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Can we expect to protect threatened species in protected areas? A case study of the genus *Pinus* in Mexico

Podemos proteger especies en riesgo en áreas protegidas? Un estudio de caso del genero *Pinus* en México

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Abstract. The distribution of 56 *Pinus* species in Mexico was modelled with MAXENT. The pine species were classified as threatened according to IUCN criteria. Our aim was to ascertain whether or not threatened pine species were adequately represented in protected areas. Almost 70% of the species had less than 10% of their modelled distribution area protected. None of the pine species reached their representation targets. Threatened pine species were less widely distributed, occurred at lower maximum elevations, and were less well represented in protected areas than other pine species. The results suggest that the present system of protected areas in Mexico fails to protect pine species adequately. Conservation targets should be especially directed to species with narrow distributions which occur at low altitudes, such as *Pinus. attenuata*, *P. cembroides* subsp. *cembroides* var. *lagunae, P. radiata* var. *binata, P. rzedowskii,* and *P. muricata.*

Key words: MAXENT, species distribution model, IUCN, conservation.

Resumen. La distribución de 56 especies del género *Pinus* en México fue modelada por medio de MAXENT. Nuestro objetivo principal fue investigar si las especies de pino clasificadas por IUCN como amenazadas tienen una representación adecuada en las áreas protegidas de México. Se encontró que casi el 70% de las especies tienen menos del 10% de su distribución modelada protegida. Ninguna de las especies alcanzó el nivel de representación propuesto como adecuado. Se observó que las especies de pino clasificadas como amenazadas tienen un distribución más estrecha, ocurren a menores elevaciones máximas y se encuentran menos representadas en las áreas protegidas en comparación con las otras especies de pino modeladas. Los resultados sugieren que la red actual de áreas protegidas en México no protege adecuadamente el genero *Pinus.* Proponemos que los esfuerzos de conservación deben estar dirigidos especialmente a especies con distribución reducida y que se encuentran principalmente distribuidas a bajas altitudes, como por ejemplo *Pinus attenuata*, *P. cembroides* subsp. *cembroides* var. *lagunae, P. radiata* var. *binata, P. rzedowskii* and *P. muricata.*

Palabras clave: MAXENT, modelos de distribución de especies, IUCN, conservación.

Introduction

The same factors that increase the probability of a species being endangered also increase its risk of not being present in protected areas. The origin for this unwanted situation is twofold. First, narrowly distributed species, *i.e.* species with small range sizes, low population densities, or occurring in widely spaced small patches, are more vulnerable than widespread species (Gaston et al., 1997; Rabinowitz, 1981; Purvis et al., 2000). Unfortunately, narrowly distributed species are not likely to occur in protected areas (Rodrigues and Gaston, 2001). Thus, species that are potentially endangered because of their population structure are prone to be misrepresented in areas designed to protect them. Secondly, many species are severely threatened by high degrees of human disturbance. Such species are likely to be underrepresented in protected areas, as these natural reserves tend to be located in areas where human influence is minimized (Cantú et al., 2004). The aim of this study is to test these 2 propositions by means of a distribution analysis of species from the genus *Pinus* in Mexico.

Mexico is recognized as a mega diverse nation with a high level of endemism (Rzedowski, 1991). In Mexico, 56 pine taxa have been recorded (Farjon, 2001), a great proportion of which are endemic to the country or have quite narrow distributions (Perry, 1991; Farjon and Styles,

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1997). The International Union for Conservation of Nature and Natural Resources (IUCN, 2009) listed 15 *Pinus* species as threatened according to 3 categories: Endangered (EN), Vulnerable (VU) or Near-Threatened (NT) (see Table 1). The Red List Criteria used by IUCN (2001) for listing species as threatened were population size, geographic range, and species probabilities of extinction. The extent of species distributions in protected areas (*i.e.* the degree of representation) was not part of these criteria.

To protect biodiversity, the IUCN proposed that 10-12% of a countries' territory should be dedicated to the establishment of protected areas (IUCN, in Rodrigues et al., 2003). However, this proposal did not take into account the distribution of biodiversity, nor did it consider specific requirements to protect species adequately, such as the size of protected areas (Rodrigues et al., 2003). Rodrigues et al. (2004a) stipulated that the total cover of protected areas in countries does not give adequate information regarding the true level of protection. In Mexico, the conservation and protection of biodiversity has not always been the primary reason to establish protected areas (CONANP-CONABIO, 2007). Despite the establishment of 166 federal protected areas which cover almost 12% of its territory (CONANP, 2009a), recent studies have reported an inadequate levels of representation for several species (Cantú et al., 2004; Riemann and Ezcurra, 2005).

In this study, the distribution of species from the genus *Pinus* was modelled by means of the Maximum entropy modeling software "MAXENT", (Phillips et al., 2006) to quantify the degree of representation of *Pinus* species in the protected areas of Mexico. We analyzed whether narrow distributions and/or occurrences at relative low elevations (high human pressure) affected the species' representation levels. We expected to find that pine taxa which were classified as threatened on the basis of IUCN criteria (Table 1) were poorly represented in the Mexican protected areas.

Materials and methods

Species distribution data. The study included the 56 pine taxa listed for Mexico in the World Checklist and Bibliography of Conifers (Farjon, 2001) (Table 1). A total of 5336 location records for these taxa were extracted from the BRAHMS database (BRAHMS database, University of Oxford, http://dps.plants.ox.ac.uk/bol/documentation). Subsequently, the records were geo-referenced to Lambert Conformal Conic and projected on a map of Mexico. The records that appeared as duplicates or were erroneously geo-referenced (1469), were deleted, leading to a total of 3 867 points used in the analysis.

Layer preparation. In total, 8 environmental layers were used in the species distribution modeling: a digital elevation model (DEM) (INEGI, 2009), slope, precipitation, temperature, soil types, humidity, soil humidity regimes and land vegetation cover (CONABIO, 2009). The DEM was downloaded at a grain size of 30 x 30 m, in fragments with a maximum size of 2 degrees square. These fragments were pasted together to obtain a single DEM layer covering the entire country. The slope layer was constructed from the DEM, using the slope function from the spatial analyst tool of the ArcInfo software version 9.3 (ESRI, 2009), at a resolution of 300 x 300 m. The layers of average annual precipitation, humidity, and soil humidity regimes were obtained in 9 classes, at a scale of 1:4 000 000. The layer of average annual temperature contained 6 categories and was also at a scale of 1:4 000 000. The land use and vegetation layer, modified by CONABIO (1999), had a scale of 1:1 000 000 and included 27 categories. Finally, the soil types layer contained 32 different categories and was available at a scale of 1:4 000 000. All layers were changed into a raster format with a resolution of 300 x 300 m at the same extent. A total of 166 federal protected areas (CONANP, 2009b) were included in a separate layer. The dataset was analyzed with the software ArcInfo version 9.3 (ESRI, 2009).

Model construction and analysis. The Maxent modeling algorithm version 3.3.0 (Phillips et al., 2006) was used to model the distribution of species, applying 500 iterations, a convergence threshold of 0.00001, and a cumulative output.

For each pine taxon a MAXENT model was generated using a cumulative output (Fig. 1). This output showed the so-called relative suitability for each grid cell, applying values from 0 to 100, with higher values meaning higher suitability.

The models generated by Maxent were evaluated by their area under the ROC curve (AUC) generated for each model, and by the test proposed by Pearson et al. (2007) in the case of species with small sample sizes. Models with AUC values from 0.75 and above were considered useful, as recommended by Elith (2000. *In* Phillips and Dudik, 2008). The AUC is a threshold-independent method that measures the overall model performance. AUC values range from 0 to 1, with values of 0.5 or below indicating a model that is no better than random and with a value of 1 when the model has perfect discrimination (Engler et al., 2004). The Maximum Training Sensitivity + Specificity (MTS+S) threshold criterion was used to create presence/absence maps for each pine taxon as suggested by Jimenez-Valverde and Lobo (2007). The presence/absence maps were converted to a polygon format yielding the total extent

Table 1. The species IUCN category, extent of modelled distribution, percentage of the modelled species distribution inside protected areas, and their representation targets

Name	*IUCN**	*Test AUC*	*Extent (Km^2)*	*Protected (%)*	*Rep. target (%)*	*Modelled elevation (m)*
Pinus arizonica Engelm. var. *arizonica*	NL	0.897	163, 460	10	41.2	1-5353
Pinus arizonica Engelm. var. *cooperi* (C.E. Blanco) Farjon	NL	0.99	121, 404.3	7	56.4	1-5353
Pinus arizonica Engelm. var. *stormiae* Martínez	NL	0.99	15, 189.0	18.1	94.8	1-3702
Pinus attenuata Lemmon	NL	NA	864.2	1.5	100	1-2511
Pinus ayacahuite Ehrenb. ex Schltdl var. *ayacahuite*	NL	0.957	206, 006.4	7.5	25.9	1-5567
Pinus ayacahuite Ehrenb. ex Schltdl var. *veitchii* (Roezl) Shaw	**LR/NT**	0.99	191, 708.6	6.3	31.0	1-5567
Pinus caribaea Morelet var. *hondurensis* (Sénécl.) W.H. Barrett & Golf.	NL	NA	14,185.2	4.9	95.2	1-711
Pinus cembroides Zucc. ssp. *lagunae* (M.-F. Passini) D.K. Bailey,	**VU**	0.777	957.5	36.6	100	111-2315
Pinus cembroides Zucc. ssp. *orizabensis* D.K. Bailey	**LR/NT**	0.9994	48,274.3	9.6	82.9	1-5567
Pinus cembroides Zucc. ssp. *cembroides* var. *bicolor* Little	NL	0.853	265,591.7	9.1	10	1-5567
Pinus cembroides Zucc. ssp. *cembroides* var. *cembroides*	NL	0.895	278,501.1	6.6	10	1-5567
Pinus contorta Douglas ex Loudon var. *murrayana* (Balf.) Engelm.	NL	0.99	53,167.1	10.6	81.1	1-3700
Pinus coulteri D. Don.	NL	0.99	16,589.7	6.7	94.3	1-3610
Pinus culminicola Andresen & Beaman	**EN**	0.99	6,791.6	11.8	97.9	1-3702
Pinus devoniana Lindl.	NL	0.895	230,631	6.6	17	55-5353
Pinus douglasiana Martínez	NL	0.881	141,147.9	7.3	49.3	1-5503
Pinus duranguensis Martínez	NL	0.834	276,827.8	8.2	10	220-5209
Pinus engelmannii Carrière	NL	0.778	318,203.6	6.3	10	17-4575
Pinus flexilis E. James var. *reflexa* Engelm.	NL	1^n	33,058.1	5.6	88.4	1-3702
Pinus greggii Engelm. Ex Parl. var. *australis* Donahue & Lopez	**VU**	0.927	39,569.2	17.5	86.0	37-4171
Pinus greggii var. *greggii* Engelm. Ex Parl.	**NT**	0.99	82,479.5	10.6	70.5	1-3702
Pinus hartwegii Lindl.	NL	0.93	121,706.2	8	56.3	1-5567
Pinus herrerae Martínez	NL	0.939	168,775.1	8	39.3	1-5353
Pinus jaliscana Perez de la Rosa	**LR/NT**	0.994	81,711.5	10	70.8	1-3083
Pinus jeffreyi Balf.	NL	0.992	25,740.8	8.4	91.0	1-3700
Pinus lambertiana Douglas	NL	0.98	3,222.5	19.4	99.2	1-3644
Pinus lawsonii Roezl ex Gordon	NL	0.796	204,127.2	6.6	26.5	1-5353
Pinus leiophylla Schiede ex Schltdl. & Cham. var. *chihuahuana* (Eng.)	NL	0.814	338,543.5	7.5	10	1-4463
Pinus leiophylla Schiede ex Schltdl. & Cham. var. *leiophylla.*	NL	0.947	227,770.8	7.1	18.0	1-5440
Pinus lumholtzii B. L. Rob. & Fernald	NL	0.89	309,537.9	7.8	10	1-5173
Pinus luzmariae Pérez de la Rosa	NL	0.864	224,542.9	7.2	19.2	217-5209
Pinus maximartinezii Rzedowski	**EN**	$>0.01^n$	29,371.3	17	89.7	38-3260
Pinus maximinoi H. E. Moore	NL	0.946	166,525.6	8.7	40.1	1-5353
Pinus monophylla Torr. & Frém.	NL	0.985	29,793.4	10.5	89.5	1-3151
Pinus montezumae Lamb. var. *gordoniana* (Hartw. ex Gordon) Silba	NL	0.98	151,990	8.7	45.4	1-5567

Table 1. Continues

Pinus montezumae Lamb. var. *montezumae*	NL	0.906	311,782.4	7.7	10	1-5567
Pinus muricata D. Don	**LR/NT**	1	11,005	25.4	96.3	1-1695
Pinus nelsonii Shaw	**VU**	0.933	111,476.7	10.6	60.0	1-5123
Pinus oocarpa Schiede ex Schltdl.	NL	0.907	425,389.5	7.1	10	1-5353
Pinus patula Schiede ex Schltdl & Cham. var. *patula*	NL	0.952	133,730.7	8.7	52.0	1-5567
Pinus patula Schiede ex Schltdl. & Cham. var. *longipedunculata* M.	NL	0.766	94,414.8	8.4	66.2	1-5353
Pinus pinceana Gordon	**LR/NT**	0.831	159,107.5	7.8	42.8	1-3702
Pinus ponderosa Douglas ex C. Lawson var. *scopulorum* Engelm.	NL	NA	31,388.7	4.2	89.0	1-3105
Pinus praetermissa Styles & McVaugh	NL	0.907	236,749.5	6.7	14.7	1-4247
Pinus pringlei Shaw	NL	0.958	227,644.7	7.6	18.0	1-5309
Pinus pseudostrobus Lindl. f. *protuberans* Martínez	NL	0.02^{n}	14,529.6	12.9	95.1	522-4374
Pinus pseudostrobus Lindl. var. *apulcensis* (Lindl.) Shaw	NL	0.925	199,698.3	7.6	28.1	1-5353
Pinus pseudostrobus Lindl. var. *pseudostrobus*	NL	0.922	315,988.4	6.9	10	40-5567
Pinus quadrifolia Parl. ex Sudw.	NL	0.985	37,986.6	6.5	86.6	1-3610
Pinus radiata D. Don var. *binata* J.G. Lemmon	**EN**	0.994	864.9	69.6	100	1-1539
Pinus remota (Little) D. K. Bailey & Hawksw.	NL	0.984	119,999.4	10.4	56.9	1-3702
Pinus rzedowskii Madrigal & Caballero	**EN**	0.02^{n}	34,090.4	1.4	88.0	1-3259
Pinus strobiformis Engelm.	NL	0.822	230,147.3	9.5	17.1	1-5353
Pinus strobus L. var. *chiapensis* Martinez	**VU**	0.976	206,290.8	6.7	25.8	1-4006
Pinus tecunumanii (Schw.) Eguiluz & Perry	**VU**	0.937	111,145.1	10.2	60.1	1-4595
Pinus teocote Schiede ex Schltdl. & Cham.	NL	0.857	321,725.2	7.5	10	1-5567

***Category abbreviations**: Lower Risk/Near Threatened (LR/NT), Endangered (EN), Vulnerable (VU) and Not listed as threatened (NL)

^{n}Represents the P-value of the test explained in Pearson et al. (2007). Models with values equal or smaller than 0.05 were considered useful.

-NA represents models from which a test AUC or P-value could not be obtained due to the small sample size available (2 observation points).

of occurrence in km^2 for each pine taxon. Representation levels of pine taxa were defined based on the overlap of the modelled distribution area with the layer of protected areas. Three representation classes (gap, partial gap or covered) were defined following Rodrigues et al. (2004b). Taxa for which the modelled distribution was fully outside any protected area were called *gap taxa*. Partial gap taxa showed a representation below a so-called target value. This value depended on the total extent of the modelled distribution of each taxon. For taxa with a total distribution of 1 000 km^2 or less the target representation value was defined as 100%. For taxa with a total distribution of 250 000 km^2 or more the target representation value was defined as 10%. For taxa with total distributions between 1 000 and 250 000 km^2, the target was interpolated as proposed by Rodrigues et al. (2004b). Covered taxa showed a representation equal or above the target value. All GIS analyses were carried out with ArcInfo version 9.3 (ESRI, 2009).

Differences in area protected between taxa classified as threatened and not threatened were tested by means of a Mann-Whitney test (Zar, 1984). Linear regression was used to examine how the area protected depended on distributional extent.

Results

All MAXENT models performed well as assessed by the AUC on the test data, which was above 0.76 for all species with the exception of 7 pine taxa. These had small sample sizes (6 or less points) and, therefore, the test proposed by Pearson et al. (2007) was applied (Table 1).

The total extent of the modelled species distributions was highly related to the total extent inside protected areas (Fig. 2). All species were classified as partial gap taxa. The representation levels did not go beyond 70% (Table 1).

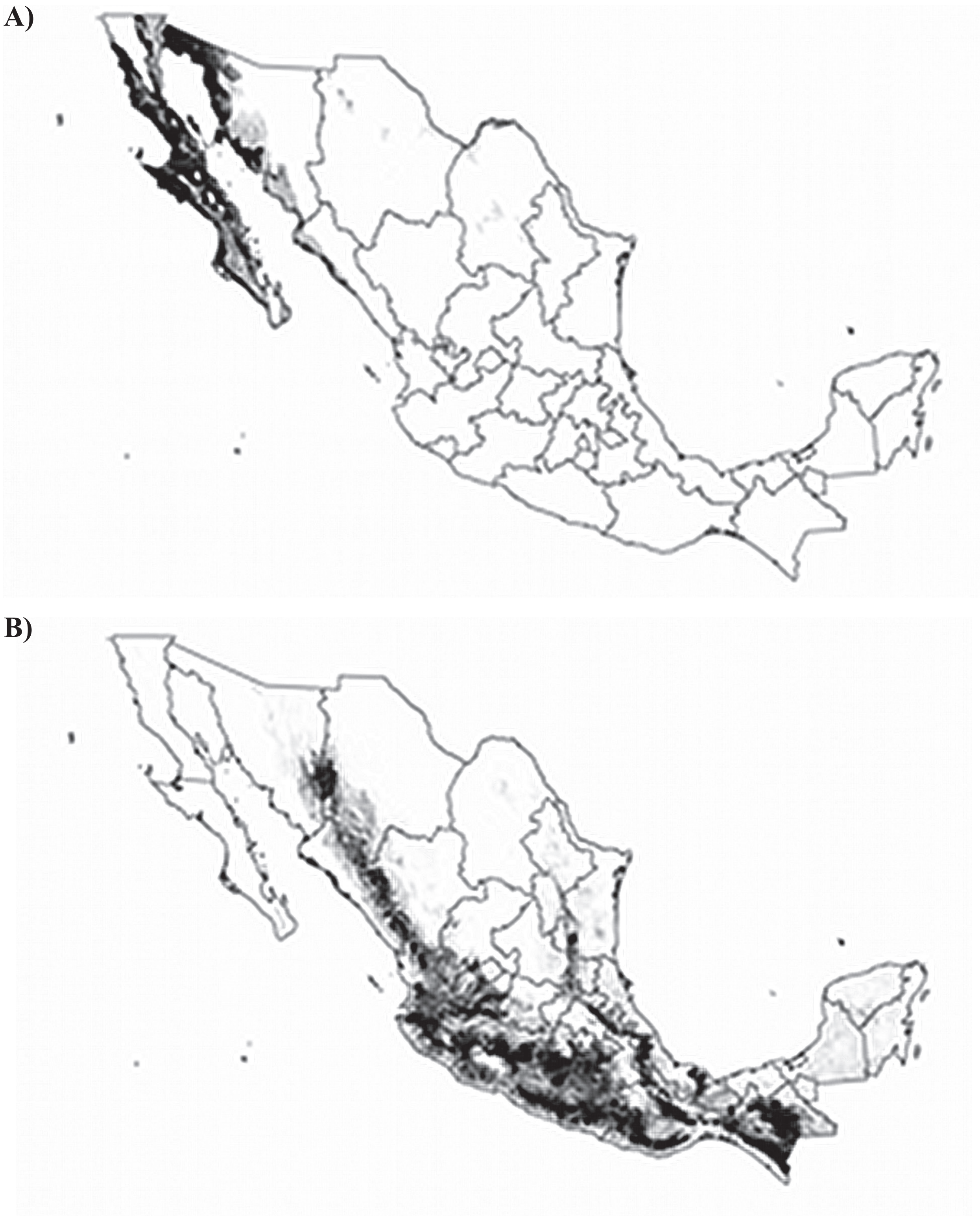

Figure 1. Examples of the species distribution models generated using Maxent (V. 3.3.0) with cumulative output. Darker tones imply higher habitat suitability. A) *Pinus muricata* B) *Pinus oocarpa*.

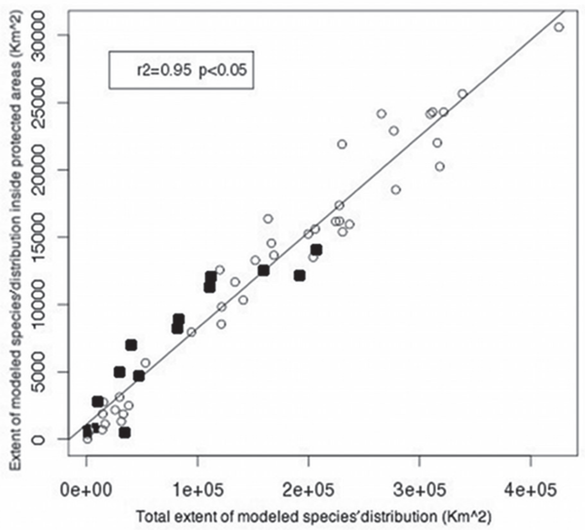

Figure 2. Correlation between the total extent of modelled species distribution and the overlap of this with protected areas, for the 56 *Pinus* taxa in Mexico. Black-filled symbols correspond to threatened species.

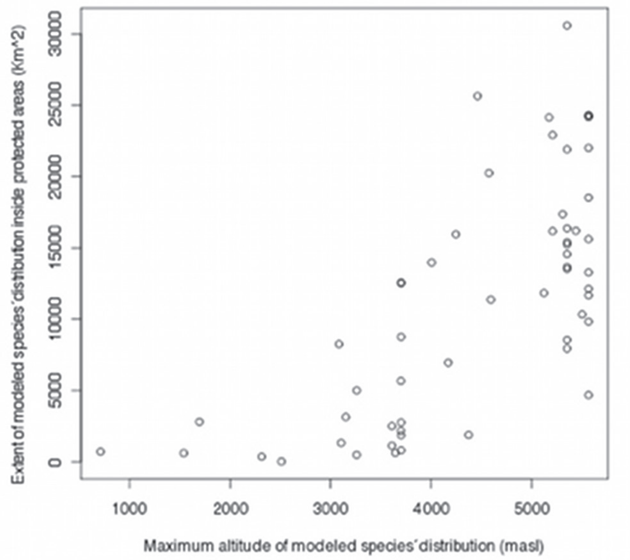

Figure 3. Scatter plot of the maximum altitude of the modelled distribution and the cover in protected areas for 56 pine species in Mexico.

Thirty nine taxa showed a representation below 10%, 14 taxa had a representation between 10% and 20%, and only 3 taxa were represented at levels of 20% or above.

The extent of the modelled distribution of threatened pine taxa was significantly smaller than that of other pine taxa (Mann-Whitney test U = 161, p<0.05) and showed a smaller overlap with protected areas (Mann-Whitney test U = 165, p<0.05). Compared to the non-threatened species, the threatened pine taxa showed a higher percentage deficit to the representation targets, which implies that they were less well represented in the Mexican protected areas (Mann-Whitney test U = 200, p<0.05).

All threatened taxa had at least 90 percent of their extent of modelled occurrence below 2800 m. *Pinus* species which prefer lower altitudes were sparse in protected areas (Fig. 3). The maximum elevation of the modelled distribution of threatened pine species was considerably lower than that of the non-threatened pine species (Mann-Whitney test U= 173.5, p<0.05).

Discussion

Overall, our results suggest that the present system of protected areas in Mexico fails to adequately protect pine species. Almost 70% of the analyzed species had less than 10% of their modelled distribution area protected. None of the taxa reached their representation targets (following Rodrigues et al., 2004b), implying that their modelled distribution had insufficient overlap with protected areas. In view of the economic importance of pines for Mexico, this outcome is troublesome, even more so if we take into account that the deforestation rate for the country is extremely high (Semarnat, 2009; INEGI, 2007).

Threatened pine species were less widely distributed than other pine species. Presumably this is because species that occur in scattered and sparsely distributed populations are prone to extinction due to anthropogenic or stochastic effects (Gaston, 2003). Also, pine species distributed at higher altitudes were better represented in protected areas than the ones distributed at lower elevations. This corroborates conclusions by Cantú et al. (2004) that high elevation areas were better represented in the Mexican protected areas. Further, it agrees with observations by CONABIO et al. (2007) that pine-oak forests in Mexico are poorly represented in protected areas and that this vegetation type should receive a conservation priority also because of its high biological value. Our results indicated that conservation targets should be directed particularly toward species with narrow distributions, which occur at low altitudes, such as *Pinus attenuata*, *Pinus cembroides* ssp. *lagunae*, *Pinus muricata*, *Pinus radiata* var. *binata,* and *Pinus rzedowskii*. Specifically, the populations of Vaca

Pinta and Chiqueritos in Michoacán for *P. rzedowskii,* Vereda and Picacho in Baja California Sur for *P. cembroides* ssp. *lagunae* and Colorado, Baja California, for *P. muricata* have been proposed by Delgado et al. (2008) as important regions for conservation following phylogenetic, genetic, and demographic information. Arguably, some of the important areas for establishing new protected areas with a focus on the conservation of the genus *Pinus* are the Sierra Madre Occidental and Sierra Madre del Sur, where many of the Mexican pine taxa exist and where protected areas are scarce.

Threatened pine species occurred at lower maximum elevations that non-threatened species, and were less well represented in protected areas. This substantiates the fact that at low elevations in Mexico, where human population density is highest, and where land cover changes and fragmentation impacts are most severe, more protection is needed (Fjeldså and Rahbek, 1998; Balmford et al., 2001; Menon et al., 2001; Cantú et al., 2004).

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