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Habitat characterization and modeling of the potential distribution of the Military Macaw (*Ara militaris*) in Mexico

Caracterización del hábitat y modelación de la distribución potencial de la guacamaya verde (*Ara militaris*) en México

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Abstract. Forest structure and composition have been used to assess the habitat characteristics that determine bird distributions. The patterns of distribution have been shaped by historical and ecological factors that play different roles at both temporal and spatial scales. The objectives of this research were to characterize the habitat of the endangered Military Macaw (*Ara militaris*) and evaluate the potential distribution of this species based on trends of land use changes in Mexico. We characterized the community structure and floristic composition of 8 forests that are currently used by the Military Macaw for breeding and feeding and compared the results with 6 similar forests characterized in other studies but without historical records of the presence of the Military Macaw. The Military Macaw preferred sites with high diversity of plant species dominated by trees from 4 to 15 m in height and from 5 to 90 cm in diameter at breast height. We identified 236 plant species in the 8 forests with 20 species (8.4%) used for nesting and feeding by the Military Macaw. The floristic composition is important for the presence of the Military Macaw because there were significant differences between forests with and without its presence. The potential area of distribution of the Military Macaw had decreased by 32% and the remnant areas are included in only 8 National Protected Areas. The protected areas of natural forests should be increased to preserve the sites of potential distribution and consequently the habitat of the Military Macaw in Mexico.

Key words: *Ara militaris*, bird conservation, ecological niche modeling, forest community structure, habitat characterization, habitat loss.

Resumen. La estructura y composición del bosque se ha utilizado para evaluar las características del hábitat que determinan la distribución de las aves. Los patrones de distribución han sido moldeadas por factores históricos y ecológicos que desempeñan diferentes papeles en ambas escalas temporales y espaciales. Los objetivos de esta investigación fueron caracterizar el hábitat de la guacamaya verde en peligro de extinción (*Ara militaris*) y evaluar su distribución potencial sobre las tendencias de los cambios de uso del suelo en México. Se caracterizó la estructura de la comunidad y la composición florística de 8 fragmentos remanentes de bosque que actualmente utiliza la guacamaya verde para reproducirse y alimentarse, y se compararon estos resultados con los obtenidos en bosques similares en otros estudios pero sin registros de la presencia de guacamaya verde. La guacamaya verde prefiere zonas con una alta diversidad de plantas, dominadas por árboles de 4 a 15 m de altura y de 5 a 90 cm de diámetro a la altura del pecho en las 8 localidades muestreadas. Ser identificaron 236 especies de plantas en los 8 sitios de bosque de las cuales 20 (8.4%) son utilizadas para la anidación y la alimentación de la guacamaya verde. La composición florística es importante para la presencia de estas aves, ya que hubo diferencias significativas en esta composición entre los bosques con y sin su presencia. El área de distribución potencial de esta guacamaya ha disminuido en un 32% y las áreas remanentes están incluidas únicamente en 8 Áreas Naturales Protegidas. Las áreas protegidas de bosques naturales deben de incrementarse para conservar los sitios de distribución potencial y en consecuencia el hábitat de la guacamaya verde en México.

Palabras clave: *Ara militaris*, conservación de aves, modelación de nicho ecológico, caracterización de hábitat, estructura de la comunidad del bosque, pérdida de hábitat.

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Introduction

Forest structure and composition have been used to assess the habitat characteristics that determine bird distributions (Gillespie and Walter, 2001). Forest structure, such as leaf structural diversity, canopy coverage, volume and density of plants, and species composition, has been significantly correlated with bird distribution patterns (Gillespie and Walter, 2001; Warketin et al., 2003). These patterns of distribution have been shaped by historical and ecological factors that play different roles at both temporal and spatial scales (Vuilleumier and Simberloff, 1980; Hutto et al., 1986; Cherril and McClean, 1997; Gaston and Fuller, 2009). Food availability and habitat type determine the geographic distribution of bird species (Hutto, 1985; Orians and Wittenberger, 1991; Luke and Zack, 2001) because habitat selection by birds must ensure the availability of resources for food, nesting areas, and refuge against natural predators (Márquez-Olivas et al., 2002; Canales-del-Castillo et al., 2010; Emrick et al., 2010).

Characterization of preferred habitat of bird species could facilitate the prediction of the species' ability to respond to changes over time and space (Rotenberry, 1978), and eventually, this information may serve to support conservation policies if populations become threatened (Brower et al., 1990).

Moreover, recording the distribution and changes in forest coverage at different scales and times and mapping the physical and environmental characteristics of different ecosystems, allow conservationists to anticipate changes in land use and to suggest plans for appropriate natural resource management (Wadsworth and Treweek, 1999; Ríos-Muñoz and Navarro-Sigüenza, 2009; Contreras-Medina et al., 2010), that enable animal preservation in species threatened with extinction.

The Military Macaw (*Ara militaris*) is a species of conservation concern in Mexico, with a current estimated population size of less than 10,000 individuals and a clearly declining trend in that number (Collar, 1997; Snyder et al., 2000; Bird Life International, 2011). This species is included in the Appendix I of the Convention on International Trade of Endangered Species of Fauna and Flora (CITES, 1998) and is considered to be globally vulnerable (Bird Life International, 2011). In Mexico, the species is considered endangered according to federal regulations (Norma Oficial Mexicana, Nom-059-Semarnat-2010). Habitat destruction and illegal trade have been recognized as the main threats for survivorship of the Military Macaw (Íñigo-Elías, 2005).

The distribution of the Military Macaw ranges from Mexico (Sonora to Oaxaca states) to South America, with a major distribution gap in Central America (Collar, 1997; Bird Life International, 2011) that is occupied by the great Green Macaw (*Ara ambigua*). The Military Macaw lives in dry to semi-humid, warm sub-humid (Carreón, 1997; Rivera-Ortíz et al., 2008), and temperate (Juniper and Parr, 1998; Cruz-Nieto et al., 2006; Nocedal et al., 2006) climates with summer rains. During the reproductive season, the species distribution ranges from 0 to 2 500 m in altitude (Carreón, 1997; Rivera-Ortíz et al., 2008; Contreras-González et al., 2009).

The Military Macaw nests in holes in cliffs and in living or dead trees with a diameter at breast height (DBH) from 67 to 205 cm (Carreón, 1997). Locally, the species is considered a specialist feeder because it consumes few plant species (13 to 20) of the total species richness of a forest (Loza, 1997; Gaucín, 2000; Flores and Sierra, 2004; Contreras-González et al., 2009).

Despite its endangered status, a habitat characterization of sites for breeding, foraging and roosting of the Military Macaw has yet to be conducted. This information and a record of the distribution range of this bird species are critical in Mexico to design conservation actions. In this paper, we characterized the habitat of the Military Macaw based on composition and structural traits of forests used by the Military Macaw for feeding and reproduction. We also modeled the potential distribution of the Military Macaw based on its ecological niche traits and the geographic distribution of associated tree species that are considered suitable habitats for the species. We conducted this study to provide information to support conservation efforts for the Military Macaw in Mexico.

Materials and methods

Study areas. This study was carried out in 8 sites in Mexico. The selected sites contained some of the largest populations reported for the Military Macaw and covered most of the distribution range of the species in Mexico (Gaucín, 2000; Gómez, 2004; Rubio et al., 2007; Rivera-Ortíz et al., 2008; Jiménez-Arcos et al., 2012). Five of the sites were located on the Pacific slope: La Sierrita, Sonora; La Reserva de Nuestra Señora del Mineral, Sinaloa; El Mirador del Águila, Nayarit; El Tuito, Jalisco, and Papalutla, Guerrero. Two other areas were located on the Gulf of Mexico slope: El Cielo, Tamaulipas and Santa María de Cocos, Querétaro, and another site was located in central Mexico: Santa María Tecomavaca, Oaxaca (Table 1; Fig. 1).

Habitat structure: characterization. Sampling was conducted in the 8 sites where the Military Macaw was observed nesting, roosting, or foraging in 2010 and 2011. We recorded the tree coverage and the density of plant species, growth form, total plant density, leaf strata

Table 1. Sampling sites for the habitat characterization of *Ara militaris*

Locality (state)	*Location*	*Altitude* (m)	Precipitation *(mm)*	*Temperature (ºC)*	*Estimated area* (km^2)	*Vegetation*	*Estimated population size of the Military Macaw*	*References*
La Sierrita (Sonora)	26 °52'48" N 108 °34' 12" W	800-1 200	60	22	928	Tropical deciduous forest	38 individuals	Rivera-Ortiz F. A., unpublished results
Nuestra Señora del Mineral (Sinaloa)	24°24'44" N 106°41'22" W	500-1 800	250	24	512	Tropical deciduous forest	25-40 individuals	Rubio et al., 2007
El Mirador del Águila (Nayarit)	21°30'28" N 104°55'47" W	600-1 200	1 121	21	524	Tropical subdeciduous forest	50 individuals	Rivera-Ortiz F. A., unpublished results
El Tuito (Jalisco)	20°17'35" N 105°23'6.4" W	0-400	800	26	1 001	Tropical subdeciduous forest	14-24 individuals	Rivera-Ortiz F. A., unpublished results
Papalutla (Guerrero)	18°01'20.3" N 98°54'16.1" W	630-1 600	1 200	30	600	Tropical deciduous forest	25-35 individuals	Jiménez-Arcos et al., 2012
Santa María Tecomavaca (Oaxaca)	17°51'43" N 97°02'40" W	660-820	400	22	41	Tropical deciduous forest	76 individuals	Rivera-Ortiz et al., 2008
El Cielo (Tamaulipas)	23°04'22" N 99°09'24" W	700-1 400	1 800	18	1 445	Tropical subdeciduous forest	35-40 individuals	Rivera-Ortiz F. A., unpublished results
Santa María de Cocos (Querétaro)	21°18'37" N 99°40'4" W	700-1 800	400	22	731	Tropical deciduous forest	70 individuals	Gaucín, 2000

diversity (LSD), plant species richness (S), plant diversity (H'), and importance-values index (IVI) (Krebs, 1985; Brower et al., 1990). The sampling included all woody trees with stems with a diameter at breast height (DBH) of 10 cm or more and shrubs taller than 1.5 m, because the Military Macaw uses different layers of the canopy forests (Forshaw, 1989).

We conducted sampling efforts directed to specific zones of nesting, roosting, or feeding the Military Macaw in each site. In these specific areas, we corroborated the presence of the species and measured vegetation cover using transects covering representative areas of vegetation used by the Military Macaw (Fig. 1). In each site, 16 transects of 50 m^2 were divided into 4 transects of 25 m^2 each, and oriented to the 4 cardinal points. The plant density was obtained by placing a rod vertically on the forest floor every 1.5 m to record the total number of plants with which the rod made contact. This procedure was repeated until 16 records were obtained along the 4 transects of each plot. For each of the trees, the name, the number of contacts with the rod as well as the height, coverage, and DBH were recorded. Plant specimens were deposited at the Herbarium of FES Iztacala (IZTA) at the Universidad Nacional Autónoma de México (UNAM).

The density of trees and shrubs (total individuals / area) and species coverage (coverage= (π x major diameter x minor diameter) / 2) according to each growth form were estimated. To estimate the LSD, the heights of the contacted plants were grouped in 16 strata of 2 m in height (0-2 m stratum, 2.1-4 m stratum and so on, up to the 26.1-28 m stratum) and the LSD based on the Shannon-Wiener diversity index was calculated within each stratification (MacArthur and MacArthur, 1961). Using the abundance, frequency, and vegetation coverage data of each species, we calculated the importance value index (Ar + Fr + Cr= 0 to 3) for plant species and growth forms.

An analysis of similarity of structure and composition of plant species between sites with and without presence of the Military Macaw to date was conducted. Information of sites without record of the Military Macaw was obtained from available reports (Table 2).

Statistical analyses: comparison of structure and floristic composition. Data were tested for statistical normality using Shapiro-Wilk test and Levene's homogeneity of variance using SPSS software (SPSS, 2003). The data were $\log_{10}$ transformed when comparisons were made using parametric tests (Sokal and Rohlf, 1979). The differences in height, coverage, and DBH were compared using an Anova (Siegel and Castellan, 2003).

Comparisons of values of plant density and diversity by sampling area were performed using a permutational analysis of variance (Permanova) (Anderson, 2001, 2005).

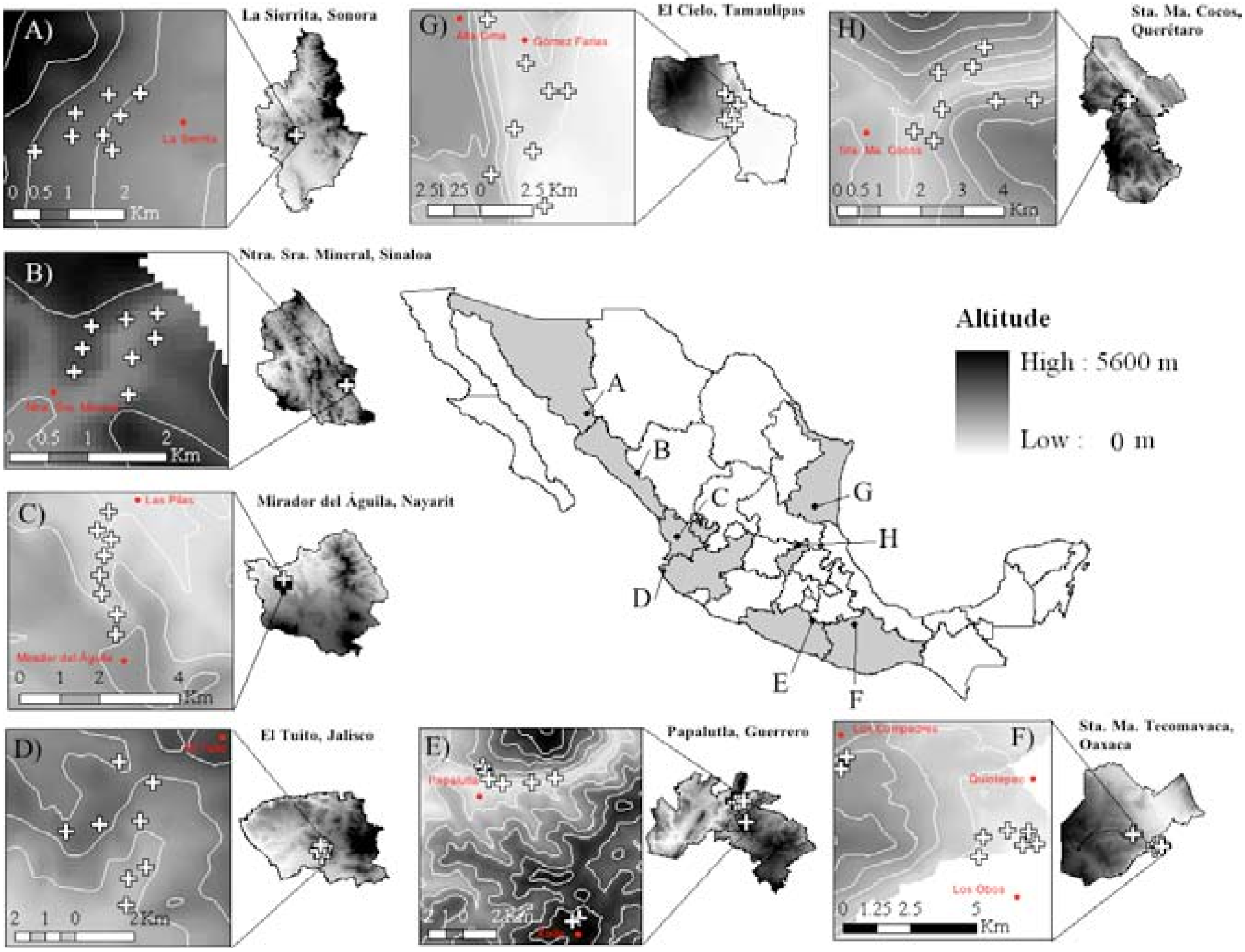

Figure 1. Sampling areas of *Ara militaris* along its distribution in Mexico. A, La Sierrita, Sonora; B, Nuestra Señora del Mineral, Sinaloa; C, Mirador del Águila, Nayarit; D, El Tuito, Jalisco; E, Papalutla, Guerrero; F, Santa María Tecomavaca, Oaxaca; G, El Cielo, Tamaulipas, and H, Santa María de Cocos, Querétaro. White crosses indicate the vegetation transects for habitat characterization of *Ara militaris*.

We used the Euclidean distance measure as recommended by Vázquez (2007). All of the tests were subjected to 9 999 permutations (α= 0.005) and the outcomes were analyzed using a t test based on an equal probability of significance.

The leaf structural diversity among localities was compared using the chi-square test (Siegel and Castellan, 2003). We used a t-test to compare the similarities in vegetation structure between the locations with and without records of Military Macaw (SPSS, 2003). In addition, the floristic composition between the localities with and without records of the Military Macaw was compared using the Sorensen's similarity index (PAST 2.12, 2001).

Distribution models, vegetation cover changes, and environmental overlap. The models were constructed using the Genetic algorithm for rule-set production (Garp) through the desktop garp interface (Scachetti-Pereira, 2001), which has proved to be a useful tool in understanding the ecological and evolutionary processes that explain the distribution of organisms (Peterson and Navarro-Sigüenza, 1999; Anderson et al., 2002; Nakazawa et al., 2004). Garp works in an iterative process where there are formation of rules that are evaluated and then considered to pass, or not, to the next generation (Stockwell and Noble, 1992, Stockwell and Peters, 1999).

We generated models of potential distribution of the Military Macaw, the potential distribution of the most important tree plant species that are used by the Military Macaw for feeding or nesting and 4 scenarios of land cover changes as follows.

Potential distribution models were created using 19 environmental variables derived from weather climatic stations stored in the Worldclim Project 1.4 (Hijmans et al., 2005) and 3 topographic layers derived from the Hydro 1k project (http://edcdaac.usgs.gov/gtopo30/hydro). Although it has been stated that the inclusion of all 19 bioclimatic variables will be prone to overfitting (Peterson and Nakazawa, 2008), the use of all variables represents a conservative and a more reliable approach to estimate the potential distribution of the species (Jakob et al., 2009).

The pixel spatial resolution was set as 0.02° by 0.02° (*ca*. 4 km^2). The biological information used for each explanatory and response species was obtained from bibliographic sources. The geographical coordinates of the historical records for Military Macaw were obtained from the "Atlas of the birds of Mexico" (Navarro-Sigüenza et al., 2003), which is the largest collection of specimens contained in Mexican and foreign collections, as well as records taken directly from fieldwork. The records obtained in the field were sightings of nesting sites, roosting, and feeding.

For plants, the geographical coordinates were obtained from the Global Biodiversity Information Facility (GBIF, http://www.gbif.org) and specialized references (Gordon, 1981; Mitchell and Daly, 1991; Gale and Pennington, 2004; Pennington and Sarukhán 2005; Rzedowski et al., 2005; Espinosa et al., 2006).

The biological information of each species was divided into training (50% of the data) and validation points (the remaining 50% of the data). In total, 100 replicates for each species were generated using a limit of convergence such that the model rules could not improve in more than 1% or 1 000 iterations. The validation of the models was made using a X^2 and using the training and testing data to evaluate the predictive capacities of the replicates (Peterson and Shaw 2003; Ríos-Muñoz and Navarro-Sigüenza, 2009). Then, we selected the 10 best models as suggested by Anderson et al. (2002) based on minor errors of omission and values of commission close to the median. These distribution models were summed to obtain only one final consensus model. The consensus model was used to establish a threshold of presence/absence for all the species, which accounted for at least 90% of the biological data (Ríos-Muñoz and Navarro-Sigüenza, 2009). Once the threshold was established, we created binary models to represent the presence/absence of the species.

The resulting distribution models were linked to watersheds and biogeographical provinces where the Military Macaw and plant species have been recorded. Hence, based upon the biogeographic history of each taxon, potential distribution models were obtained (Illoldi-Rangel and Escalante, 2008; Ríos-Muñoz and Navarro-Sigüenza, 2009). The resulting distribution scenarios were overlapped to depict coincident areas, and the final model considered as the potential distribution of the Military Macaw was the intersection with the plant species potential distributions.

To evaluate the change in vegetation cover, we used 4 databases of land use change in the country, the first for 1973-1976 was based on serial photographs (Peterson et al., 2006, Ríos-Muñoz and Navarro-Sigüenza, 2009), and the series II (1990's), III (2005), and IV (2010) of land use change in Mexico (Inegi, 2000, 2005, 2010). The use of the database linkage permitted an identification of the Military Macaw habitat loss assessment (Ríos-Muñoz and Navarro-Sigüenza, 2009). In this sense, the 4 databases were reclassified and were considered unsuitable zones for the distribution of the plant species and the macaw. These zones were urban, agricultural, forestry, livestock, grassland, and non-vegetated areas (Sánchez-Cordero et al., 2005; Peterson et al., 2006; Contreras-Medina et al., 2010). Finally, we calculated the percentage of the area occupied in each temporary stage to obtain the pattern of habitat loss for the area associated with tree species richness. For this calculation, we considered the areas remaining in the year 2011 that were contained in the Natural Protected Areas system (NPAs) and the Important Bird Areas (IBAs) for Mexico.

Data from the same climatic layers used in the creation of the models of potential distribution for each recording site were extracted to construct a matrix to determine

Table 2. Community structure of deciduous and subdeciduous tropical forests reported without the presence of *Ara militaris*

Locality	*Type of vegetation*	*Coverage (m^2 ha^{-1})*	*Height (m)*	*DBH (cm)*	*Source*
El Limón, Morelos	Tropical deciduous forest	34.7	5.7	5.35	Trejo (1998)
Región Costa, Oaxaca	Tropical deciduous forest	23.4	5.53	6.58	Salas-Morales (2002)
La Trinitaria, Chiapas	Tropical deciduous forest	46.5	7.8	6.14	Trejo (1998)
Papantla, Veracruz	Tropical subdeciduous forest	152.95	27.0	50.75	Basañez et al. (2008)
Sayil, Yucatán	Tropical deciduous forest	36.7	7.9	3.3	Trejo (1998)
Tzucacab, Yucatán	Tropical subdeciduous forest	—	8.7	4.31	Zamora et al. (2008)

the environmental overlap between the Military Macaw and the most important associated tree species. With this matrix, the variation of 19 environmental parameters and altitude were subjected to Principal Component Analysis (Pca) (Novak et al., 2010; Janzekovic and Novak, 2012) and to a discriminant analysis to identify if there was a separation between species (Military Macaw and tree species). Ellipses at 95% confidence for each species were estimated (Novak et al., 2010; Janzekovic and Novak, 2012). The overlap between the areas of the ellipses was calculated using the Jacquard index ranging from 0-1 (Real and Vargas, 1996). The statistics were performed in R 3. 0. 1. (R Development Core Team, 2008).

Results

Habitat characterization. A total of 236 plant species were recorded in the 8 sampled sites. We quantified a total of 1 353 trees and 424 shrubs in the 8 sampling sites. The sites with the highest plant density were Salazares (297 ind/ha) and El Tuito (291 ind/ha). In contrast, the sites with the lowest densities were La Sierrita (177 ind/ha) and Papalutla (121 ind/ha). However, no significant differences among sites were detected ($F_{7, 56}$= 0.95, p> 0.05). The tree growth form prevailed in all the sites (Table 3).

The vertical forest structure composed of 16 strata showed significant differences among the 8 sampled sites (X^2= 36.124, D. F.= 15, p< 0.001); the height strata varied from 0 to 28 m across the sites (Table 3). Trees and shrubs ranging from 2 to 10 m in height dominated the vertical forest stratification in the 8 sites; however, in the localities of El Mirador del Aguila and El Cielo, the tallest trees reached over 26 m (Fig. 2).

The highest species richness was documented in El Tuito (63 species), followed by Papalutla (59 species) and Nuestra Señora del Mineral (46 species); the site with the lowest species richness was Santa María de Cocos (22 species) (Table 3). The sites with the highest plant diversity were Papalutla (H' = 3.8) and El Tuito (H' = 3.5), while Santa María de Cocos had the lowest diversity (H'= 2.2). The analysis of permutational variance indicated that the diversity of plant communities was not significantly different among the sampling sites ($F_{7, 40}$= 0.83, p> 0.05) (Table 3).

The tree coverage significantly differed among the sites ($F_{7, 38}$= 0.56, p< 0.001) (Table 3). The sites with the greatest tree coverage were Mirador del Águila (162.85 m^2) and El Cielo (118.28 m^2). In contrast, the lowest tree coverage was documented in Papalutla (39.26 m^2) and Santa María de Cocos (50.73 m^2). The tree growth form had the highest coverage values in all of the sampling sites. The areas with plant species with greater height and larger DBH were Mirador del Águila, El Cielo, and El Tuito (Table 3). We found significant differences in height ($F_{7,38}$= 20.17, p< 0.001) and DBH ($F_{7, 38}$= 5.63, p< 0.001) among the sites.

The IVI values showed that plants sampled in all of the sites were highly variable (Appendix 1, supporting information). A total of 14 tree species (*Brosimum alicastrum*, *Bursera simaruba*, *Ceiba aescutifolia*, *Ceiba pentandra*, *Cyrtocarpa procera*, *Guaiacum coulteri, Guazuma ulmifolia*, *Hura polyandra*, *Haematoxylon brassileto*, *Ipomea arborences*, *Lysiloma divaricata*, *Lysiloma microphylla, Plumeria rubra*, and *Taxodium mucronatum*) had an IVI above 0.20 and were used for modeling their distribution in association with the modeling of the Military Macaw (see the corresponding section below).

The plants that showed the highest values of IVI were *Lysiloma divaricata, L. microphyla, Brosimum alicastrum, Hura polyandra*, and *Cyrtocarpa procera*. Important plant species that were present in more than one site were: *L. divaricata, B. alicastrum, H. polyandra, Taxodium mucronatum*, *Bursera simaruba*, and *Guazuma ulmifolia*. With the results of structure and composition obtained, it was observed that plant species with highest IVIs are those that the Military Macaw uses for feeding and nesting (Appendix 1).

Comparison of structure and floristic composition. In the vegetation structure, no significant differences were found comparing the cover height and DBH between sites with and without the Military Macaw [coverage ($t_{(11)}$= 0.987, p> 0.05), height ($t_{(12)}$= 1780, p> 0.05) and DBH ($t_{(12)}$= 15, p> 0.05)], indicating that the forests were structurally similar. A comparison of Sorensen´s similarity index among the sites confirmed 2 clearly separated groups; one contained those sites with records of the presence of the Military Macaw, and a second group formed by sites without the bird (Fig. 3).

Distribution models, land cover changes, and environmental overlap. All the models obtained presented predictions above the expected by random (X^2 test, all models: p< 0.01, D. F.= 1), Also, the potential distribution of the Military Macaw showed low levels of omission (i.e., the model was successful in predicting most of the primary source data), indicating a predictive power above 90%. Figure 4 shows the modeled distribution potential map of the Military Macaw and the most important plant species for feeding and nesting.

We analyzed the potential distribution and species richness of the important plants associated with the Military Macaw under 4 scenarios of land use change for the country (Fig. 4). In the potential distribution map without land use, the sites located in the Pacific slope had greater availability

Table 3. Habitat characteristics of *Ara militaris* in Mexico

Locality	*LSD*	*H´*	*S*	*Coverage* ($m^2 ha^{-1}$)	*Height* (*m*)	*Density* (*Ind./ ha*)		*DBH* (*cm*)
						Trees	*Shrubs*	
La Sierrita	1.78	3.1	36	68.44 ± 14.11	16.41 ± 4.93	107	70	7.35 ± 0.74
Nuestra Señora del Mineral	1.90	3.2	46	81.44 ± 10.46	17.10 ± 1.16	179	90	8.88 ± 0.63
Salazares	2.57	2.7	37	162.85 ± 22.83	27.23 ± 3.00	149	48	140.50±1.7
El Tuito	2.13	3.5	63	96.24 ± 16.21	18.79 ± 2.36	245	46	74.70± 0.38
Papalutla	1.52	3.8	59	39.26 ± 6.74	10.66 ± 2.30	90	41	4.52 ± 0.74
Santa María Tecomavaca	1.19	3.2	38	58.82 ± 14.93	13.82 ± 2.42	166	21	2.93 ± 0.20
El Cielo, Tamaulipas	2.43	2.8	35	118.28 ± 22.40	23.91 ± 3.95	199	69	123.10±1.1
Santa María de Cocos, Querétaro	1.54	2.2	22	50.73 ± 4.52	9.78 ± 1.25	218	39	5.62 ± 0.39

LSD= leaf strata diversity; H´= plant diversity; S= plant richness; DBH= diameter at breast height.
General values of coverage, DBH and height are the averages of each sampling site ± standard deviation.

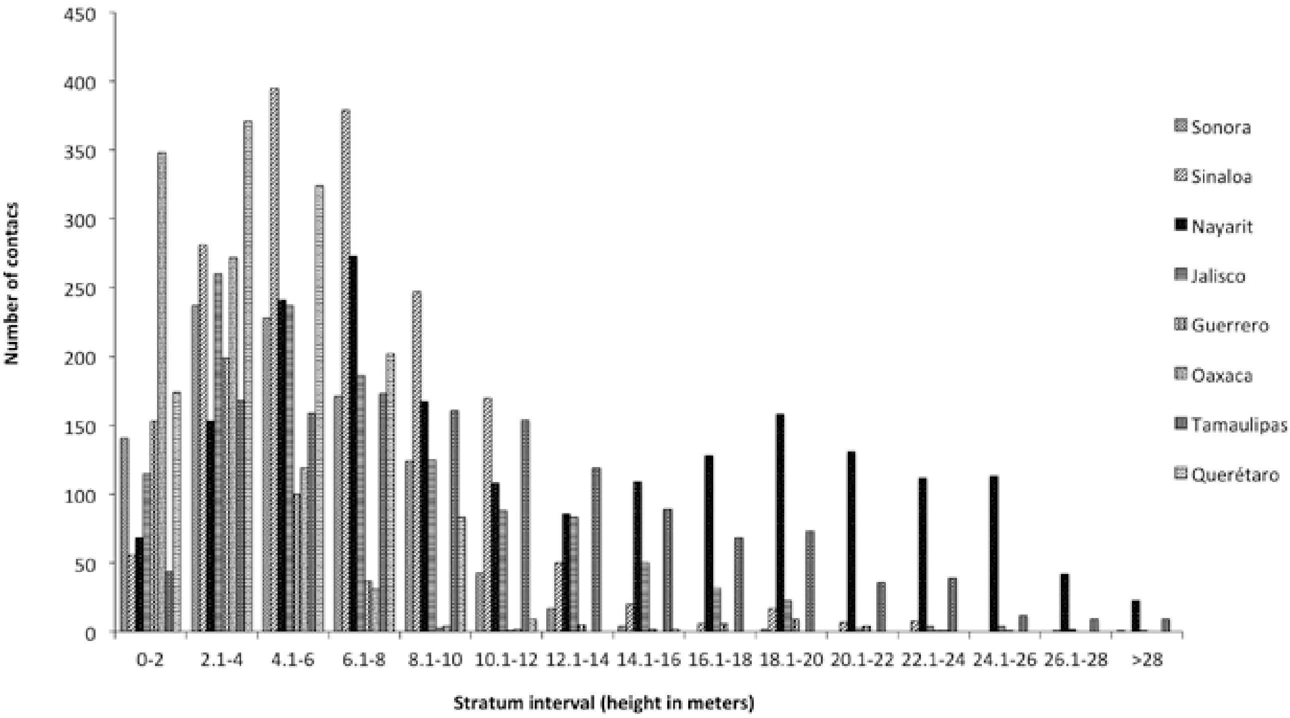

Figure 2. Vertical structure of the habitat of *Ara militaris* in Sonora, Sinaloa, Guerrero, Oaxaca, Querétaro, Jalisco, Nayarit, and Tamaulipas.

of resources (plant richness) compared with sites in eastern Mexico (Fig. 4). The highest number of species (12 to 14 species) was found scattered from Nayarit to Oaxaca in forest fragments that occupied less than 7% of the potential range of the Military Macaw habitat (Fig. 5). The 4 species that the Military Macaw predominantly relies on for food resources occupied slightly more than 28% of the potential distribution (Fig. 5).

Analyzing the changes in land use from those observed in the original map (without land use) in the 1976 scenario indicated that areas with 2 to 6 species have been the most affected by the change in land use, with a reduction of 32% to 48% of their original distribution. In the Series III and Series IV, it is shown that the areas with 4 and 6 species have had a decrease of 2% and 3% respectively with respect the Series II, showing a decrease of 50%-51% of the potential distribution in comparison with the original distribution. This finding is in contrast to other areas that had 7 and 14 plant species, which were not significantly affected by land use changes, with only 10%

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of the original distribution reduced under the 4 scenarios (1976, 2000, 2005, 2010) (Figs. 4, 5).

The potential distribution of Military Macaw in Mexico suggests the existence of 226 000 km^2 of suitable climatic area without considering any impact caused by changing land use. When changes were considered, the estimated remaining area was 182 000 km^2, a 21.12% reduction of the original area in the 1976 scenario. For Series II, the estimation was 160 000 km^2 (28.82% reduction) and for Series III, the estimated remaining habitat was 158 000 km^2 (30.23% reduction), similar to Series IV with an estimated potential distribution of 154 000 km^2 (32%) (Fig. 4). This pattern showed a drastic decrease in the percentage of forest cover reaching up to 32% for the species. In 2011, the calculation of protected areas available for the Military Macaw in NPAs and IBAs only accounted for 5% and 15%, respectively, of 100% (154 000 km^2) of the area distributed in 26 NPAs and 43 IBAs, along the Sierra Madre Occidental and 5 NPAs and 19 IBAs in the Sierra Madre Oriental. In the western zone, the potential area was in Sinaloa, Durango, and Guerrero, and did not include any NPAs. In the eastern zone, the NPAs and IBAs were well represented through the potential distribution of the Military Macaw.

In the PCA, component 1 explained 37.8% and component 2 explained 25.8% of the total variance of 19 environmental variables and altitude; PCA showed a single group (Fig. 6). In the discriminant analysis, the component LD1 explained 53.0 % and LD2 component explained 18.0 %; there was a clear overlap of environmental requirements of the Military Macaw with the 14 most important tree species associated to its distribution (Fig. 6). The projections of the environmental dimensions of Military Macaw and the 14 tree species are represented by ellipses in Figure 6. According to the Jacquard index, tree species distributions that showed the highest overlap with those of the Military Macaw were: *Lysiloma microphylla* (0.64), *Lysiloma divaricata* (0.53), *Guaiacum coulteri* (0.50), *Ipomea arborences* (0.50), *Hura polyandra* (0.46), *Plumeria rubra* (0.45), *Guazuma ulmifolia* (0.39), *Haematoxylon brassileto* (0.37), and *Ceiba aescutifolia* (.36). Species that showed lower overlap with Military Macaw were: *Cyrtocarpa procera* (0.27), *Taxodium mucronatum* (0.26), *Ceiba pentandra* (0.22), *Bursera simaruba* (0.16), and *Brosimum alicastrum* (0.14)

Discussion

Habitat characterization. The structural variables of the Military Macaw habitat indicated that the type of vegetation influenced the habitat selection. The Military Macaw is considered a canopy species (Íñigo-Elías, 1996; Loza,

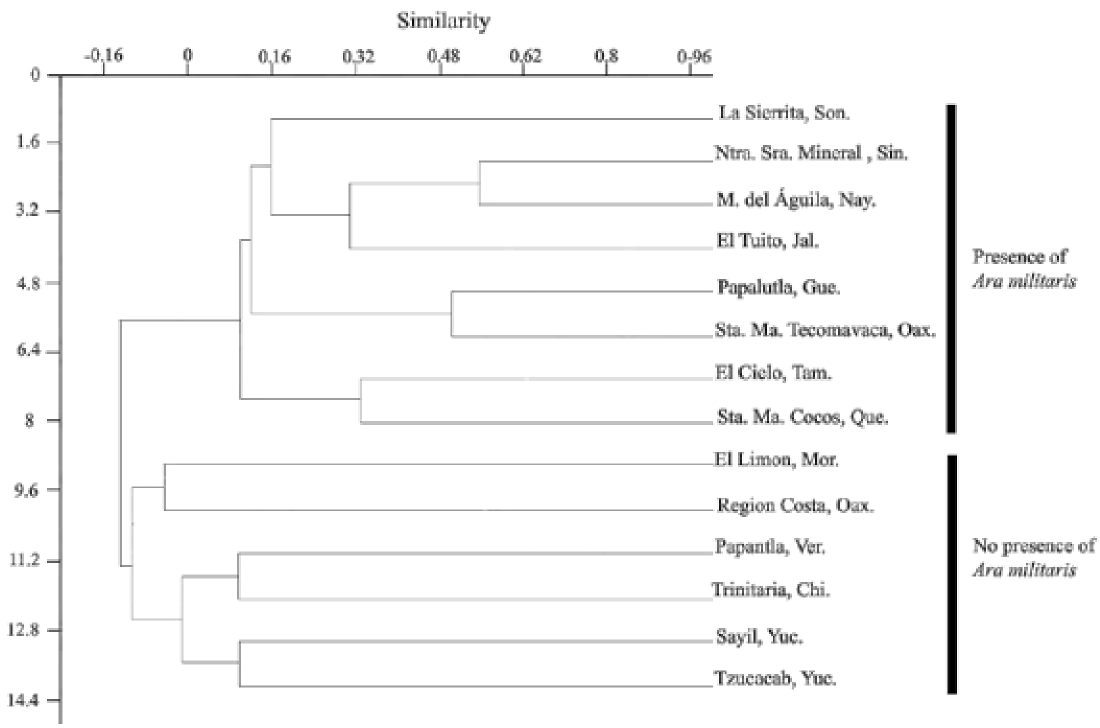

Figure 3. Cluster analyses using the Sorensen's similarity values of sites with and without presence of *Ara militaris*.

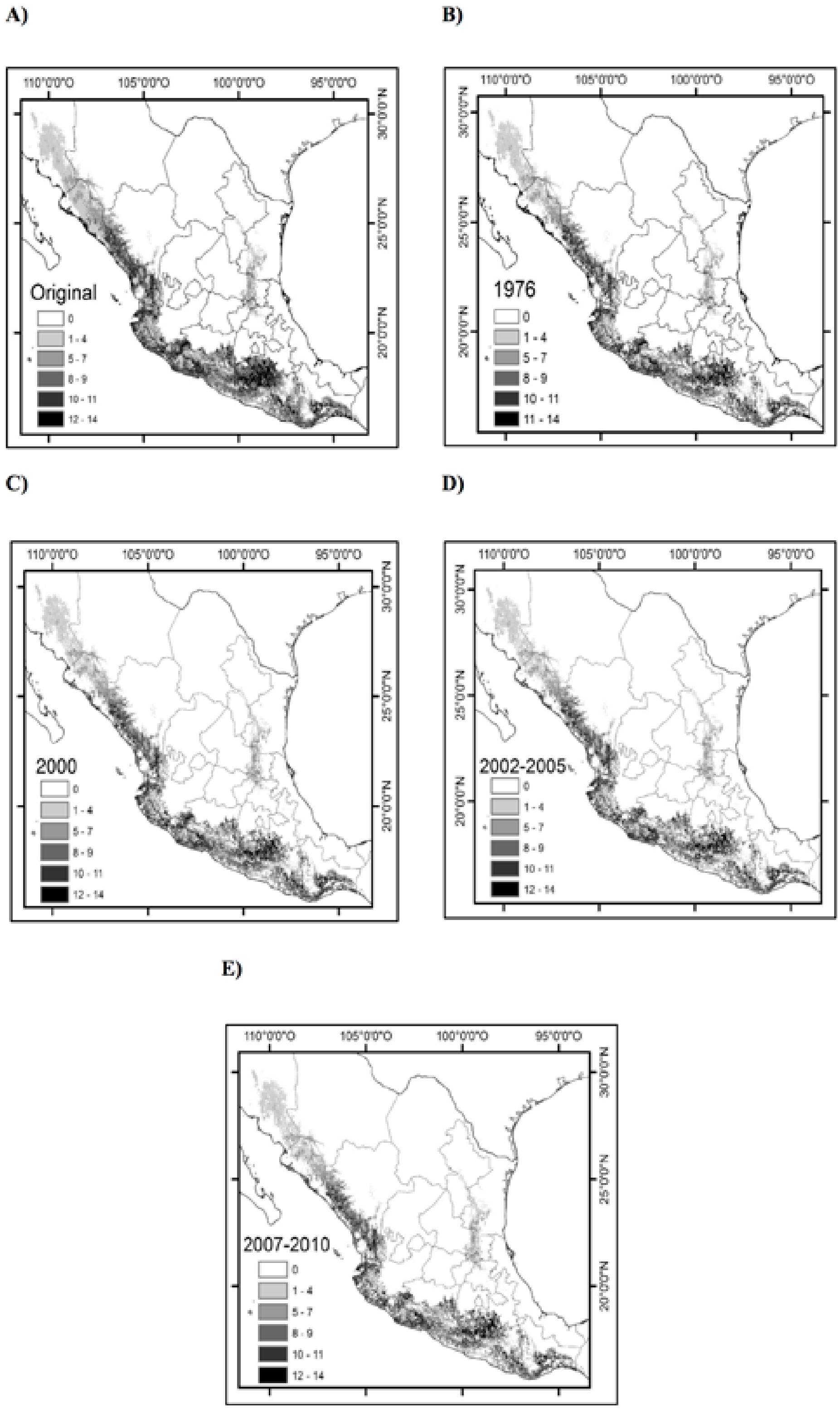

Figure 4. Models of potential geographical distribution of *Ara militaris* in Mexico. A, regardless of changing land use; B, scenario of changing land use of 1976; C, scenario of changing land use of year 2000 (Series II); D, scenario of changing land use of 2005 (Series III), and E, scenario of changing land use of 2010 (Series IV).

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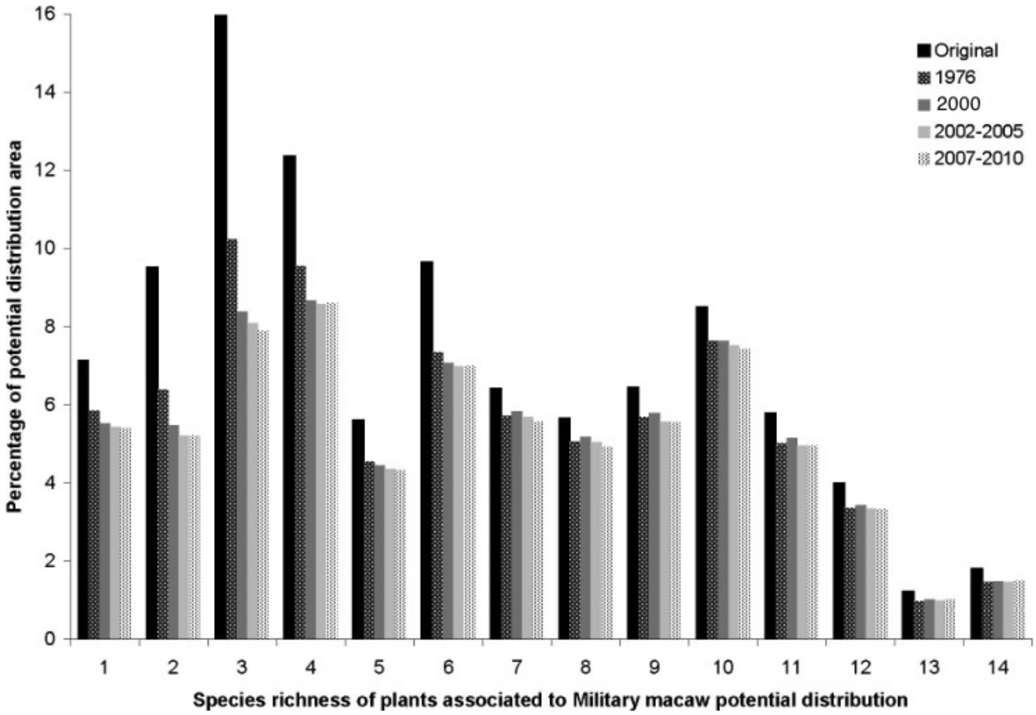

Figure 5. Patterns of plant species richness associated with the hypothetical distribution of *Ara militaris* in Mexico. They represent the conditions of the original vegetation and its amendments considering vegetation cover assessments for 1976, 2000 (Series II), 2005 (Series III), and 2010 (Series IV).

1997; Gómez, 2004) because it requires large canopy trees of deciduous and subdeciduous forests for feeding, breeding, and nesting behavior as well as protection against predators and thermal cover (Forshaw, 1989; Collar and Juniper, 1992; Collar, 1997; Loza, 1997; Íñigo-Elías, 1999; Salazar, 2001; Peterson et al., 2004; Rivera-Ortiz et al., 2008; Contreras-González et al., 2009). This species nests in trees of at least 15 m in height and the nests are 90 cm wide. In the nesting sites of El Mirador del Aguila, El Tuito, and El Cielo, the trees had the required structural characteristics for nesting (Collar, 1997; Loza 1997). The Military Macaw has the ability to shift its nesting sites to inaccessible sites such as steep cliffs in well-preserved areas: in La Sierrita, Papalutla, Santa María Tecomavaca, and Santa María de Cocos (Carreón, 1997; Gómez, 2004; Rivera-Ortiz et al., 2008).

The suitability of habitats for the Military Macaw requires the presence of certain genera of trees, such as *Brosimum*, *Cyrtocarpa*, *Celtis*, *Hura*, *Quercus*, *Bunchonsia*, *Lysiloma*, and *Bursera*; plant species of these genera have been reported in the distribution of the Military Macaw in Mexico as important sources either for nesting or as food supply by different authors (Carreón, 1997; Loza, 1997; Gaucín, 2000 and Contreras-González et al., 2009). In populations of Colombia and Peru, species of *Hura* and *Bursera* are also reported as important trees for feeding (Flores and Sierra, 2004); these plant species contain a large amount of nutrients, such as lipids, carbohydrates, and proteins, that are important for egg laying and the development of chicks (Contreras-González et al., 2009)

Comparing the vegetation structure and floristic composition in sites with and without presence of the Military Macaw, we found significant differences in the floristic composition but structural similarities. These findings indicate the reliance of the Military Macaw on specific floristic composition, commonly found in bird specialists (such as the Military Macaw). This pattern is due to the close relationship between the availability of food resources and reproductive effort (Saunders, 1977; Saunders, 1990; Collar and Juniper, 1992) with significant implications for the conservation of this species (Ruth et al., 2003).

The information available to establish conservation strategies for the Military Macaw has been based mainly on the effects of illegal traffic and other biological and ecological aspects, such as abundance, demography, and reproduction (Carreón, 1997; Loza, 1997; Gaucin, 2000; Íñigo-Elías, 2000; Rivera-Ortíz et al., 2008; Contreras-

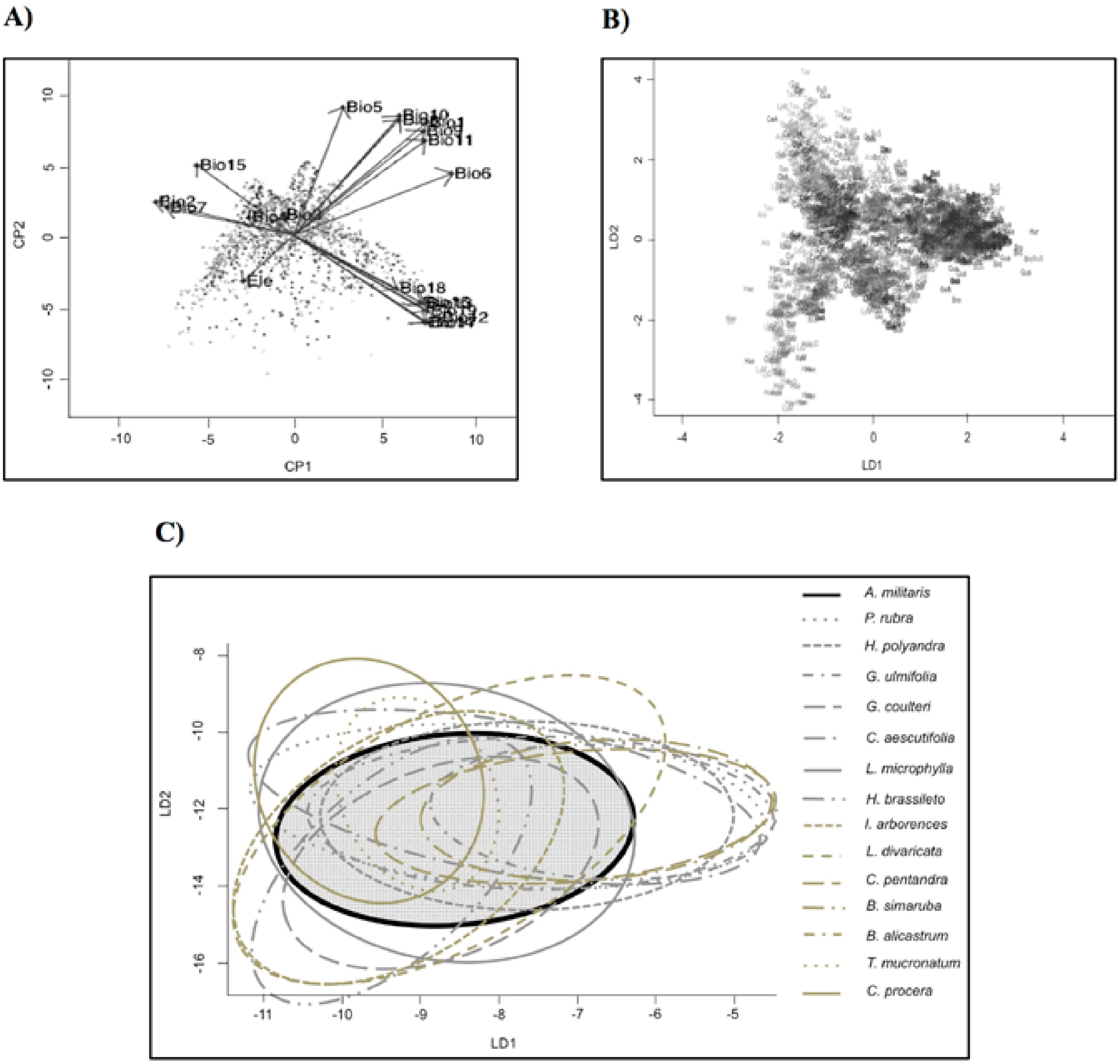

Figure 6. Environmental overlap. A, Pca of the 14 tree species and *Ara militaris* associated to 20 variables ecological (arrows) in the correlation circle; B, discriminant analysis of the 14 tree species and *Ara militaris*; C, ordination of the 19 environmental variables and altitude in 1st and 2nd LD axes. Ellipses (95% confidence) represent spatial overlap in the 14 tree species and *Ara militaris*.

González et al., 2009). Feeding and reproductive habitat modification has not taken into account in the analysis of land-use changes (Jetz and Rahbek, 2002).

The Military Macaw is not adequately protected in Mexico because only 5% of the potential distribution for the species is covered by the NPAs and 15% by IBAs. Of the 8 studied sites, 3 are located within a Biosphere Reserve (El Cielo, Santa María de Cocos, and Tecomavaca); one site is considered subject to ecological conservation (Cosalá), and la Sierrita Alamos is considered an area under the Protection of Flora and Fauna, while the other sites (El Tuito, Papalutla, and Salazares) are not protected (<htpp:/ www.economiadgm.gob.mx/ecologia /lista_ecolog.htm> November 18, 2010). We suggest that at least 30% of forests of the potential distribution should be protected to guarantee specific areas of nesting and feeding of the

Military Macaw.

Distribution models, vegetation cover changes, and environmental overlap. Ecological niche modeling represents a conceptualization of the distribution of favorable environmental conditions in which a species could be found (Peterson, 2001). Our models indicate that Military Macaw and 14 arboreal plant species are found in areas with similar characteristics, at least in a coarse environmental space; this is reinforced by the high overlap environmental found in the discriminant analysis. The reciprocal prediction of environmentally based overlap could indicate few ecological differences between the Military Macaw and tree species.

It is important to identify and preserve the habitats of endangered species with particular requirements such as the Military Macaw. We estimated a reduction of 32% in the potential distribution of the Military Macaw comparing 4 land-use change scenarios since 1976 to 2010. These changes were particularly dramatic when only 6 of the plant species that the Military Macaw relies on were present *(Lysiloma microphylla*, *Lysiloma divaricata*, *Hura polyandra*, *Ceiba aescutifolia*, *Guaiacum coulteri*, and *Ipomea arborences*). These findings indicated the potential negative impacts on the survival of the Military Macaw if reductions of available habitats occur as land-cover changes continue in the future (Peterson et al., 2006; Ríos-Muñoz and Navarro-Sigüenza, 2009; Contreras-Medina et al., 2010). This is supported by previous studies. Ríos-Muñoz and Navarro-Sigüenza (2009) reported a reduction of 28.5% in the available habitat of the Military Macaw by the year 2000. Marin-Togo et al. (2011) and Monterrubio-Rico et al. (2010) declared the Military Macaw locally extinct in the Mexican Pacific Coast (i.e., Michoacán, Guerrero, and Oaxaca states) and in coastal areas of more than 400 m in altitude, with a decrease of 16% of the distribution as of 2000.

The land-cover change in tropical rain forests has caused the highest rates of deforestation in the country (Trejo and Dirzo, 2000), and as a consequence, Mexican parrots have suffered severe habitat declines. Specifically, a drastic decrease has been reported in habitat occupied by *Ara macao* (Scarlet Macaw) (86% reduction), *Aratinga astec* (Aztec Parakeet) (48%), and *Pionus senilis* (White-crowned Parrot) (49%) (Ríos-Muñoz and Navarro-Sigüenza et al., 2009; Marín-Togo et al., 2011). Renton and Salinas-Melgoza (2004) found that fragmentation and climatic variations of habitats in seasonally dry forests could adversely affect the reproductive success of *Amazona finschi* (Liliac-crowned Parrot).

According to our results, the habitat of the Military Macaw in tropical dry forests has already been reduced drastically by almost 32%, endangering the viability of its populations. In addition, the illegal international trade of wild species has also seriously affected populations of the Military Macaw and this directly affects the loss of species distribution (Gaucín, 2000; Marín-Togo et al., 2011). Although models based on the intended habitat are very important to detect changes in the potential distribution of the Military Macaw in different scenarios, we must take into account the use of updated cartographic information of land-cover change and factors such as hunting and illegal capture to make better predictions for this species (Marin-Togo et al., 2011; Monterrubio-Rico et al., 2011).

Conservation implications. The present study provides information regarding the type of vegetation and species composition that is critical for the preservation of the Military Macaw. Our findings suggest the importance of knowing the floristic composition of the habitat of endangered species and the impact of land-use variation over time on the potential distribution of those species as a tool to direct conservation efforts. It is worth noting that the use of ecological niche models and geographic data of land-use change are fundamental tools to be considered in the conservation efforts of the Military Macaw. Therefore, the protection of suitable habitats and the implementation of sustainable activities should be prioritized in conservation strategies for the Military Macaw. Habitat degradation and capture of the Military Macaw for illegal trade must be stopped and the size and number of natural protected areas must be increased.

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