Biodivers Conserv (2007) 16:1885–1900
DOI 10.1007/s10531-006-9091-0

ORIGINAL PAPER

Ecological niche modeling and geographic distribution of the genus *Polianthes* L. (Agavaceae) in Mexico: using niche modeling to improve assessments of risk status

Eloy Solano · T. Patricia Feria

Received: 16 November 2005 / Accepted: 7 July 2006 / Published online: 29 November 2006

Abstract The genus *Polianthes* (Agavaceae) is endemic to Mexico and is important at the scientific, economical, and cultural level since prehispanic times. Habitat destruction is one of the main factors affecting populations of *Polianthes* species, yet little is known about the geographic distribution of this genus, and thus its vulnerability to habitat change. We compared three different approaches to measure the *Polianthes* species area of distribution to assess the risk of species extinction applying the MER (Method of Evaluation of Risk extinction of wild species for Mexico): area of occupancy, extent of occurrence, and ecological modeling. We also found the richness areas of distribution of this genus. We compared the species distributions with Terrestrial Protected Regions (TPR) and Natural Protected Areas (NPA). Although the three methods used to calculate the species area of distribution agree about the highly restricted nature of *Polianthes* species. The area of occupancy sub-estimate the species distribution, while the extent of occurrence over-estimate it for species with disjoint distribution. Thus, we recommend the use of ecological modeling to improve the assessment of the current species distribution area to apply the MER. Most *Polianthes* species are distributed in the Sierra Madre Occidental and Transvolcanic Belt. Three species do not occur in any of the NPA or TPR, one species has suitable habitat in three TPR but has not been recorded there, and one species, *P. palustris*, is likely extinct.

Keywords Agavaceae · Area of occupancy · Conservation · Distribution · Extent of occurrence · Ecological niche · Endemism · Genetic algorithm · MER · *Polianthes*

E. Solano (✉)
Herbario FEZA, Facultad de Estudios Superiores Zaragoza, UNAM,
AP 9-020, Mexico D. F., Mexico
e-mail: solanoec@correo.unam.mx

T. P. Feria
Department of Biology, University of Missouri-St. Louis, St. Louis, MO 63121, USA

Introduction

The genus *Polianthes* (Agavaceae) is endemic to Mexico, and includes 14 species, three varieties, and two cultivars (Solano 2000). Most species in this genus are used for ornamental and ceremonial purposes. The best-known taxon is *Polianthes tuberosa*, which has been cultivated and used for medicinal, ornamental, and ceremonial practices since prehispanic times. Other species (e.g. *P. bicolor*, *P. geminiflora*, *P. longiflora*) are important for their medicinal properties (Solano 2000). To date, however, there have been few attempts to determine geographic distributions at fine scales or to evaluate the conservation status of *Polianthes* species, despite the fact that habitat destruction has been identified as one of the main factors affecting populations of these species in Mexico (García-Mendoza 1995, 2004; IUCN 1997), where the rate of habitat alteration has been high (Mas et al. 2004). Furthermore, since this is an endemic genus, documenting the areas of high species richness of *Polianthes* will help to measure the conservation significance (Brooks et al. 2002) of the protected areas already established in Mexico.

Species of *Polianthes* have been recorded in 18 Mexican states, where most occur in pine forest, oak forest, or pine-oak forest, some in grasslands, and a few in tropical dry or semideciduous forests (Solano 2000). Five species (*Polianthes densiflora*, *P. howardii*, *P. longiflora*, *P. palustris*, and *P. platyphylla*) are listed as rare by the IUCN (IUCN 1997) and are considered to be in the category of special protection according to Mexican law (SEMARNAT 2002). The geographical distribution of a species is one of the main criteria required for the Mexican government to evaluate the risk of species extinction applying the MER (Method of Evaluation of Risk extinction of wild species for Mexico; SEMARNAT 2002). Therefore, understanding the distribution of species, and thus is imperative to establish their species conservation status in Mexico.

Environmental variables are frequently used to estimate species' distributions (Austin 2002) because survival and reproduction can occur only within a certain range of environmental conditions, the species' ecological niche (Brown et al. 1996). Using species' occurrence data and environmental variables, GIS technology can be used to model and visualize the ecological niche using a variety of different algorithms (reviewed by Guisan and Zimmermann 2000; Elith et al. 2006) and to predict species' distributions by projecting a model of the ecological niche onto geographic space GARP (Genetic Algorithm for Rule set Production) has seen particularly strong statistical support for its predictive abilities under diverse conditions (Feria and Peterson 2002; Illoldi-Rangel et al. 2004; Martínez-Meyer et al. 2004; Nakazawa et al. 2004; Peterson and Cohoon 1999; Peterson 2001; Peterson and Vieglais 2001; Peterson et al. 2002a; Raxworthy et al. 2003; Stockwell and Peterson 2002, 2003; but see Elit et al. 2006).

Maps obtained using GARP have been interpreted as maps of the potential distribution of a species (Anderson and Martínez-Meyer 2004). A more realistic distribution is obtained by matching the predicted distribution based on the ecological niche with those geographic features (i.e., basins, drainages, ecoregions) where the species has been recorded (Soberón and Peterson 2005) and overlaying these maps with a map of current land use (Ortega-Huerta and Peterson 2004; Sánchez-Cordero et al. 2005a). The current area of distribution can then be calculated considering the number of grid cells where the species has been predicted to occur, converting those grids to an equal area projection.

The reliability of extinction risk assessments is often compromised by biases in collection data, particularly for species with very few collections or disjoint distributions. As a consequence of the sparseness of collections, calculating the area of occupancy by counting the number of cells occupied by each species tends to underestimate the species' true distribution whereas calculating the extent of occurrence based on the minimum convex polygon defined by all known localities typically overestimates the area occupied. In comparison to these approaches, maps of species' distributions derived from SDM are superior for conservation planning because they allow distinguishing suitable and unsuitable environments for populations within the extent of occurrence. Therefore, we propose to follow the use of ecological niche models to estimate a more realistic assessment of the area of distribution of the species (Anderson and Martínez-Meyer 2004; Ortega-Huerta and Peterson 2004; Peterson et al. 2002b; Sánchez-Cordero et al. 2005a; Soberón and Peterson 2005) and thus more objectively assign risk status based on MER criteria.

Here we have three different objectives based on the following questions: (1) How the different approaches to estimate the area of distribution (area of occupancy, extent of occurrence, and ecological modeling) vary on the assessment of risk status criteria?; (2) are all *Polianthes* taxa included in any of the already protected areas in Mexico?; and (3) what are the richness areas of distribution of *Polianthes*?; thus, our goals in this paper are: (1) to assess the current species area of distribution and to assign the risk status scores to each *Polianthes* species based on three different approaches; (2) to determine whether species' ranges are effectively included in national natural protected areas; and (3) to find the richness areas of *Polianthes* taxa in Mexico. We calculated the area of occupancy, extent of occurrence, and modeled the ecological niches of 12 species and three varieties of species of the genus *Polianthes*. Ecological niches were modeled and projected onto geographic space using the GARP algorithm.

Methods

Distributional data

We compiled a database of 885 locality records of a total of 14 species and three varieties of *Polianthes* based on historical voucher specimens from different herbaria, recent field work conducted by Solano from 1994 to 2004, and on consultation of databases at the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (Conabio; http://www.conabio.gob.mx) and REMIB (Red Mundial de Información sobre Biodiversidad; http://www.conabio.gob.mx/remib/remib.html). All historical records without geographical coordinates were georeferenced via direct consultation of 1:50,000 topographic maps and evaluated by Solano prior to modeling in order to avoid the use of imprecise distributional information.

Less than ten independent locality records (i.e., records $\geq$ 1 km distance) exist for 7 of the 14 *Polianthes* taxa and the three varieties (Table 1). *Polianthes geminiflora* var. *geminiflora* was the taxon with the highest number of independent localities (128), while whereas *Polianthes palustris* was recorded only in one locality. Two species were excluded from this analysis, *Polianthes tuberosa* and *P. palustris*. The first is a widely cultivated species and the second has only one historical record.

Table 1 Distributional data for all the species of the genus *Polianthes* analyzed

Species	Records	Localities
Polianthes bicolor E. Solano & García-Mend.	20	6
P. densiflora (B.L. Rob. & Fernald) Shinners	13	5
P. geminiflora var. *clivicola* McVaugh	65	34
P. geminiflora (Lex.) Rose var. *geminiflora*	248	128
P. geminiflora var. *pueblana* E. Solano & García-Mend.	29	10
P. graminifolia Rose	29	12
P. howardii Verh.-Willl.	11	7
P. longiflora Rose	59	33
P. montana Rose	12	6
P. multicolor E. Solano & Dávila	26	18
P. nelsonii Rose	74	25
P. oaxacana García-Mend. & E. Solano	4	3
P. palustris[a] Rose	1	1
P. platyphylla Rose	70	30
P. sessiliflora (Hemsl.) Rose	140	64
P. venustuliflora E. Solano & Castillejos	6	3

[a] *P. palustris* was not considered for the ecological niche modeling analysis

Geographical distribution and risk status assessment

We employed three different approaches to characterize the geographic distribution of species, and thereby assess their risk status: (1) calculation of area of occupancy; (2) calculation of extent of occurrence; and (3) ecological niche modeling of potential distributions. Area of occupancy was calculated for all taxa by superimposing a grid of 1 km^2, cells onto the distributional species data and counting the number of cells occupied by each species using an avenue script developed by T. Consiglio. The cell size of 1 km $\times$ 1 km was chosen to allow comparisons with the results gathered by the ecological modeling procedure (see below). Extent of occurrence was calculated for each taxa (except for *P. palustris* and *P. venustuliflora* due to the small number of distributional data) as the area encompassed by a convex polygon enclosing all occurrence points using an avenue script developed by Willis et al. (2003) which implements the Rapoport (1982) mean propinquity method. Here, all distributional data (points) were joined by the shortest distance with straight lines and distances between points were measured, allowing for the calculation of the arithmetic mean distance between localities.

Ecological niche models were developed for 12 species and three varieties of *Polianthes*, using the following environmental variables: total annual precipitation, absolute maximum temperature, absolute minimum temperature, mean maximum temperature, and mean minimal temperature, aspect (sine and cosine transformations), slope, soils, elevation, and solar radiation. These environmental data were available in digital format from Conabio. The grain resolution of all the environmental variables was 0.01° (approximately 1 $\times$ 1 km^2 grid cells). Models of potential distributions were built based on these environmental variables using the desktop-computer implementation of GARP (http://www.lifemapper.org/desktopgarp). GARP is a machine-learning procedure based on a genetic algorithm (Stockwell and Noble 1992) that divides distributional data into training and test data sets, and works in an iterative process of rule selection, evaluation, testing, and incorporation or rejection. Here a method is chosen from a set of possibilities (e.g., logistic regression, bioclimatic rules), applied to the training data (i.e., distributional data), and a rule is developed or evolved. Testing data are used to internally evaluate the predictive accuracy. Because each run results in a different prediction due to the genetic-based algorithm, final products are based on the best results from 100 runs for each species. From the 100 models, we selected best models from among those with 0% omission error (i.e., no instances of prediction that a species is absent from a location when in fact it is present). Then, we ranked these 0% omission error models by their commission error (this error occurs when the model predicts that the species is present at a location when in fact it is not) and selected five models with less than 20% of commission error. The best output models were exported to ArcGIS as grids, where we summed them to obtain a unique map per species where cell values varied from 0 to 5 (5 indicates that all five models scored the species as present in a particular cell). These predictions were converted to binary predictions assigning values of 1 for grid cells with value of 5 and 0 for grid cells with values from 1 to 4.

To have a more realistic scenario of the geographic distribution of taxa in this genus taking into account biogeographic considerations, we restricted predicted distributions to those Mexican biogeographic provinces and sub-basins (http://www.conabio.gob.mx) in which each species had actually been recorded (Fig. 1; The genus is distributed in eight biogeographic provinces: Balsas Basin, Mexican Pacific Coast, Mexican Plateau, Sierra Madre Oriental, Sierra Madre Occidental, Sierra Madre del Sur, Tamaulipeca, and Transmexican Volcanic Belt.), and calculated the current area of distribution by overlaying the resulting maps on a map of land use and vegetation (http://www.inegi.gob.mx). Biogeographic provinces are reasonable estimates of areas of endemism (Lomolino et al. 2005) and together with sub-basins provide historical information as barriers for *Polianthes* species dispersal. Due to the small number of locality records available for most of the species, we only evaluated

Fig. 1 Mexican biogeographic provinces and sub-basins: apn: North Altiplano, aps: South Altiplano, bal: Balsas basin, bc: Baja California, cab: Del Cabo, chis: Los Altos de Chiapas, clf: California, gm: Gulf of Mexico, nus: Soconusco, oax: Oaxaca, pac: Mexican Pacific Coast, ptn: Peten, sme: Sierra Madre Oriental, smo: Sierra Madre Occidental, sms: Sierra Madre del Sur, son: Sonorense, tam: Tamaulipeca, vol: Transmexican Volcanic belt, yuc: Yucatán

the distributional maps for those species with more than 20 localities (Table 1). Model accuracy was tested originally via a random 50% partition of input data; test points were set aside prior to modeling and overlaid on the resulting prediction. Model significance was evaluated using a chi-square test (df = 1). After converting maps to an equal area projection, the area of distribution was calculated for each species by summing the number of cells where the species was predicted to occur and multiplying this number by the area of the cell. All process were developed on ArcView 3.2 (ESRI 1999).

We followed the first MER criterion (A) to evaluate risk of species extinction. Species that have a distribution range that represents < 5% of the national territory are considered highly restricted and are assigned a risk factor of 4; those between 5% and 15% are considered restricted and have a risk factor of 3; those between 15% and 40% are considered widely distributed or moderately restricted and have risk factor of 2; and those > 40% are considered widely distributed and have a risk factor of 1 (SEMARNAT 2002).

Richness areas and species distribution on the current protected areas on Mexico

Areas of high species richness were assessed by summing of all the resulting distribution maps. Geographic distributions of each species as well as the areas of endemism were compared with Terrestrial Protected Regions (TPR) (Arriaga et al. 2000) and Natural Protected Areas (NPA) (Instituto Nacional de Ecología 1999). The former (TPA) are areas based on different taxa and the knowledge of several experts on every group, and thus it is one of the most formal proposes for areas of conservation, but without a legal decree for their protection. The later are the already protected areas with a national decree for protection.

Results

Geographic distribution and risk status assessment

The three different approaches to calculate the species area of distribution give different results (Table 2) (Fig. 2 shows an example of the area of distribution assessed for the three approaches followed in this paper). In all cases the species with the greater area of distribution was *Polianthes geminiflora* var. *geminiflora* followed for *P. sessiliflora* (Table 2).

Assessments based on area of occupancy consider all taxa as ''highly restricted'' since all their total current distribution is less than 5% of the National Mexican surface. MER criteria based on extent of occurrence and ecological niche include all species, except *Polianthes geminiflora* var. *geminiflora* (Fig. 3) and *P. sessiliflora* (Fig. 5), as ''highly restricted.'' *Polianthes geminiflora* var. *geminiflora* and *P. sessiliflora* are considered as ''restricted'' since their distribution is greater that the 5% but less than 15% of the total area of Mexico.

Ecological niche models (Figs. 3–6) were statistically significant (Chi-square; $P < 0.05$) for all taxa. The species that occur at the northern limits of the distribution are *P. nelsonii* (Fig. 3) and *Polianthes densiflora* (Fig. 4); *P. bicolor* (Fig. 5) and *P. oaxacana* (Fig. 3) establish the southern limit of the distribution. Only one species

Table 2 Area of distribution per species and MER risk category based in tree different criteria

Species	AOO[a] (km^2)	MS[b] (%)	MER[c]	EOO[d] (km^2)	MS (%)	MER	CA[e] (km^2)	MS (%)	MER
Polianthes bicolor	6	0.0003	4	1284.56	0.0654	4	1413	0.0719	4
P. densiflora	5	0.0003	4	3616.38	0.1841	4	1462	0.0744	4
P. geminiflora var. *clivicola*	33	0.0017	4	52349.0	2.6649	4	34843	1.7737	4
P. geminiflora var. *geminiflora*	118	0.0060	4	282650.	14.3888	3	179414	9.1334	3
P. geminiflora var. *pueblana*	10	0.0005	4	156.81	0.0080	4	17	0.0009	4
P. graminifolia	12	0.0006	4	11232.0	0.5718	4	1898	0.0966	4
P. howardii	7	0.0004	4	1235.6	0.0629	4	187	0.0095	4
P. longiflora	31	0.0016	4	29138.4	1.4833	4	15303	0.7790	4
P. montana	6	0.0003	4	22355.4	1.1380	4	3444	0.1753	4
P. multicolor	18	0.0009	4	16003.4	0.8147	4	8727	0.4443	4
P. nelsonii	25	0.0013	4	57933.3	2.9492	4	54925	2.7961	4
P. oaxacana	3	0.0002	4	40.246	0.0020	4	262	0.0133	4
*P. palustris**	1	0.0001	4	–	–	–		0.0000	–
P. platyphylla	29	0.0015	4	38576.9	1.9638	4	43021	2.1901	4
P. sessiliflora	59	0.0030	4	194662.	9.9096	3	155867	7.9347	3
P. venustuliflora	3	0.0002	4	–	–	4	20	0.0010	4

[a] Area of Occupancy based on 1 km × 1 km grids.

[b] Mexican surface based in Mexico total area = 1 964 375 km^2 (http://www.inegi.gob.mx)

[c] 4 = Highly restricted and 3 = restricted

[d] Extent of occurrence

[e] Current area of distribution based on ecological niche modeling by GARP, biogeographic provinces, sub-basins, and current land use

is widely distributed occurring in seven provinces (*Polianthes geminiflora* var. *geminiflora*: Fig. 3), while seven species are narrowly distributed and restricted to a single province (Table 3). The most important Mexican Biogeographic Provinces for the distribution of this genus are the Sierra Madre Occidental and the Transmexican Volcanic Belt, in which eight species and the three varieties occur. Three of those species are highly restricted across the Transmexican Volcanic Belt province (*Polianthes geminiflora* var. *pueblana*, Fig. 5; *P. longiflora*, Fig. 6; and *P. venustuliflora* sp. nov. [E. Solano and Castillejos in prep.], Fig. 4). Two species are highly restricted to the Sierra Madre del Sur (*P. bicolor* and *P. oaxacana* sp. nov. [García-Mend. and E. Solano in prep.],), specifically in the state of Oaxaca. Three more species can be considered as endemic to a particular state of Mexico: *P. densiflora* is endemic to Chihuahua, in the northern part of the Sierra Madre Oriental; *P. multicolor* is endemic to Guanajuato, Fig. 4; and *P. venustuliflora* is endemic to Michoacán in the central part of the Transmexican Volcanic Belt.

Richness areas

Areas of species richness can be visualized as the sum of the individual species maps (Fig. 7), which suggests zones of high and low richness across Mexico. The areas with highest predicted richness (six species) occur along the southern part of the Sierra Madre Occidental and the northwest part of the Transmexican Volcanic Belt.

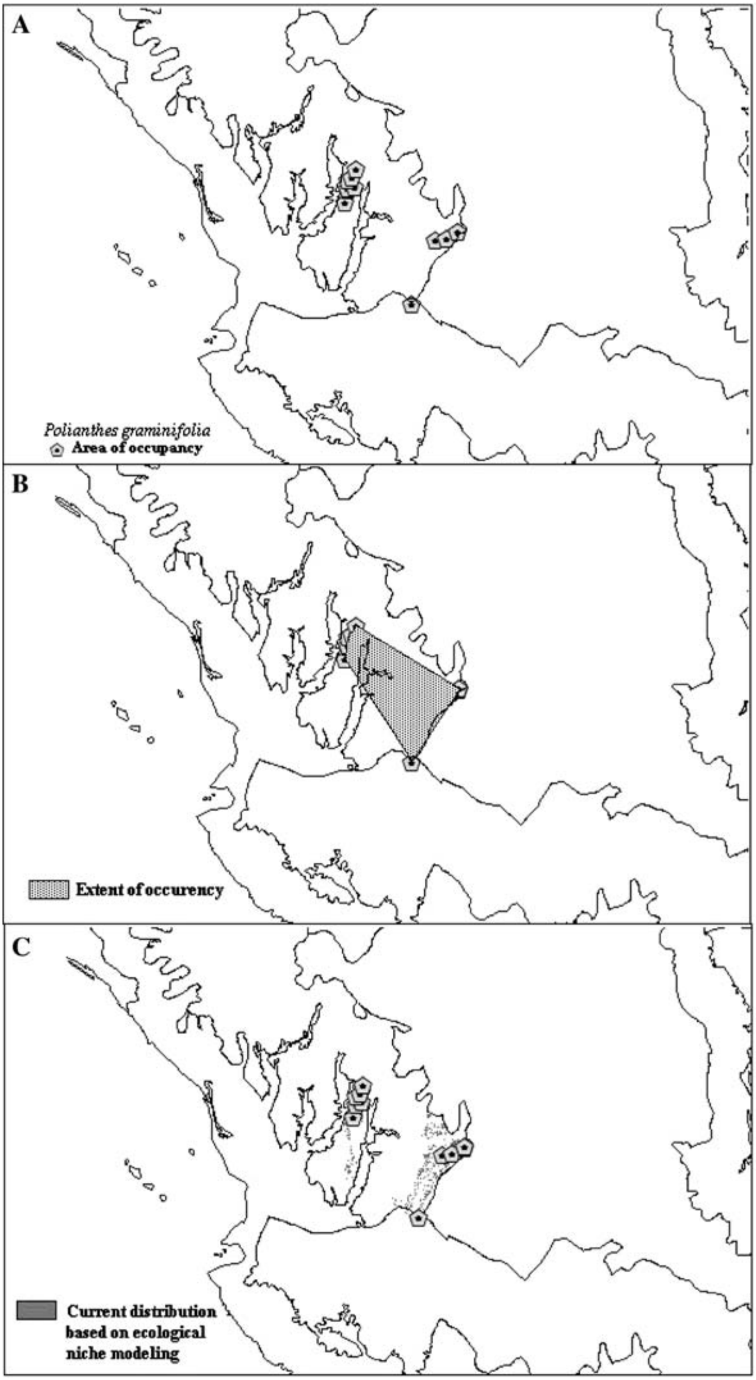

Fig. 2 Example of the three different approaches used to estimate the species area of distribution for *Polianthes graminifolia*: (A) area of occupancy, (B) extent of occurrency, and (C) ecological niche after overly the biogeographic provinces, sub-basins, and current land use and vegetation

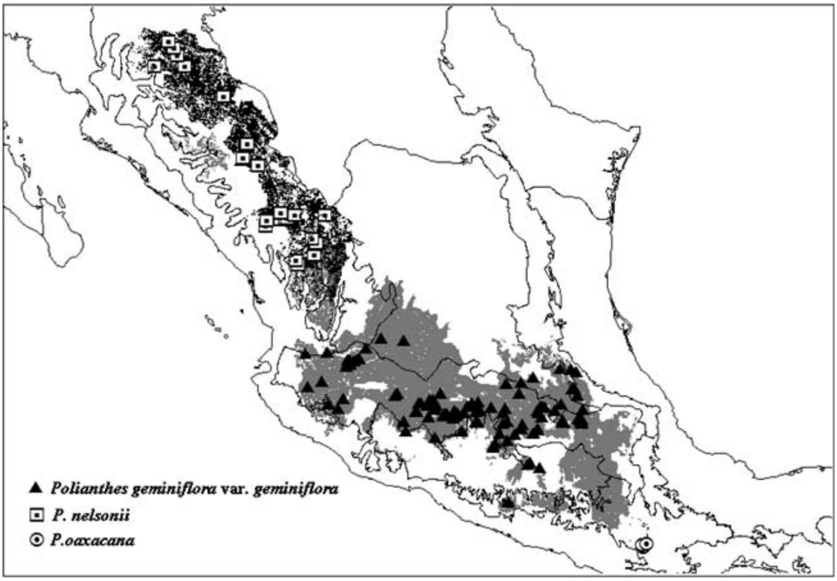

Fig. 3 Modeled ecological niches per species using a genetic algorithm. Distribution of species is ordering to show not overlapping species distributions. Species localities are indicated by different symbols per species. Shadow color represents the potential distribution predicted

The highest richness occurs in the state of Jalisco, where six species and two varieties of *Polianthes* were found (*Polianthes geminiflora* var. *clivicola*, Fig. 5; *P. geminiflora* var. *geminiflora*, Fig. 3; *P. graminifolia*, and *P. howardii*, Fig. 4; *P. longiflora*, *P. montana*, and *P. platyphylla*, Fig. 6; and *P. sessiliflora*, Fig. 5).

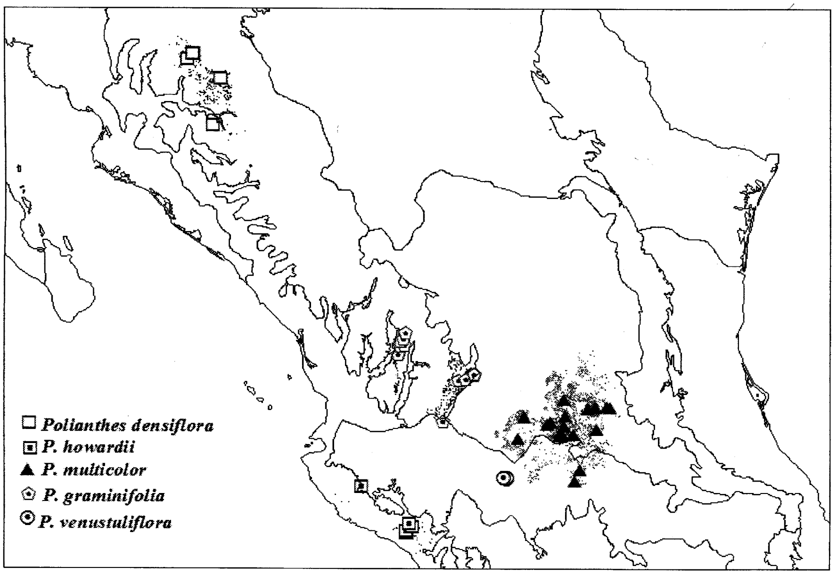

Fig. 4 Modeled ecological niches per species using a genetic algorithm. Distribution of species is ordering to show not overlapping species distributions. Species localities are indicated by different symbols per species. Shadow color represents the potential distribution predicted

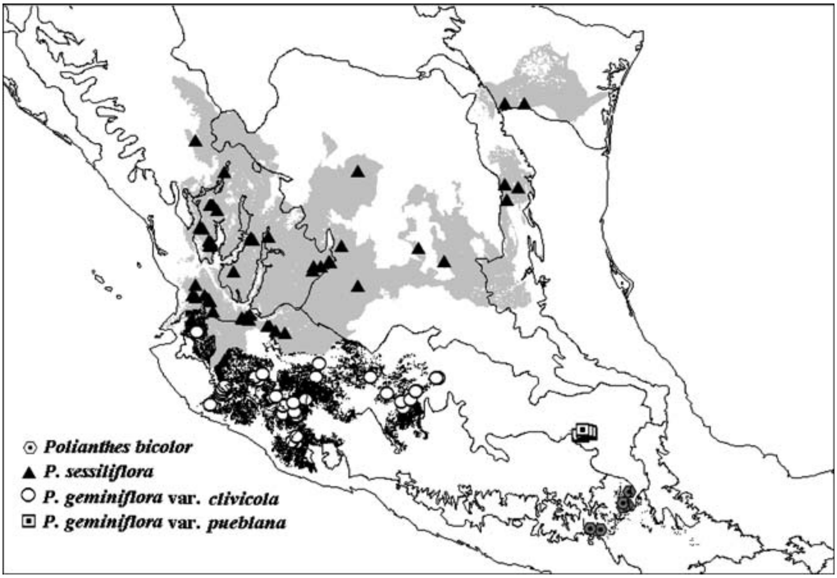

Fig. 5 Modeled ecological niches per species using a genetic algorithm. Distribution of species is ordering to show not overlapping species distributions. Species localities are indicated by different symbols per species. Shadow color represents the potential distribution predicted

Species distribution vs. NPA and TPR

Four species and two varieties occur on both NPA and TPR (*Polianthes geminiflora* var. *geminiflora*, *P. geminiflora* var. *clivicola*, *P. longiflora*, *P. montana*, *P. nelsonii*,

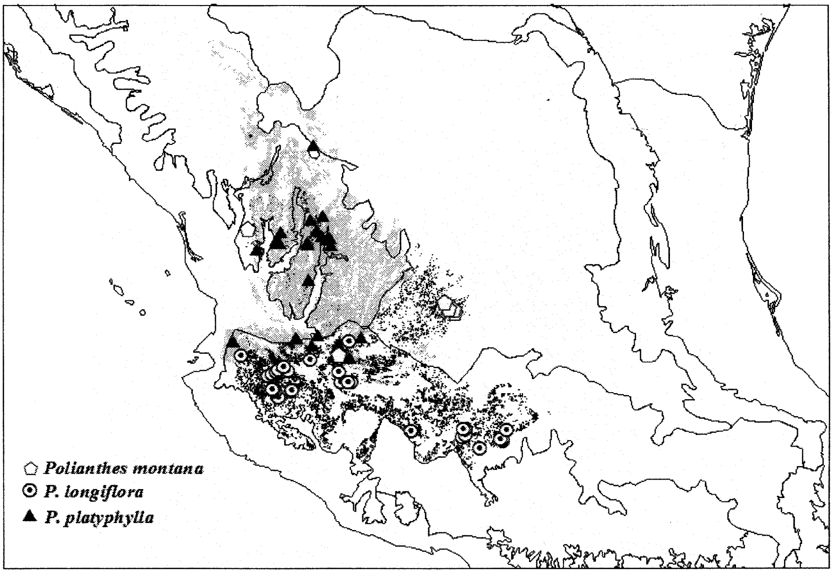

Fig. 6 Modeled ecological niches per species using a genetic algorithm. Distribution of species is ordering to show not overlapping species distributions. Species localities are indicated by different symbols per species. Shadow color represents the potential distribution predicted

Table 3 Distribution of *Polianthes* spp. by Mexican biogeographic provinces

Species	MBP							
	bal	pac	mpl	sme	smo	sms	tam	vol
Polianthes bicolor						X		
P. densiflora					X			
P. geminiflora clivicola	X	X				X		X
P. geminiflora geminiflora	X	X	X	X	X	X		X
P. geminiflora pueblana								X
P. graminifolia					X			X
P. howardii		X						X
P. longiflora								X
P. montana			X		X			X
P. multicolor			X					X
P. nelsonii		X	X		X			
P. oaxacana						X		
P. palustris		X						
P. platyphylla		X	X		X			X
P. sessiliflora		X	X	X	X		X	X
P. venustuliflora								X

MBP: Mexican biogeographic provinces; bal: Balsas Basin; pac: Mexican Pacific Coast; mpl: Mexican Plateau; sme: Sierra Madre Oriental; smo: Sierra Madre Occidental; sms: Sierra Madre del Sur; tam: Tamaulipeca; vol: Transmexican Volcanic Belt (Morrone et al. 2002)

and *P. sessiliflora*). Five species occur only on some TPR (*Polianthes bicolor*, *P. densiflora*, *P. multicolor*, *P. oaxacana*, and *P. platyphylla*). In contrast, three species (*Polianthes geminiflora* var. *pueblana*, *P. howardii*, and *P. venustuliflora*,) are not found in any of the TPR or NPA. Three TPR (Sierra Los Huicholes, Sierra de Morones, and Sierra Fría) include suitable habitat for one species (*P. graminifolia*), but the species has not been recorded there (Fig. 8).

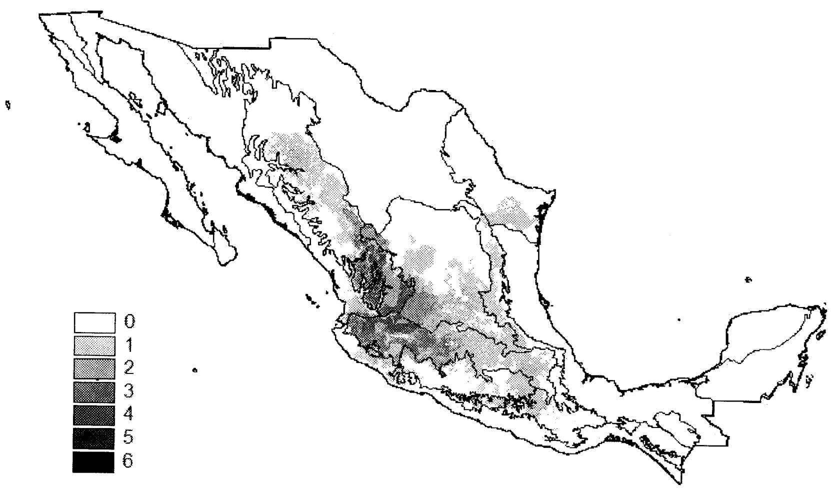

Fig. 7 Endemism pattern summed across 12 species and three varieties of the genus *Polianthes* in Mexico: (*top*) species patterns of endemism (gray scale, 0 species; white, 6 species; black)

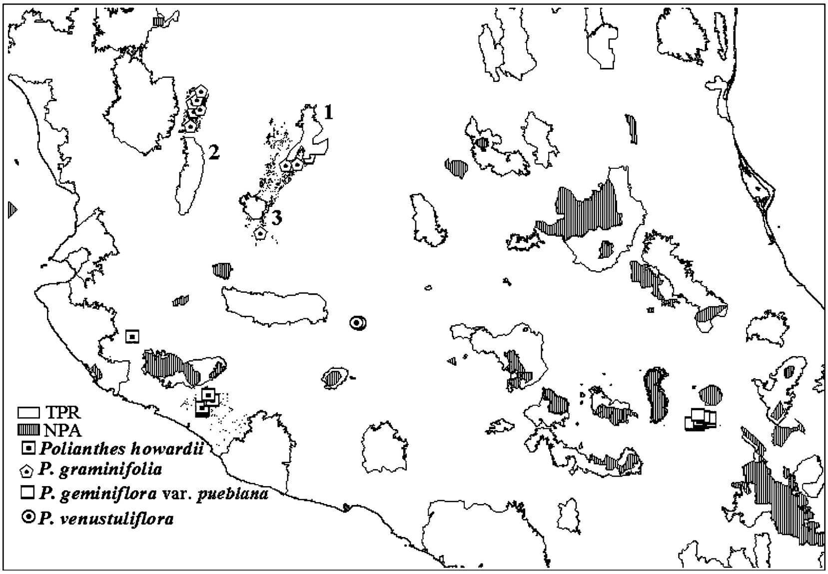

Fig. 8 Distribution of *Polianthes geminiflora* var. *poblana*, *P. howardii*, *P. venustuliflora*, and *P. graminifolia* vs. TPR and NPA. Numbers 1: Sierra Fría, 2: Sierra los Huicholes, and 3: Sierra de Morones

Discussion

Geographic distribution and risk status assignment

MER criterion A (geographical distribution of species) was assessed for 12 species and three varieties of *Polianthes* based on three different approaches to measure the species area of distribution. Area of occupancy sub-estimates the species distribution. No one species has even a distribution of 1% of the Mexican surface based on this approach. Following this criteria all species will have the highest risk score based on MER or other methods of risk status assessment (e.g., IUCN (http://www.iucn.gob) upholds that ''only the criteria for the highest category of threat that the taxon qualifies for should be listed''). This result is not realistic since for most species, such as *Polianthes geminiflora* var. *geminiflora*, results clear that its distribution is greater that the estimated, but not all the areas where the species can occur have been sampled, and maybe never will be due to economic and time constrains. Extent of occurrence, on the other hand, frequently over-estimates the species distribution particularly for species, such as *Polianthes graminifolia*, which has a disjoint distribution. This fact is not considered by this method since the estimated distribution is based on a solid convex polygon. SDM give frequently intermediate values of area of distribution between area of occupancy and extent of occurrence. This method includes the current species distribution when ecological niches match geographic features (i.e., biogeographic provinces, sub-basins) where the species has been recorded (Soberón and Peterson 2005) and current land use and vegetation (Ortega-Huerta and Peterson 2004; Sánchez-Cordero et al. 2005a), thus consider both punctual (area of occupancy) and disjoint distribution, and therefore can give a better picture of the current species area of distribution.

Although five species of *Polianthes* (*P. densiflora*, *P. howardii*, *P. longiflora*, *P. palustris*, and *P. platyphylla*) are listed as rare by the IUCN (IUCN 1997) and considered to be in the category of special protection according to the Mexican Official law, most, if not all the species in this genus should be considered as threatened (e.g., vulnerable) due to their highly restricted distribution in Mexico and the fact that their habitat has been severely modified. Currently, *Polianthes palustris*, is under special protection by the Mexican Official Norm, but according to our findings this species is likely extinct as no individuals were found during 10 years of field work by Solano.

Detailed knowledge of a species distribution is needed before management decisions can be made (Lim et al. 2002). In general, less than a quarter of vascular plants have been evaluated for their conservation status, such is the case of the genus *Polianthes*. MER has been required by Mexican law since 2002 for listing organisms for protection. Although MER may be vulnerable to subjectivity or misinterpretation (i.e., criterion B—habitat condition—and criterion D—impact of human activity—are not independent from each other), ''MER can meet its intended goals of facilitating timely conservation decisions and generating testable hypotheses'' (Olson et al. 2005). Criterion A (geographical distribution of species) of this method of evaluation of risk extinction is generally the most important criterion (i.e., small distribution is a major factor contributing to the status of species for conservation concern) and should be assessed carefully. By just considering the ''punctual'' (distributional data) distributions were the species have been recorded sub-estimate the species area of distribution, whereas the opposite, over-estimations, can occur by considering the extent of occurrence when species have a disjoint distribution. The approach followed on this paper (Anderson and Martínez-Meyer 2004; Ortega-Huerta and Peterson 2004; Sánchez-Cordero et al. 2005a; Soberón and Peterson 2005) provides a methodology that can be readily applied to most species, and can be more useful for these species poorly sampled or that have a disjoint distribution. More work is already being considered to evaluate all the criteria of the MER (B: habitat conditions, C: The intrinsic biological vulnerability of the species, and D: impact of human activity) for *Polianthes* in order to establish a final conservation status for all the species in this genus (Feria and Solano in prep.).

Richness areas

Due to their restricted ranges, endemic taxa are potentially more sensitive to habitat perturbation, and thereby, are especially vulnerable to extinction; these forms are generally considered critical in indicating areas of importance for conservation action (Peterson and Watson 1998). Endemic taxa with very small ranges are likely to also have small total population sizes, which makes them highly prone to extinction as a consequence of stochastic factors. The fact that most species of *Polianthes* are distributed in the Sierra Madre Occidental and the Transmexican Volcanic Belt has serious conservation implications since natural habitats have been extensively transformed in those regions (Mas et al. 2004; Sánchez-Cordero et al. 2005b). In general, at the national level, between 1976 and 2000 more than 20,000 km^2 of temperate forest, 60,000 km^2 of tropical forest and 45,000 km^2 of scrubland were cleared, which represents an annual average of habitat loss of 90,000, 265,000, and 195,000 ha, and rates of deforestation of 0.25%, 0.76% and 0.33% per year, respectively (Mas et al. 2004).

Centers of endemism are identified as areas where the distributions of endemic species overlap (or concentrate), in this case these areas are the areas where the highest *Polianthes* species richness. The degree of endemism in an area is often used as a measure of conservation significance (Brooks et al. 2002), and thus predicting areas with potentially high concentrations of endemic species becomes particularly important in the Neotropic where several areas remain unexplored (Vargas et al. 2004). Although it is well known that the genus *Polianthes* is endemic to Mexico (García-Mendoza 1995; Solano 2000), the present work is the first attempt to understand the current distribution and areas of concentration of *Polianthes* species within Mexico through ecological niche modeling and use this information to inform assessment of risk status for these species. In general, most species have a highly restricted distribution to only one Mexican Biogeographic Province or state of Mexico.

The genus *Polianthes* has the highest concentration of species in the southern Sierra Madre Occidental and the northwest side of the Transmexican Volcanic Belt. This same pattern of species richness has been shown in different groups such as birds (Escalante et al. 1993), mammals (Fa and Morales 1993), grasses (Valdés and Cabral 1993), and Lamiaceae family (especially *Salvia*, Ramamoorthy and Elliott 1993). The patterns of distribution found for this genus agree with the region delimited and named by McVaugh (1989) as Nueva Galicia (see García-Mendoza 1995 and Solano 2000). In particular, the Transvolcanic Belt is considered very important as a biographic barrier for *Polianthes* species dispersal, thus this might be the main factor for which only two species (*Polianthes bicolor* and *P. oaxacana*) occur in Oaxaca (Solano 2000).

Species distribution vs. NPA and TPR

The four species not included in any of the NPA or TPR are highly restricted, implying a high risk of future extinction. The case of *P. howardii* is of particular concern because even though it is considered in the category of special protection by the Mexican official law, it is not included in any NPA or TPR. The results of this study can be used to propose modifications to present protected area systems. In Mexico, NPA are formally protected through a government decree, but the TPR are just proposed regions for conservation without a current legal status. Consequently, without effective management for the TPR, five more species (*Polianthes bicolor*, *P. densiflora*, *P. multicolor*, *P. oaxacana*, and *P. platyphylla*) would not be protected, increasing the risk for the other two already proposed species as in special protections category by the Mexican Official Norm (*P. densiflora* and *P. platyphylla*).

Acknowledgements This paper has been supported by Comision Nacional para el Conocimiento y Uso de la Biodiversidad (Conabio, project FB291/H-230/96), led by the first author. We thank Carlos Correa D., for his kind assistance during field work. We also thank Abisaí García-Mendoza, Bette Loiselle, Daniel Cadena, and Trish Consiglio for their helpful comments on this manuscript. Modeling was developed at GEOMATICA lab at FES Zaragoza, UNAM with the kind assistance of Eliseo Cantellano. Curators at the following herbaria were most helpful with specimen loans: A, CHAPA, ENCB, FEZA, GH, GUADA, HUAA, IEB, MICH, MEXU, NY, RSA, UAMIZ, UAT, US and XAL. Data were also gathered from REMIB.

References

Anderson RP, Martínez-Meyer E (2004) Modeling species' geographic distributions for preliminary conservation assessments: an implementation with the spiny pocket mice (*Heteromys*) of Ecuador. Biol Conserv 116:167–179

Arriaga L, Espinoza-Rodríguez JM, Aguilar-Zúñiga C, Martínez-Romero E, Gómez-Mendoza L, Loa-Loza E, Larson J (2000) Regiones prioritarias terrestres de México. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, México, DF

Austin MP (2002) Case studies of the use of environmental gradients in vegetation and fauna modelling: theory and practice in Australia and New Zealand. In: Scott JM, Heglund PJ, Morrison ML, Haufler JB, Raphael MG, Wall WA, Samson FB (eds) Predicting species occurrences. Issues of accuracy and scale. Island Press, London, pp 73–82

Brooks TM, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Rylands AB, Konstant WR, Flick P, Pilgrim J, Oldfield S, Magin G, Hilton-Taylor C (2002) Habitat loss and extinction in the hotspots of biodiversity. Conserv Biol 16:909–923

Brown JH, Stevens GC, Kaufman DM (1996) The geographic range: size, shape, boundaries, and internal structure. Annu Rev Ecol Syst 27:597–623

Elith J, Graham C, Anderson RP, Dudik M, Ferrier S, Guisan A, Hijmans RJ, Huettmann F, Leathwick JR, Lehmann A, Li J, Lohmann LG, Loiselle BA, Manin G, Moritz C, Nakamura M, Nakazawa Y, Overton JMcC, Peterson AT, Phillips SJ, Richardson KS, Scachetti-Prereira R, Schapire RE, Soberón J, Williams S, Wisz MS, Zimmermann NE (2006) Novel methods improve prediction of species' distributions from occurrence data. Ecography 29:129–151

Escalante PP, Navarro SA, Peterson AT (1993) A geographic, ecological and historical analysis of land bird diversity in Mexico. In: Ramamoorthy TP, Bye R, Lot A, Fa J (eds) The biological diversity of Mexico: origins and distribution. Oxford Press, New York, USA, pp 281–307

ESRI (1999) ArcView GIS ver 3.2. Environmental System Research Inc., USA

Fa JE, Morales LM (1993) Patterns of mammalian diversity in Mexico. In: Ramamoorthy TP, Bye R, Lot A, Fa J (eds) The biological diversity of Mexico: origins and distribution. Oxford Press, New York, USA, pp 319–361

Feria ATP, Peterson AT (2002) Prediction of bird community composition based on point-occurrence data and inferential algorithms: a valuable tool in biodiversity assessments. Divers Distrib 8:49–56

García-Mendoza A (1995) Riqueza y endemismos de la familia Agavaceae en México. In: Linares E, Chiang F, Bye R, Elias TS (eds) Conservación de Plantas en Peligro de extinción: Diferentes Enfoques. Instituto de Biología, Jardín Botánico, UNAM, México, DF, pp 51–75

García-Mendoza A (2004) Agaváceas. In: García-Mendoza AJ, Ordoñez MJ, Briones-Salas M (eds) Biodiversidad de Oaxaca. Instituto de Biología, UNAM-Fondo Oaxaqueño para la Conservación de la Naturaleza-Worldlife Fund, México, DF, pp 159–169

Guisan A, Zimmermann NE (2000) Predictive habitat distribution models in ecology. Ecol Model 135:147–186

Illoldi-Rangel P, Sánchez-Cordero V, Peterson AT (2004) Predicting distribution of Mexican mammals using ecological niche modeling. J Mammal 85:658–662

Instituto Nacional de Ecología (1999) Red del Sistema Nacional de Áreas Naturales Protegidas. México, DF

IUCN (1997) Cactus and succulent plants. Status survey and conservation plan. Sara Oldfield (comp). Gland, Switzerland and Cambridge, UK

Lim BK, Peterson AT, Engstrom MD (2002) Robustness of ecological niche modeling algorithms for mammals in Guyana. Biodivers Conserv 11:1237–1246

Lomolino MV, Riddle BR, Brown JH (2005) Biogeography. 3rd edn. Sinauer Associates, Inc, Sunderland, MA

Martínez-Meyer E, Peterson AT, Navarro Sigüenza AG (2004) Evolution of seasonal ecological niches in the Passerina buntings (Aves: Cardinalidae). Proc Roy Soc Lond B 271:1151–1157

Mas JF, Velásquez A, Díaz-Gallegos JR, Mayorga-Saucedo R, Alcantara C, Bocco G, Castro R, Fernández T, Pérez-Vega A (2004) Assessing land use/cover changes: a nationwide multidate spatial database for Mexico. Int J Appl Earth Observ Geoinform 5:249–261

McVaugh R (1989) Liliaceae. In: Anderson WR (ed) Flora Novo-Galiciana. A descriptive account of the vascular plants of western Mexico, vol.15. Annals arboretum. The University of Michigan Herbarium, USA, pp 20–293

Morrone JJ, Espinosa-Organista D, Llorente-Bousquets J (2002) Mexican biogeographic provinces: preliminary scheme, general characterizations, and synonymies. Acta Zool Mex 85:83–108

Nakazawa Y, Peterson AT, Martínez-Meyer E, Navarro-Sigüenza AG (2004) Seasonal niches of Neartic-Neotropical migratory birds: implications for the evolution of migration. Auk 121:610–618

Olson ME, Lomeli JA, Cacho I (2005) Extinction treat in the *Pedilanthus* clade (*Euphorbia*, Euphorbiaceae), with special reference to the recently rediscovered *E. conzatti* (*P. pulchellus*). Am J Bot 92:634–641

Ortega-Huerta MA, Peterson AT (2004) Modelling spatial patterns of biodiversity for conservation prioritization in North-eastern Mexico. Divers Distrib 10:39–54

Peterson AT (2001) Predicting species' geographic distribution based on ecological niche modelling. Condor 103:599–605

Peterson AT, Cohoon KC (1999) Sensitivity of distributional prediction algorithms to geographical data completeness. Ecol Model 117:159–164

Peterson AT, Vieglais DA (2001) Predicting species invasions using ecological niche modelling. BioScience 51:363–371

Peterson AT, Watson M (1998) Problems with aerial definitions of endemism: the effects of spatial scaling. Divers Distrib 4:189–194

Peterson AT, Ball LG, Cohoon KC (2002a) Predicting distributions of tropical birds. Ibis 144(on-line):E27–E32

Peterson AT, Ortega-Huerta M, Bartley G, Sánchez-Cordero V, Soberón J, Buddemeier RH, Stockwell D (2002b) Future projections for Mexican faunas under global climate change scenarios. Nature 416:626–629

Ramamoorthy TP, Elliot M (1993) Mexican Lamiaceae. In: Ramamoorthy TP, Bye R, Lot A, Fa J (eds) The biological diversity of México: origins and distribution. Oxford Press, New York, USA, pp 513–539

Rapoport EH (1982) Aerographic-geographic strategies of species. Pergamon Press, New York

Raxworthy CJ, Martínez-Meyer E, Horning N, Nussbaum RA, Schneider GE, Ortega-Huerta MA, Peterson AT (2003) Predicting distributions of known and unknown reptile species in Madagascar. Nature 426:837–841

Sánchez-Cordero V, Cirelli V, Munguia M, Sarkar S (2005a) Place prioritization for biodiversity representation using species' ecological niche modeling. Biodivers Inform 2:11–23

Sánchez -Cordero V, Iloldi-Rangel P, Linaje M, Sarkar S, Peterson AT (2005b) Deforestation and extant distributions of Mexican endemic mammals. Biol Conserv 126:465–473

SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales) (2002) Norma Oficial Mexicana NOM-059-ECOL-2001, Protección ambiental-Especies nativas de México de flora y fauna silvestres-Categorías de riesgo y especificaciones para su inclusión, exclusión o cambio-Lista de especies en riesgo. Diario Oficial de la Federación. 6 de marzo de 2002, Primera sección, México, DF

Soberón J, Peterson AT (2005) Interpretation of models of fundamental ecological niches and species' distributional areas. Biodivers Inform 2:1–10

Solano CE (2000) Sistemática del género *Polianthes* L. (Agavaceae). Tesis de Doctorado. Facultad de Ciencias, División de Estudios de Posgrado, UNAM, México, DF

Stockwell D, Noble R (1992) Induction of sets of rules from animal distribution data a robust and informative method of data analysis. Math Comput Simul 33:385–390

Stockwell D, Peterson AT (2002) Effects of sample size on accuracy of species distribution models. Ecol Model 148:1–13

Stockwell D, Peterson AT (2003) Comparison of resolution of methods for mapping biodiversity patterns from point-occurrence data. Ecol Ind 3:213–221

Valdés RJ, Cabral CI (1993) Chronology of Mexican grasses. In: Ramamoorthy TP, Bye R, Lot A, Fa J (eds) The biological diversity of Mexico: origins and distribution. Oxford Press, New York, USA, pp 439–446

Vargas JH, Consiglio T, Jørgensen PM, Croat TB (2004) Modelling distribution patterns in a species-rich plant genus, *Anthurium* (Araceae), in Ecuador. Divers Distrib 10:211–216

Willis F, Moat J, Paton A (2003) Defining a role for herbarium data in Red list assessments: a case study of *Plectranthus* from eastern and southern tropical Africa. Biodivers Conserv 12:1537–1552