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Methodological Approach to Identify Mexico's Terrestrial Priority Sites for Conservation

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Introduction

A significant proportion of the world's species and habitats is in danger of disappearing as human domination continues to gain pace; current rates of extinction are a thousand times higher than background rates throughout earth's life history (Pimm et al. 1995). One of the key strategies implemented by most countries to reduce or halt these trends has been the establishment of protected areas; nonetheless, existing systems of protected areas are seldom designed to conserve biodiversity systematically, and are often inadequate to represent the biodiversity of a given area (Pressey et al. 1994). The imminent declines in biodiversity have triggered considerable efforts to develop methods to select priority sites for conservation (Eken et al. 2004; Sarkar et al. 2006) and the adoption of national and international agreements. The Programme of Work on Protected Areas adopted by the Conference of Parties of the United Nations Convention on Biological Diversity, at its 7th meeting in Kuala Lumpur, Malaysia, in February 2004, is one such example. The aim is not simply to increase the number of protected areas but to ensure that, as far as possible, protected areas should be designed and located in the best places to conserve biodiversity (UNDP 2004). To fulfil these agreements Mexico decided to generate, with solid and technical criteria, an updated and complete assessment of conservation gaps of the protected areas network that will serve as a guide to expand the area comprised by protection decrees, as well as bringing into consideration other complementary instruments for conservation. The National Commission for the Knowledge and Use of Biodiversity (CONABIO), in collaboration with the National Protected Areas Commission (CONANP), several other institutions and specialists have conformed a working group (12 members of the executive group and 28 participants) that decided to broaden the context of this evaluation in a comprehensive manner, incorporating several approaches and spatial scales to identify priority sites for conservation of terrestrial biodiversity. One of the key goals was the identification of precise priority sites at a finer scale than previous prioritization exercises (ie. Mittermeier et al. 2004; Arriaga et al. 2000). In this paper we present the methodological framework used to identify priority sites for conservation of terrestrial vulnerable species and environments.

Methods

Data Sets

Species distribution maps were generated by expert-lead technical groups using the Genetic Algorithm for Rule-set Prediction (GARP; Stockwell and Peters 1999) at a spatial resolution of 1 km^2 (mammals: Ceballos, 2008; birds: Navarro-Sigüenza and Peterson 2007; amphibians and reptiles: Ochoa-Ochoa and Flores-Villela 2006, Flores-Villela 2008; plants in the Mexican red list: CONABIO, unpub. data). GARP is a robust tool that has been successfully tested and used in various fields of research mainly because of its power to extrapolate into unsampled areas, a quality needed when species' ecological niches are reconstructed from incomplete occurrence data (Illoldi-Rangel et al. 2004; Papes and Gaubert 2007) as is the case of many Mexican data sets, while inventory completeness varies greatly across regions and taxa (Ochoa-Ochoa and Flores-Villela 2006; Soberón et al. 2007). In consequence, to assess the conservation status of a great number of species at a national scale, the use of an algorithm like GARP was preferred for its ability to extrapolate into broad unsampled areas (Peterson et al. 2007).

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Species geographical distributions were constructed from raw occurrence data obtained from the National Biodiversity Information System (SNIB, CONABIO), the Atlas of Mexican Bird Distributions and The World Information Network on Biodiversity (REMIB). For birds, maps were generated for 936 species, according to the American Ornithologists' Union taxonomy (1998) using 453,540 georeferenced data points. For more information on how these niche models were generated see Nakazawa et al. (2004) and Peterson et al. (2006); see Navarro et al. (2003) for more information on the Atlas of Mexican Bird Distributions. Models for 1,012 amphibians and reptiles species were generated using 181,191 validated georeferenced data points. Species geographic and taxonomic validation followed (Flores-Villela 1993a, 1993b; Flores-Villela and Canseco-Márquez 2004; Frost et al. 2006). Species with more than 10 records were modeled following the "best subsets" procedure using half of the points to build the model and the other half to test the predictive ability, for less than 10 records a soft omission threshold was used. A minimum of five records were used to model the species potential distribution. For more information see Flores-Villela (2008). Ecological niche models for mammals were generated for 213 species, using 37,070 validated georeferenced data points. For plant species in the Mexican red list, 245 models were generated using a database containing 7,709 validated georeferenced data points; models were generated with a minimum of eight data points. Modeling followed similar procedures as the groups previously mentioned.

In all cases environmental data sets (raster GIS data layers) known to affect taxa distributions in Mexico were assembled. Data layers included climatic variables from WORLDCLIM (Hijmans et. al 2008), topographic and hydrologic parameters from Hydro1k (Earth Resources Observation and Science 2008) in addition to thematic national data sets from National Institute of Statistics, Geography and Informatics (INEGI) and CONABIO. Ecological niche models summarize species potential distribution, and as such do not include the effects of historical constraints and limitations on dispersal abilities on species distributions (Soberón and Peterson 2005). To obtain estimates of actual species distribution, all GARP results for vertebrates were edited by experts on Mexican taxa distributions (mammals: Ceballos 2008; birds: Navarro-Sigüenza 2008 and Peterson 2007; amphibians and reptiles: Flores-Villela 2008). Distributions were trimmed with expert knowledge on the species biogeography, the aid of available, coarse-scale range maps (Howell and Webb, 1995, for birds; Ceballos and Oliva, 2005, for mammals) and regionalization maps (e.g. ecoregions). For more information see Navarro and Peterson (2008) and Flores-Villela (2008).

The vast number of plant species and the lack of expert knowledge for most plant groups hindered use of distribution maps for plant species (except species included in the Mexican red list). Moreover, the completeness of sampling is far better at the family and genera level than at the species level (Soberón et al. 2007). Therefore the phanerogamic flora was included using species records of several families (*Asteraceae, Cactaceae, Euphorbiaceae, Poaceae*) and other genera (*Pinus, Quercus*) obtained from the SNIB and REMIB biological database which were then generalized at a higher taxonomic level by means of an index that considers both the number of species and their geographic distribution. This index was constructed by assigning weights to species within a family or genera (*Pinus, Quercus)* using the following formula:

$$Weight_{spi} = \square(NumPU_{sp} x(-k) + \square MaxPUxk + 1) \quad , \qquad (1)$$

where

$Weight_{spi}$ is an integer,

$NumPU_{sp}$ is the number of planning units in which the species in question is present,

$MaxPU$ is the number of planning units in which the most widely distributed species is present, and

k is a constant obtained by dividing 22/MaxPU.

MaxPU was divided by 22 to normalize the scale. Total weights and weights within a planning unit for each family or genera were obtained as follows:

Σ $weight_{spi}$, where $weight_{spi}$ is the weight of the *i*th species. (2)

Land use and extent of vegetation types of Mexico were obtained from the INEGI vegetation and land use chart (INEGI 2005a). This map, scaled 1:250,000, is based on Landsat ETM+ satellite imagery interpretation with additional field validation. The map was also used to generate various GIS products and layers related to land use change, fragmentation, loss of habitat, and agricultural activities. In addition, social factors such as population growth (INEGI 1990, 2005b) and size (inhabitants for towns and area for cities) of georeferenced population clusters were derived from official census data (INEGI 2005b). A relatively novel approach was the use of heat points time series as a surrogate for wildfires. For this, a summary of heat points, generated on a daily basis from satellite imagery from 1999 to 2005, was used (CONABIO 2006). Finally, infrastructure like paved highways and dirt roads were incorporated from digital maps (IMT 2001).

Place Prioritization for Biodiversity Conservation

Five expert workshops took place during 2005 and 2006 with the purpose of discussing and defining the criteria to implement prioritization algorithms. Central to the analysis is the size of the planning units, which need to match the available data. The size was set at 256 km^2 (8,045 hexagons) placing a balance between the scale of the input data and computational time.

The identification of priority sites was carried out based on biological variables, and on pressure factors using the simulated annealing algorithm in the marxan software (Ball and Possingham 2000) . The program was run with 1,000,000 iterations and 10,000 runs using the adaptive annealing schedule with normal iterative improvement at the end of each run (Cook and Auster 2005; Chan et al. 2006). The type of data and criteria used in the process of assigning conservation goals to biodiversity elements and cost values to represent pressure factors follow methodology suggested by Groves et al. (2000), Ball and Possingham (2000) and Ulloa et al. (2006).

Biological Data

A total of 2,546 layers were considered, but only 1,450 were selected for the analysis after considering different attributes of their distribution and endangerment status (Tables 1 and 2). The final data set considered plant and vertebrate species, vegetation types, records of phanerogamic flora, and high diversity areas. For terrestrial vertebrates and plants recorded in the Mexican red list, goals were based on different criteria such as the degree of rarity (using as a threshold the last quartile of the geographic distribution range of each taxonomic group), endemism, extinction risk status in the Mexican red list (NOM-059-SEMARNAT-2001) and international red list (IUCN) and pressure from international commerce (CITES). Values assigned to each conservation criteria (Table 2) were summed to obtain the percentage target as follows: 5 percent (∑ = 1–21); 10 percent (41–22); 30 percent (42–63); 40 percent (64–85). Goals for natural and seminatural vegetation were established according to its coverage following criteria described in Table 3a and 3b. For example vegetation types with a critical low coverage of less than 0.75 percent of the national territory (e.g. cloud forests, tall evergreen forest, dry coastal scrub) were assigned the highest conservation goals of 99 percent. The desired conservation goals were expressed in terms of the percentage of geographic range size within the country held by biodiversity elements in relation to the extension of the national territory and goals ranged from 5–99 percent.

Table 1. Selected biodiversity elements to identify terrestrial priority sites.

[**Abbreviations**: SNIB, National Biodiversity Information System; REMIB, The World Information Network on Biodiversity; INEGI, National Institute of Statistics, Geography and Informatics]

Biodiversity elements	Layers	Source of information
Species		
Amphibians	208	Distribution maps
Reptiles	424	Distribution maps
Birds	273	Distribution maps
Mammals	242	Distribution maps
Plant species (Mexican Red list, NOM-059-SEMARNAT-2001)	214	Distribution maps
Plant families	12	SNIB and REMIB records
Natural and seminatural vegetation	68	INEGI (2005), land cover map
Species richness	9	Sum of distribution maps (one-half of the total area with the highest species richness)
Total	**1,450**	

Table 2. Example of conservation goals allocation according to biodiversity criteria values.

[**Abbreviations**: IUCN, international red list; E, possibly extinct in the wild; P, at risk of extinction; A, threatened; Pr, subject to special protection; Cr, critically endangered; En, endangered; Vu,vulnerable. Biodiversity criteria values are shown on the table heading]

	Endemicity	Rarity	Red list	IUCN red list	CITES	Total	Percent goal
	Yes/No 20/0	(Fourth quartile divided in four) 4, 3, 2, 1 20/16/13/10	(NOM-059) E, P, A, Pr 25/25/15/0	Cr/En/Vu 15/10/5	I/II 10/5		
Species 1	20	10	25	5	5	65	40
Species 2	20	0	0	0	5	25	10

Table 3a. Criteria and goal values for natural vegetation types.

[**Abbreviations**: <, less than; >, greater than]

Primary vegetation types or second-growth for vegetation types lacking coverage of primary vegetation	
Mexico's country area (percent)	**Conservation goals (percent)**
<0.75	99
0.75–1.0	70
1.0–2.0	40
2.1–5	20
>5	5

Table 3b. Criteria and goal values for seminatural vegetation types.

[**Percentage of Mexico's country area**: Coverage of second-growth and primary vegetation were summed. **Abbreviations**: <, less than; >, greater than]

Second-growth vegetation	
Mexico's country area (percent)	**Conservation goals (percent)**
<1.1	90
1.0–1.4	60
1.5–2.5	30
>2.6	10

Goals for the phanerogamic flora were set at 25 percent of total families and genera weight (see data set), this percentage was defined by experts criteria during workshops.

Finally, two additional biodiversity elements were considered in the analyses, indicating areas with elevated species richness and areas with a high diversity of endemic species, inferred from the accumulation of distribution model maps by taxonomic group. Conservation goals were assigned for each vertebrate group, depending on the area of coverage of each layer; goals ranged from 5 to 50 percent.

Pressure Factors

Threats to biodiversity were selected based on known impacts on ecological systems, communities and to flora and fauna species. The aim was to use high quality data to characterize pressure factors in order to select sites that could still be valuable to invest in conservation or restoration. The data used by the prioritization algorithm for representing threats is often referred as costs, following the logic that areas suffering from negative impacts are more difficult to protect and require higher conservation investment. Cost information is used to distribute conservation priorities to sites amenable to long-term persistence of conservation features (Chan et al. 2006).

After defining different pressure factors and specifying data availability for representing them in planning units, 19 threat layers were hierarchically grouped, based on the magnitude of their negative impact on biodiversity. The next step consisted in assigning weights to each layer in accordance to its hierarchical level; weights then were used to calculate final cost of each parameter (Table 4). It is well known that land use change is the main driver of biodiversity loss (Sala et al. 2000). Therefore, variables related to habitat loss, deterioration and fragmentation were assigned highest values. Lower values were assigned to dynamic social processes (population growth, recently established settlements) and to infrastructure such as roads, which produces habitat fragmentation and also increases human accessibility for hunting and extraction of other non-timber and timber products (Wilkie et al. 2000). Next in the hierarchical list is the area covered by shrubby and herbaceous secondary vegetation. It was considered important to include secondary vegetation in an early state of succession as a pressure factor, even though some arboreous secondary vegetation types were considered as conservation goals, following the logic that a recent disturbance is thought to indicate an increased human pressure over the area which will result in frequent future disturbances, and thus in lower biodiversity after the intermediate disturbance hypothesis (Connell 1978). Other variables (cities and localities) related to resource overexploitation and pollution represent the end of the hierarchical list. The final cost for each planning unit was obtained by summing up the different weighted values of pressure factors.

Once the algorithm was supplied with the different input data and results were obtained, the terrestrial priority sites were classified into three categories based on the selection frequency performed by the optimisation program. The selection frequency of a planning unit provides a fundamental measure of conservation value for the unit (Stewart et al. 2007) indicating its relative importance to meet given targets. Planning units included in all the marxan solutions are considered irreplaceable, and thus were designated as high priority sites. We ran two site selection scenarios in marxan, the first with goal values as defined in experts workshops, the second was run reducing goals for vegetation types by 20 percent in order to redefine high priority sites as these irreplaceable planning units occupied a large proportion of the country's area in the first run (16.6 percent). The irreplaceability of these units was given in part by high conservation goals (99 percent) given to critical fragmented vegetation types. Irreplaceable planning units in the first and second conservation scenarios were designated as extreme priority sites, irreplaceable planning units in the first scenario were designated as high priority sites, and planning units selected 90–99 percent of all runs in the first scenario were designated as medium priority sites.

Table 4. Allocation of threat values in planning units.

[**Abbreviations**: FAO, Food and Agriculture Organization; x, multiplied by; INEGI, National Institute of Statistics, Geography and Informatics; ha, hectare; CONABIO, Comisión Nacional para el Conocimiento y Uso de la Biodiversidad; #, number; m, meter; IMT, Instituto Mexicano del Transporte ; <, less than; >, greater than]

Threat layer	Calculation	Weight	Data type	Data source
Rate of primary vegetation loss	Rate of land use change for primary vegetation (FAO, 1996) x weight[1]	10, 000	Land use change: destruction of habitat and fragmentation	Land use and cover maps, INEGI 1993, 2005a.
Fragmentation in primary vegetation	Area-perimeter index (Fragstats)[2]	8300	Land use change: fragmentation	Land use and cover map, INEGI 2005.
Secondary vegetation, shrubs	Area (ha) x weight	100	Land use change: destruction of habitat and fragmentation	Land use and cover map, INEGI 2005.
Secondary vegetation, herbaceous	Area (ha) x weight	200	Land use change: destruction of habitat and fragmentation	Land use and cover map, INEGI 2005.
Heat points 2 from satellite images	Area (ha) x weight[3]	7500	Land use change: destruction of habitat and fragmentation	CONABIO 2006.
High impact cattle (goats and lambs)	# points x weight	6700	Livestock farming: destruction of habitat and fragmentation	Land use and cover map, INEGI 2005.
Low impact cattle (bovine and equine)	# points x weight	6100	Livestock farming: destruction of habitat and fragmentation	Land use and cover map, INEGI 2005.
Introduced and cultivated grasslands	Area (ha) x weight	6000	Livestock farming: destruction of habitat and fragmentation	Land use and cover map, INEGI 2005.
Irrigation agriculture	Area (ha) x weight	5800	Agriculture: destruction of habitat and fragmentation	Land use and cover map, INEGI 2005.
Seasonal agriculture	Area (ha) x weight	4000	Agriculture: destruction of habitat and fragmentation	Land use and cover map, INEGI 2005.
Road density (paved roads)	Longitude (m) x weight	3000	Infrastructure: fragmentation and accessibility	IMT 2001.
Road density (unpaved roads)	Longitude (m) x weight	2000	Infrastructure: fragmentation and accessibility	IMT 200.
New localities	# points x weight	1000	Demography and settlements (dynamic): Increased use of natural resources and destruction of habitat and fragmentation	Census data, INEGI 2002.
Population growth (1990-2005)	Rate of geometric population growth x weight	900	Demography and settlements (dynamic): Increased use of natural resources and destruction of habitat and fragmentation	Census data, INEGI 1990, 1995, 2000, 2005.
Localities <1000 inhabitants	# points x weight	10	Increased use of resources and contamination	Census data, INEGI 2002.
Localities 1000–10,000 inhabitants	# points x weight	20	Increased use of resources and contamination	Census data, INEGI 2002.
Localities 10,000–100,000 inhabitants	# points x weight	30	Increased use of resources and contamination	Census data, INEGI 2002.
Localities 100,000–200, 000 inhabitants	# points x weight	40	Increased use of resources and contamination	Census data, INEGI 2002.
Localities > 200, 000	Area (ha) x weight	50	Increased use of resources and contamination	Extract of topographic map 1:250,000, INEGI unknown year.

[1] Only negative values were considered, multiplied by –100 to obtain meaningful positive values.

[2] Mean value per vegetation type was calculated. For each hexagon the maximum value was taken.

[3] Heat points represent the threat of potential wildfires.

Results and Discussion

Conservation of Mexico's extraordinary biodiversity is a great challenge, in particular given spatial patterns of biodiversity and current trends of land use change, habitat degradation, and human population growth (Palacio-Prieto et al. 2000; INEGI 2007). Although it is impossible to represent adequately the full range of biodiversity in a given region or country (Rondinini and Boitani 2006; Sarkar et al. 2006), this study represents a big step towards better identifying conservation gaps in Mexican terrestrial biodiversity. It considered the largest amount of information on Mexican biodiversity which comprises a wide range of biodiversity surrogates including nationally and globally threatened species, restricted-range species (criteria proposed to identify key biodiversity areas, Eken et al. 2004) and habitats (e.g. primary vegetation) that might serve as umbrella to represent a great number of other plant and animal species and to consider important ecological services.

Terrestrial priority sites for conservation detected in the optimisation analysis (Figure 1) cover 594,894 km^2; extreme priority sites (SE) cover 2.18 percent of the continental area, the percentage increases to 16.6 percent of the territory and to 30.6 percent when the sites of high priority (SA) and of high and medium priority (SM) are respectively considered. For more information see CONABIO-CONANP-TNC-Pronatura-FCF, UANL (2007). Currently, protected areas of México cover about 12 percent of the country's continental surface; nevertheless, the existing nature reserve network falls short of effectively representing Mexican terrestrial biodiversity. Only 12.9 percent of priority sites surface is under protection of federal, state and municipal nature reserves (3.91 percent of the country's continental territory). Previous studies have also demonstrated that nature reserves alone are insufficient to protect biodiversity (Brandon et al. 2005; Cantú et al. 2004; see Ceballos 2007; Ortega-Huerta and Peterson 2004). On the whole, protection of 10–12 percent of the land, promoted in the past as a target to be achieved (IUCN 1993) has been proven insufficient to protect biodiversity for a region or a country (Rodrigues et al. 2004; Rondinini and Boitani 2006), and particularly for biodiversity rich countries such as México.

Conservation goals could not be met for all the species and habitat targets; extreme priority sites alone were able to meet conservation goals for 34.9 percent of all the biodiversity elements. When also considering high priority sites, conservations goals were met for 81.2 percent of all the biodiversity elements. In spite of increasing the priority area by twofold when adding the medium priority sites, conservation goals were met for only 90.5 percent of all species and habitat targets. Targets were met with the "best solution" given by the optimisation software; however, this area covers 43 percent of Mexico, which clearly does not help to set conservation priorities. It is therefore not possible to attain the goals for all the biodiversity elements in a reduced area of the country, a fact that reflects the high level of heterogeneity that characterizes Mexico as a megadiverse country.

To represent effectively a larger number of biodiversity elements, extreme and high priority sites should be ideally destined for conservation but it will not be possible to cover these gaps only with protected areas. It is indispensable to have a sustainable management outside the protected areas. New protected areas and other mechanisms for conservation should be preferably determined by a multi-stakeholder process; researchers, technical experts, and other sectors of society should assess priority areas at other scales (i.e. regional, local) in order to promote local conservation actions integrating social data and planning opportunities, so as to effectively address the limited conservation resources. Some successful examples of local and regional conservation actions by organized communities are promising (Ramos-Fernández et al. 2005; Luján-Alvarez et al. 2000; Durán-Medina et al. 2007) for the conservation and sustainable use of biodiversity if adopted throughout the country. Such examples demonstrate that providing alternative sources of income that promote human well-being and biodiversity conservation are essential in order to conserve Mexico's great natural capital on the long term.

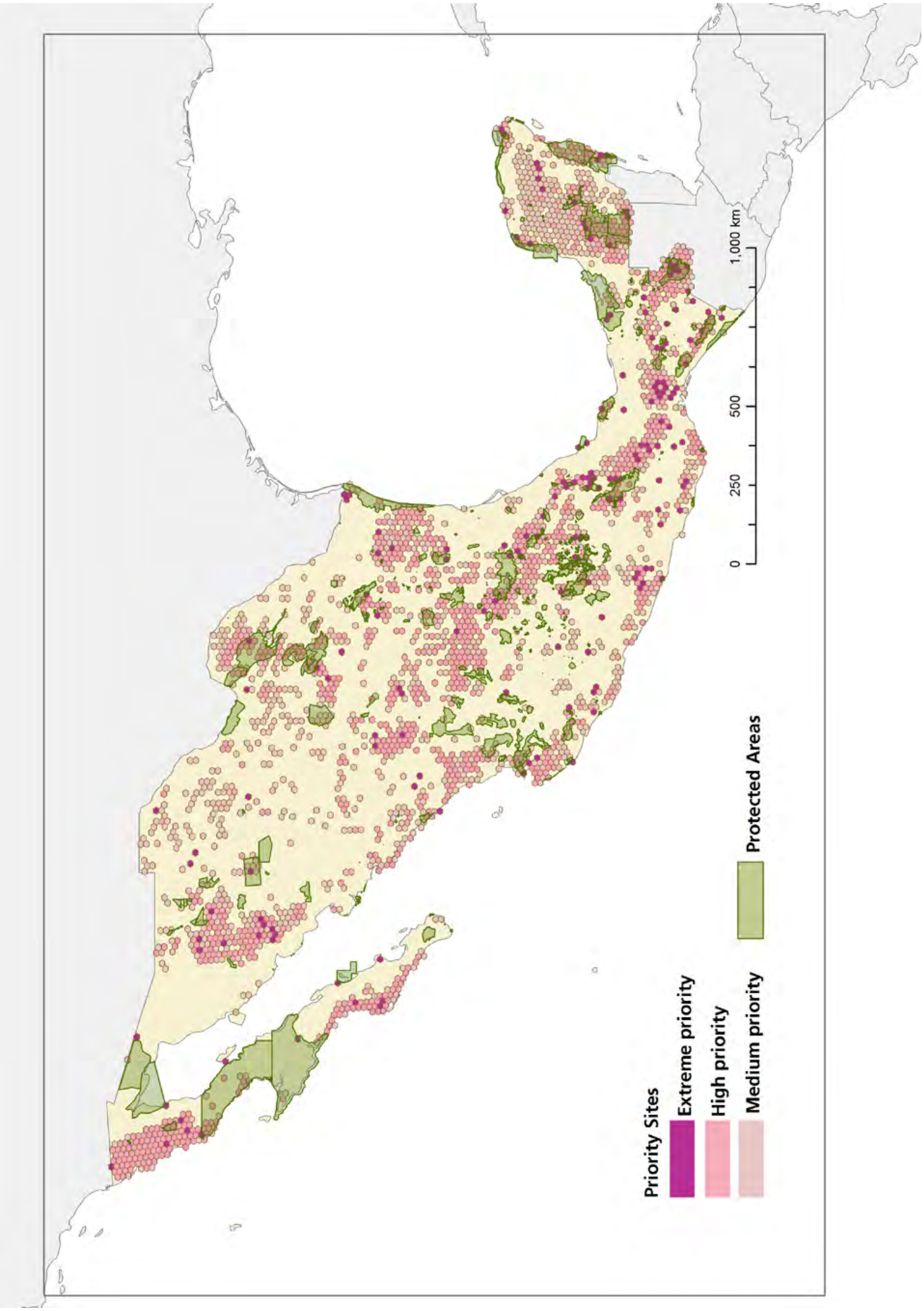

Figure 1. Priority sites and protected areas in Mexico.

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