency of the cell in the possible combinations within the 100 set solutions (Csuti et al., 1997). A cell that is 100% irreplaceable must be included within the set of priority cell if all targets are to be achieved (Ferrier et al., 2000). If an irreplaceable cell is not selected, one or more targets will not be attained unless a larger number of cells are selected, thus compromising the efficiency of the resulting set.

Additionally, we used the major vegetation types (fig. 2) and land use information (Dinerstein et al., 1995; SEMARNAT, 2000) to determine some biological and physical characteristics within the irreplaceable cells selected in the analyses. The percentage of each vegetation type was calculated for all irreplaceable cells obtained for the three representation targets explored.

Results and discussion

Patterns in the distribution of species richness for different subsets of mammals are illustrated in figure 3. The richness of all terrestrial mammals, including bats, peaked in southern Mexico, with high values following the distribution of tropical moist forest (fig. 3). Areas of lowest richness were found in the Baja California Peninsula and the Sonora Desert. Non–volant mammals showed a more dispersed richness pattern with a consistent trend towards greater species richness in southern highlands (fig. 3D). Endemic species were generally concentrated in areas with intermediate values of overall species richness (fig. 3B). The most endemic rich areas were along the trans–Mexican Volcanic Belt, the Pacific Coast and the Sierra Madre del Sur, while the most endemic–poor areas were in the Sonora and Chihuahua deserts and the eastern slopes of the Sierra Madre Oriental. Similar patterns are reported by other studies (Ceballos & Navarro, 1991; Ramírez–Pulido & Castro–Campillo, 1993; Fa & Morales, 1998; Escalante et al., 2002).

Complementarity analysis showed that the minimum set of sites required for the representation of each mammal species varied between 38 (5.4%) grid cells for at least one occurrence, 110 (15.6%) grid cells for at least three occurrences, and 173 (24.5%) grid cells for at least five occurrences. Ninety–three, 126 and 193 grid cells were identified within the 100 optimal solutions for the representation of each mammal species one, three and five times, respectively. Selected complementary cells were spread across the country. Generally, complementary cells for the three–representation scenario tended to cluster in the same regions, highlighting the conservation relevance of these areas (fig. 4). The first of these regions was located across central and western Mexico (Trans Volcanic Belt and Pacific Coast natural provinces). This region mainly consists of pine, pine–oak, and tropical dry forest. Some previous studies suggested that the region is centre of endemism for different taxa (Escalante et al., 1993; Flores–Villela, 1993). The region supports intermediate values of mammal species richness, high values of endemic species richness (fig. 3B), and have the highest concentration of rare endemic species (Ceballos et al., 1998; Escalante–Espinosa, 2003).

The second region of conservation priority was located in southern Mexico (Sierra Madre del Sur and the Highlands of Chiapas). For mammals, this was the most species–rich region in the country (fig. 3). Although this region is considered key for the conservation of Mexican tropical habitats, and also is

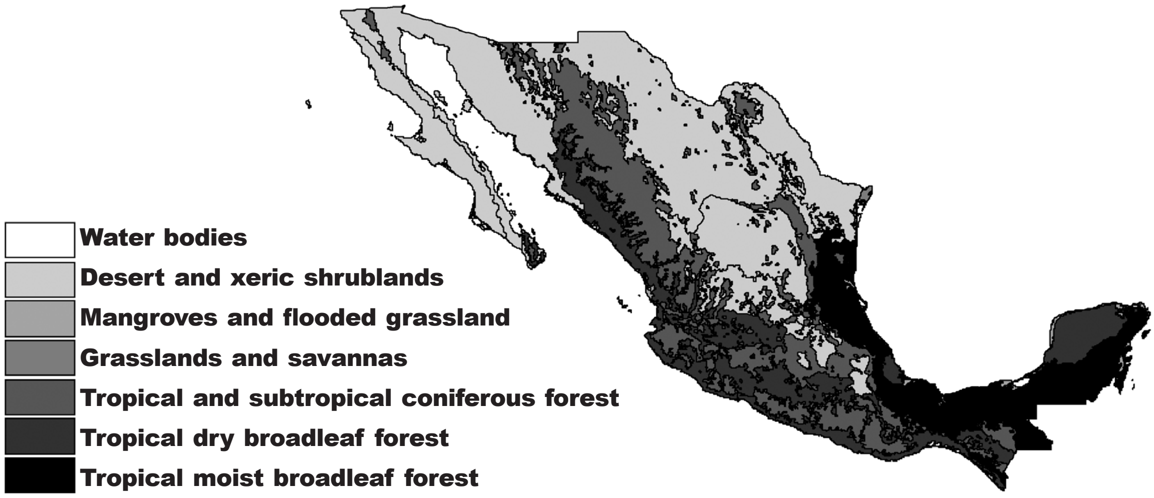

Fig. 2. Maps illustrating major vegetation types in Mexican protected areas (modified from Dinerstein et al., 1995).

Fig. 2. Mapas que ilustran los tipos principales de vegetación en las áreas protegidas de México (modificado a partir de Dinerstein et al., 1995).

recognised as an important hotspot (Mittermeier et al., 1999; Andelman & Willig, 2003), in this region the conservation status for all biodiversity is poor.

The third region corresponded to the northern arid and semi–arid lands and the northern portion of the Sierra Madre Occidental. These regions are generally characterised by the presence of xeric formations but temperate coniferous forest also occurs. Because of its high vulnerability and endemism, these regions are recognised as an important "wilderness" area with relevant conservation importance (Escalante–Espinosa, 2003; Mittermeier et al., 2003). However, this northern region is poorly represented within the national protected areas network (Riemann & Ezcurra, 2005).

Overall, protected areas and complementarity–cells presented a poor spatial–overlap. So that each mammal species was represented at least once, 19 (20.4%) and 59 (63.4%) of the complementary grid cells overlapped with CPA and TPA cells, respectively. At higher representation the coincidence between complementary sets and protected areas was similar. Twenty–two (17.5%) and 77 (61.1%) complementary cells overlapped with CPA and TPA cells, respectively, for the representation of each mammal species for at least three occurrences. For the representation of each species by at least five occurrences, 37 (19.7%) and 120 (62.2%) complementary cells contained some of the CPA and TPA sites, respectively.

Spatial congruence between protected areas and complementary cells was not consistently distributed across different regions of Mexico. Some regions showed a better overlap, which was also more evident for TPA protected areas (fig. 4). For example, in southern Mexico (Sierra Madre del Sur and Chiapas Highlands) between 85% and 90% of complementary cells overlapped with cells containing TPAs at the three representation scenarios analysed. In northern Mexico, complementary cells and protected areas overlapped poorly; only a single protected cell (containing Vizcaino Biosphere Reserve, in Baja California Peninsula, which is completely desert habitat) and 10 TPAs overlapped with complementary sites for the single–site scenario. For the scenario of at least three occurrences, four CPA cells and 18 TPA cells overlapped with the complementary sets, while 10 CPA cells and 22 TPA cells corresponded with complementary cells in the five–occurrence scenario.

A total of 173 irreplaceable cells (determined as grid cells with ≥ 90% of occurrence within 100 optimal solutions) were identified as priorities for mammal conservation across Mexico for the three conservation scenarios explored. For the target of one representation of each species, 17% of the total complementary grid cells showed high irreplaceability, accounting for nearly half of the minimum set of 38 cells required (figs. 4A–4B). The proportion of irreplaceable grid cells in the minimum set increased the higher the target representation (figs. 4C–4F). One hundred and four (ca. 94%) and 166 (96%) grid cells were irreplaceable for 3–unit and 5–unit scenarios, respectively.

To evaluate the potential use of the irreplaceable cells identified for conservation purposes, we examined predominant land–use practices. This study was based on the types of vegetation within these cells and how they matched the proposed priority areas for the conservation of biodiversity in Mexico (fig. 2).

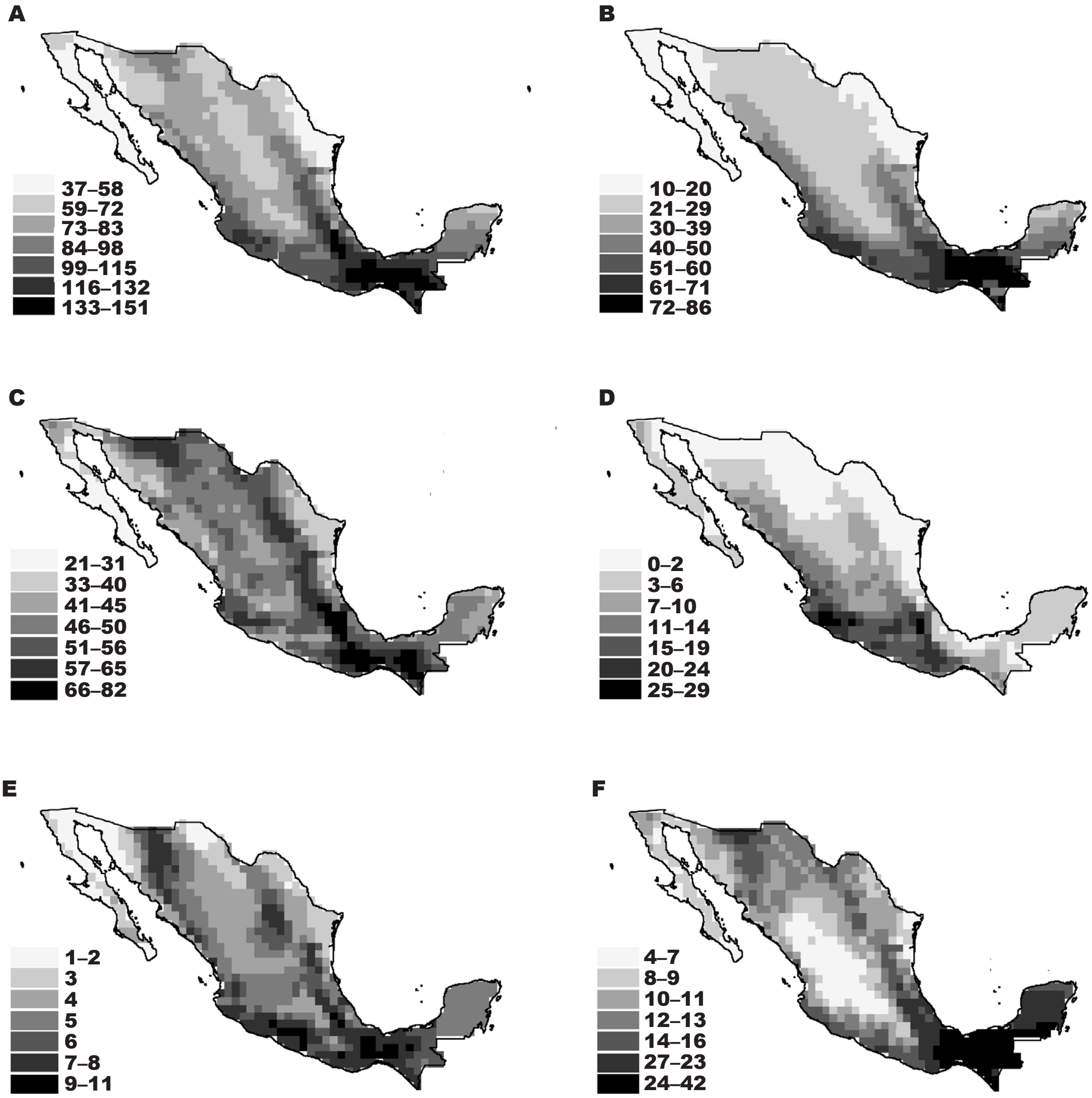

Fig. 3. Patterns of distribution of richness of: A. All mammal species; B. Endemic species; C. Bat species; D. Non–volant species; E. IUCN threatened species; F. Threatened species listed in the Mexican Red List.

Fig. 3. Patrones de distribución de riqueza de especies: A. Todas las especies de mamíferos; B. Las especies endémicas; C. Las especies de murciélagos; D. Las especies no voladoras; E. Especies amenazadas incluidas en la IUCN; F. Especies amenazadas incluidas en la NOM–059.

Irreplaceable cells (or priority sites) occurred within six terrestrial ecoregions present in Mexico (fig. 5). Thirty percent of the 173 priority sites corresponded to coniferous forests, followed by desert and xeric shrub–lands (27%), tropical dry–forest (24%), tropical moist forest (12.8%), mangroves (5.4%), and montane grasslands (0.71%). Overall, cells requiring conservation attention lay mostly in central Mexico, mainly across the Trans–Mexican Volcanic Belt, Mexican Plateau and the Oaxaca and Guerrero highlands regions, all regions characterised by intermediate values of mammal richness and high endemic species richness, and also considered to be the most populous areas in Mexico (Vázquez & Gaston, 2006). These results seem to concur with those of other studies, which highlights the fact that areas of importance to biodiversity are also very productive regions facing large human threats (Balmford et al.,

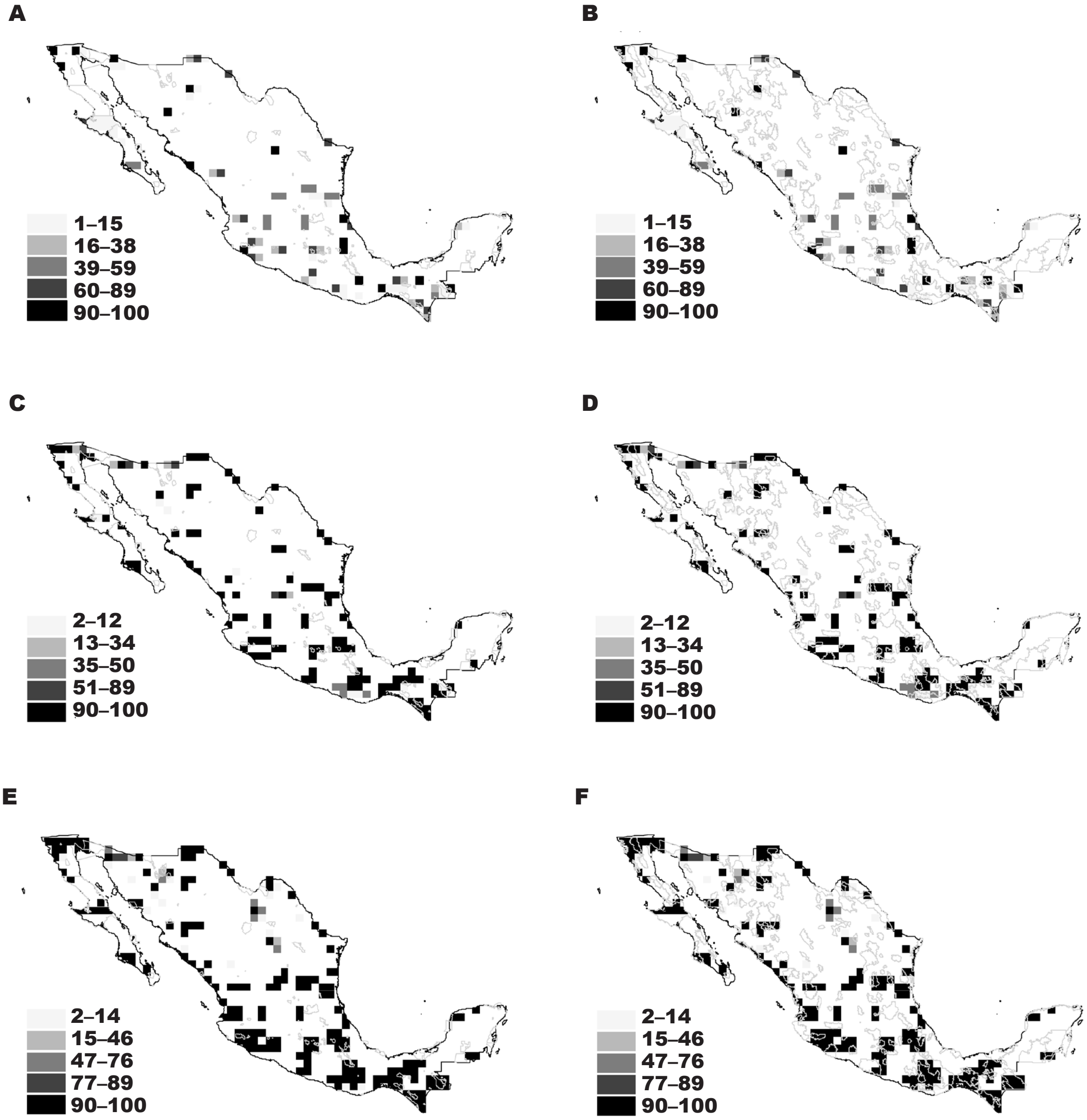

Fig. 4. Spatial location of all complementarity optimal solutions (100 complementary sets) obtained to the problem of finding the minimum number of sites which represents all species of mammals across Mexico: A–B. Each species at least once; C–D. Each species at least three times; E–F. Each species at least five times. Darkest squares are irreplaceable cells. Polygons represent: existing protected areas (CPA) in the left–hand column and CONABIO's Terrestrial Priority Areas (TPA) in the right–hand column.

Fig. 4. Localización espacial de todas las soluciones óptimas de complementariedad (100 series complementarias) obtenidas para hallar un número mínimo de lugares que representen a todas las especies de mamíferos de México: A–B. Cada especie al menos una vez; C–D. Cada especie al menos tres veces; E–F. Cada especie al menos cinco veces. Los cuadrados más oscuros representan células insustituibles. Los polígonos representan: las áreas protegidas ya existentes (CPA) en la columna de la izquierda, y las áreas terrestres prioritarias de CONABIO (TPA) en la columna de la derecha.

2001; Chown et al., 2003; Valenzuela–Galván et al., 2008). Another important area for high irreplaceability scores is in northern Mexico, characterised by desert and temperate forest ecoregions, supporting low and intermediate values of species richness and endemic species (fig. 4).

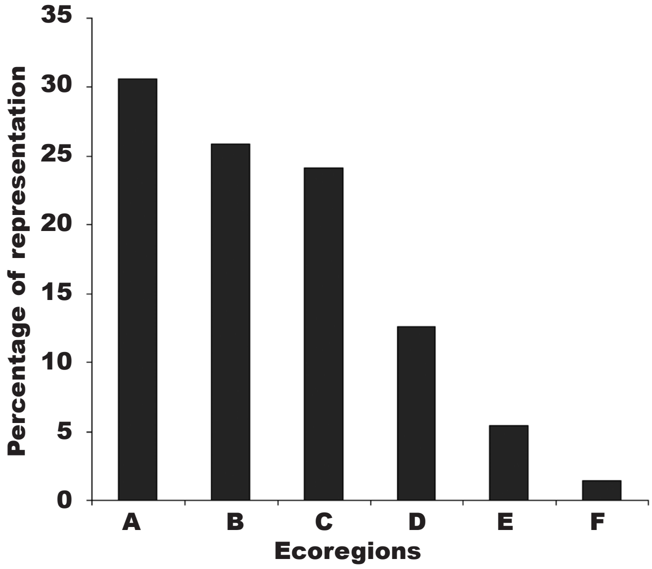

Fig. 5. Representation of ecoregions (modified from Dinerstein et al., 1995) within irreplaceable grid cells: A. Tropical and subtropical coniferous forest; B. Desert and xeric shrublands; C. Tropical dry broadleaf forest; D. Tropical moist broadleaf forest; E. Flooded grasslands; F. Grassland and savannas.

Fig. 5. Representación de las ecorregiones (modificado a partir de Dinerstein et al., 1995) de las celdas insustituibles: A. Bosques de coníferas tropicales y subtropicales; B. Desierto y matorral xerofítico; C. Selva tropical seca de hoja ancha; D. Selva tropical húmeda de hoja ancha; E. Praderas inundadas; F. Praderas y sabanas.

The spatial location of priority sites for the three– and five–occurrence representation scenarios occupied similar regions to those found in the complementary sets at the same representation targets (see above). The congruence between priority cells and CPA and TPA protected areas for all representation targets was variable.

For the single–occurrence conservation scenario, three and nine priority cells overlapped with cells containing CPA and TPA, respectively. One of the priority areas located in Southern Mexico (Chiapas) included three protected areas (Chankin, Lacan–Tún, and Montes Azules), all considered key conservation areas for Mexican tropical regions and considered internationally important as a hotspot (Andelman & Willig, 2003). Another two protected areas (Sierra de Manantlán Biosphere Reserve and La Malinche) are located along the Trans–Mexican Volcanic Belt covered mainly by coniferous forest and tropical dry–forest. Unfortunately, 75% of these priority cells do not include much of the currently designated reserve network. Indeed, only two cells selected included currently designated reserves, suggesting that the inclusion of other reserves would substantially raise the human population density included in the network.

Most agricultural and populated areas in Mexico are concentrated within or near priority areas. A recent study in Mexico found that an important number of small–size protected areas are located where the highest human population density also occurs (Vázquez & Gaston, 2006). The limited size of these protected areas, their progressive isolation because of constant agricultural expansion, and a high concentration of human population density in their surroundings are causes for concern (Parks & Harcourt, 2002).

We raise several some caveats in the interpretation of our results: (i) the distributional data used here are too general. The distributions of the species we used were based on the historical extent of occurrence maps. It is known that the distribution range of several species in Mexico decrease by more than 20% in relations to their historical ranges (Laliberte & Ripple, 2004). This kind of information tends to overestimate the real distribution of those mammal species with more complex distributional patterns. Naturally, any complementary process is affected by identity as well as number of species involved in the analytical process; consequently, results as shown here are affected, for example, by the way taxonomical criteria are used or the way in which the geographical distribution of each species is estimated. It is clear that new distribution maps are needed. (ii) The complementarity analysis we present here could be refined by adding other variables such as vegetative cover, estimation of real land costs or connectivity with other reserves (Balmford et al. 2000; Briers, 2002). Further refinement would be possible if species specific information were available, such as species density or abundance, the fraction of its population inside each planning unit, life history details or likelihood of persistence (Mace et al., 2007). (iii) Detection data used in our analyses does not account for possibly biases from non–detection of species, which may be heterogeneous over space and between species. A finer–scale analysis would require dealing with this issue, e.g., via occupancy analysis (MacKenzie et al., 2006).

Finally, the implementation of conservation strategies in the real world frequently implies much more than the proposal of an optimal set of areas to be protected. Final decisions should ideally be based on comparing alternatives and involving several institutions and individuals (Pressey et al., 1997).

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