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MAESTRÍA Y DOCTORADO EN CIENCIAS AGROPECUARIAS Y RECURSOS NATURALES

DISTRIBUCIÓN POTENCIAL DE RAPACES AMENAZADAS EN MÉXICO: IMPLICACIONES PARA LA CONSERVACIÓN

TESIS

QUE PARA OBTENER EL GRADO DE DOCTOR EN CIENCIAS AGROPECUARIAS Y RECURSOS NATURALES

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I. RESUMEN

Las rapaces son un grupo de aves depredadoras que cubren un rol fundamental en los ecosistemas. Las amenazas principales a su sobrevivencia en México son: la perdida y fragmentación de su hábitat, la contaminación, en particular por plaguicidas, la cacería y el tráfico ilegal. Los objetivos principales del proyecto han sido determinar la distribución potencial de cuatro especies de aves rapaces, *Aquila chrysaetos*, *Spizaetus ornatus*, *Spizaetus tyrannus* y *Sarcoramphus papa*, el porcentaje de hábitat idóneo incluido en Áreas Naturales Protegidas e identificar las áreas prioritarias para la conservación. Las especies objeto de estudio están incluidas en diferentes categorías de riesgo de la lista IUCN y de la NOM-059 de SEMARNAT (2010) y el nivel de conocimiento y conservación de estas es muy bajo en el país, en particular se sabe muy poco de su distribución, lo cual es básico y necesario para planear estrategias de manejo y conservación. Para obtener la distribución potencial de las cuatro especies utilizamos el modelado de nicho ecológico, eligiendo ocho algoritmos y el método de consenso de la media ponderada. En el caso de *Aquila chrysaetos* el área altamente idónea para la especie resulta reducida en comparación a las pocas referencias que se tienen de su distribución histórica y las Áreas Naturales Protegidas insuficientes para su conservación. El área de alta idoneidad común a las tres especies neotropicales encuentra su máxima extensión y continuidad en la provincia del Petén donde domina la selva húmeda perennifolia o selva tropical, un ecosistema rico de biodiversidad e importante para la conservación de muchas especies. Un bajo porcentaje de áreas de alta idoneidad se encuentra incluido en Áreas Naturales Protegidas. En todos los casos el hábitat altamente idóneo para las especies resulta fragmentado, debido al sobrepastoreo bovino y ovino, a la deforestación para ganadería, agricultura y extracción de madera.

***Palabras claves**: águilas, conservación de rapaces, modelado de nicho ecológico, perdida de hábitat, rapaces, zopilote rey*

II. INTRODUCCIÓN GENERAL

En México se encuentran 1150 especies de aves de éstas, 212 son endémicas y 388 se encuentran en alguna categoría de riesgo. Las especies de rapaces son 58 y pertenecen a las familias Accipitridae, Falconidae y Cathartidae (SEMARNAT, 2010; Navarro-Sigüenza *et al*., 2014). Además, en todo el país ocurren 230 AICAs (Áreas de Importancia para la Conservación de las Aves) en las cuales están incluidas el 96% de todas las especies de aves presentes en México, el 90% de las especies amenazadas y todas las endémicas. Estas áreas son una herramienta útil para los tomadores de decisiones, para los científicos y para el sector turístico (CONABIO, 2014) pero no necesariamente son áreas protegidas legalmente (Arizmendi & Berlanga, 2007).

Las rapaces son un grupo de aves depredadoras que cubren un rol fundamental en los ecosistemas y muchas de ellas son especies sombrilla, centinela (o indicadoras) y banderas (Sergio *et al*., 2006; Newton, 2010); están al tope de la cadena alimenticia y tienen dietas muy diferenciadas y especializadas, por esto algunas de sus funciones en los ecosistemas pueden ser útiles también para la especie humana, por ejemplo, controlan las poblaciones de mamíferos pequeños, algunas de las cuales son dañinas para los cultivos, y los zopilotes eliminan rápidamente las carroñas de ganado o de otros animales, evitando la difusión de enfermedades peligrosas para el ganado y para la especie humana. Las amenazas principales a su sobrevivencia son: pérdida y fragmentación de su hábitat, contaminación, en particular por plaguicidas, cacería y tráfico ilegal (Puebla-Olivares *et al*., 2002; Thiollay, 2007; Sanvicente-López *et al*., 2010; Monroy-Ojeda *et al*., 2014).

Este proyecto se enfocó en el estudio de cuatro especies, tres águilas y un zopilote: *Aquila chrysaetos*, *Spizaetus ornatus*, *Spizaetus tyrannus* y *Sarcoramphus papa*, por la cantidad y calidad de datos disponibles de estas especies. El águila real (*A. chrysaetos canadensis* en el continente americano) tiene distribución neártica en México (Newton, 2010) mientras las demás (águila elegante, águila tirana y zopilote rey) tienen distribución neotropical (Birdlife, 2017). El nivel de conocimiento y conservación de las especies objetivo es muy bajo en el país, en particular se sabe muy poco de su distribución, un aspecto básico de la ecología de las especies y sobre todo necesario para planear estrategias de manejo y conservación. Los objetivos del trabajo fueron: 1) determinar la distribución potencial de las cuatro especies en México; 2) identificar las áreas de alta idoneidad y evaluar el porcentaje de coincidencia de estas con las áreas protegidas ya existentes en México; 3) proponer áreas y/o acciones prioritarias para el manejo y la conservación de las especies a nivel nacional.

Uno de los métodos actualmente más usados para estimar la distribución potencial de las especies a gran escala, reduciendo tiempos y costos de investigación, es el modelado de nicho ecológico (Monroy-Vilchis *et al*., 2015; Sunny *et al*., 2017). El uso de modelos ecológicos, se ha convertido cada vez más importante en la biología de la conservación y en el manejo de recursos naturales, debido a su versatilidad para una gran cantidad de aplicaciones, tales como: planificación de reservas, gestión de las especies invasoras, epidemiología, estudios a gran escala y cartografía de la biodiversidad, caracterización de la pérdida de hábitat, proyección del impacto del cambio climático en distribución de especies, elaboración de teorías evolucionistas, biogeografía y filogeografía (Corsi *et al*, 1999; Guisan & Zimmerman, 2000; Scott *et al*, 2002; Guisan y Thuiller, 2005; Araújo & New, 2006; Elith *et al*, 2011). Estos modelos pueden ser particularmente útiles en circunstancias de cantidad limitada de datos de sólo presencia, procedentes de bases de datos de herbarios, museos y observaciones directas, datos de literatura (Franklin, 2009); cuando se estudian especies raras o cuya abundancia y datos de entrenamiento son poco conocidos (Phillips *et al*., 2006) y sobre todo para estudios a gran escala (Corsi *et al*., 1999; Guisan & Zimmerman, 2000; Zarco-González *et al*., 2013; Rodríguez-Soto *et al*., 2017) y escala múltiple (Illera *et al*., 2010), donde un muestreo clásico necesitaría mucho más tiempo, dinero y recursos en general (Guisan & Zimmerman, 2000).

III. PRIMER ARTÍCULO

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Potential distribution of *Aquila chrysaetos* in Mexico: implications for conservation

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Abstract

The Golden Eagle (*Aquila chrysaetos*) has been poorly studied in Mexico. Even though it is listed as threatened in this country, partly because of habitat fragmentation and direct persecution, little is known of its distribution. We assessed the potential distribution of this species in Mexico using ecological niche modelling (ENFA, ANN, GARP, ED, SVM, Maxent) and the weighted average ensemble method. The models were evaluated using the Area Under the Curve (AUC) of the Receiver Operating Characteristics (ROC). We applied a threshold of 50% probability to obtain high suitability areas, we considered marginality and specialization calculated by ENFA and the most important variables to the model. We assessed and evaluated the percentage of high suitability area occurring in all Mexican NPAs (Natural Protected Areas). The performance of the ensemble model was high (AUC=0.93) and the most important variables contributing to the model were grasslands and tree cover percentage. The resulting high suitability area is considerably fragmented, it comprises 16% of the country, and just 8% of it is located in NPAs. We propose some urgent actions and conservation measures to face the main problems that are threatening the species in Mexico.

Keywords: ecological niche modelling, ensemble method, Golden Eagle, habitat loss, high suitability areas

1. Introduction

The Golden Eagle (*Aquila chrysaetos*, Linnaeus 1758) is largely distributed in the Nearctic and Palearctic regions and marginally in Indomalaya and tropical Africa with six subspecies (Watson, 2010). The species is included in the Appendix II of CITES and it is internationally categorized as Least Concern (IUCN, 2015) but its conservation status varies at a local level. In fact, the Golden Eagle is listed as threatened (P = en Peligro de extinción) in Mexico (SEMARNAT, 2010). *Aquila chrysaetos canadensis* is distributed in North America from Alaska and Canada to the centre of Mexico according to current reports (Kochert *et al*., 2002). Its populations were reported as stable in North America over the last 40 years (Birdlife International, 2018) but little is known about resident and migrating Mexican populations (Nocedal, 1993; Rodríguez-Estrella, 2002; De León-Girón *et al*., 2016).

Some local studies have been published in different states of Mexico (Rodríguez-Estrella *et al*., 1991; Rodríguez-Estrella, 2002; Lozano-Román, 2008; Urbina-Torres *et al*., 2009) and government management programs have been established (SEMARNAP, 1999; SEMARNAT, 2008). However, there remains much to learn about the natural history, abundance, and distribution of this species in the country.

Golden Eagle breeding populations are distributed mainly in northern and central Mexico (Rodríguez-Estrella, 2002; Ruiz-Campos *et al*., 2005; Lozano-Román, 2007, 2008; Jiménez-Pérez *et al*., 2009; Guerrero-Cárdenas *et al*., 2012; Bravo *et al*., 2015), although the species has been reported breeding in some southern locations (Winker *et al*., 1992; Urbina-Torres *et al*., 2009). As many as 600 pairs are estimated to present in Mexico (Lozano-Román, 2008).

The habitat of the Golden Eagle is characterized by the presence of cliffs, hills, mountains, and coniferous forests alternating with open spaces (grasslands and shrublands) from 0 to

5500 m.a.s.l. (Ferguson-Lees and Christie, 2006). It nests on cliffs and occasionally on trees (Rodríguez-Estrella, 1991; Eccardi, 2008; Watson, 2010). It is a territorial species, its home range can be extended for about 2,000 to 9,000 ha (Collopy and Edwards, 1989) and one pair can use different nests during different breeding seasons (Watson, 2010).

The Golden Eagle is an opportunistic species. Its main preys in Mexico are rodents and lagomorphs: *Lepus californicus* (Lozano-Román, 2007), *Sylvilagus audobonii* (Lozano-Román and Villalobos-Sánchez, 2003; Lozano-Román, 2007), *Spermophilus variegatus* (Lozano-Román, 2007; Eccardi, 2008), *Spermophilus mexicanus* (Lozano-Román, 2007).

The Golden Eagle is internationally recognized as flag and umbrella species (Leader-Williams and Dublin, 2000; Fascione *et al*., 2004) and is of special importance in Mexico because of its local historic and cultural significance (SEMARNAP, 1999).

Its populations suffered a substantial decline across the whole range, in the period between 1945 and 1965 due to the use of organochlorine pesticides (as DDT), direct persecution (hunting, poaching), and more recently because of electrocution from power lines (Eccardi, 2008; Katzner *et al*., 2012).

Nowadays the most important threat factors, for this species, are habitat loss and fragmentation (Watson, 2010; Katzner *et al*., 2012) because of deforestation, climate change, urbanization, permanent agriculture, overgrazing (Watson, 2010), and energy development projects (namely wind turbines and gas extraction) (Hawks Aloft Inc. 2005, 2006; Watson, 2010; Katzner *et al*., 2012), human disturbance and persecution (Watson, 2010).

The Mexican government has carried out a range of different conservation plans and promoted studies designed to generate information about the species since 1983. These have however delivered poor results at a local level (SEMARNAT, 2008), pointing to the need for a more complete, nation-wide study.

It is of utmost importance to update our knowledge of the distribution of this species, as well as to analyse how it has changed in recent years in order to plan better national conservation strategies.

In recent years, ecological niche modelling has become an important instrument in conservation biology, because of its versatility. It has been used in a range of applications such as: conservation planning (Corsi *et al*., 1999), invasive species management (Peterson & Robins, 2003), epidemiology (Peterson & Shaw, 2003), cartography of biodiversity (Ferrier *et al*., 2002), characterization of habitat loss (Preston *et al*., 2008), phylogeography (Chan *et al*., 2011), and assessing the impact of climate change on species distribution (Araújo and New, 2007).

Ecological niche models are based on hypotheses about the relationships between environmental variables and species occurrences (Guisan and Zimmerman, 2000). Models necessarily require numerous assumptions resulting in some variability in the final prediction. This is due to data quality and quantity, sampling method, scale choice, identification and selection of the predictor variables and limiting factors (Guisan and Zimmerman, 2000; Elith *et al*., 2002; Phillips *et al*., 2006). This predictive uncertainty can be reduced by using ensemble methods (Thuiller, 2004; Marmion *et al*., 2009; Comte and Grenouillet, 2013) a combination of individual models that ultimately lead to a more accurate prediction (Araújo and New, 2007; Marmion *et al*., 2009).

The goals of the present study are: 1. To generate an ecological niche model for the Golden Eagle in Mexico; 2. To identify the high suitability areas for the species in the country and assess the overlap with Natural Protected Areas; 3. To propose priority areas and actions for the conservation and management of the species in the country.

2. Methods

2.1 Study area

The study area (Figure 1) was delimited by biogeographic provinces (CONABIO, 1997) according to literature and available records. It includes almost the whole Mexican republic, excluding the Yucatan peninsula, where the species has never been recorded.

The area measures 1,813,375.44 km^2 and it is limited by the United States of America in the North, the Yucatan peninsula in the South-East, the Gulf of Mexico and the Caribbean Sea in the East, and the Pacific Ocean in the West. The extreme coordinates are: 32.74°N, 14.57°S, -118.39°W, -90.36°E. It includes all the Mexican climatic groups, from the driest to the most humid (De Alba and Reyes, 1998). The altitudinal range is 0-5,444 m.a.s.l.

2.2 Species data

We collated a database consisting of georeferenced records of the Golden Eagle, obtained from literature and online databases (GBIF, VertNet, Naturalista of CONABIO). We assessed each record according to locality, source, type of record (observation/collection), and observation, capture or collection date. We filtered the records deleting those lacking either geographical coordinates or date, as well as those deemed unreliable. Furthermore, only records from 1990 and later dates were considered for analysis, considering that the higher deforestation rate occurred in Mexico from 1964 to 1990 (FAO, 2001). We finally divided the filtered data in two groups: 70% were used to calibrate the models and 30% to evaluate them (Guisan and Zimmerman, 2000).

2.3 Predictive variables

We identified the most important variables related to the species' distribution and downloaded them as digital maps (Table 1). We unified the data for extreme coordinates, projection and resolution (1 km) (Monroy-Vilchis *et al*., 2015) using IDRISI Selva 17.0 (ClarkLabs, 2012) and verified possible correlations between them in Biomapper4 (Hirzel *et al*., 2009).

2.4 Models

We developed the models on Biomapper4 (Hirzel *et al*., 2009) which works with the Ecological Niche Factor Analysis (ENFA) algorithm (Hirzel *et al*., 2002), Maximum Entropy (MaxEnt) Species Distribution Modeling 3.3.3k (https://www.cs.princeton.edu/~schapire/maxent/) (Phillips *et al*., 2004) and openModeller 1.1.0 (http://openmodeller.sourceforge.net/index.html) using the algorithms: Artificial Neural Network (ANN) (Gevrey *et al*., 2003; Pearson *et al*., 2004), Environmental Distance (ED) (Hirzel and Arlettaz, 2003), Genetic Algorithms for Rule-set Production (GARP with Best Subsets–new openModeller implementation and DesktopGARP implementation) (Stockwell and Peters, 1999) and Support Vector Machine (SVM) (Cristianini and Scholkopf, 2002).

We evaluated the performance of the models using the AUC (Area Under the Curve) of the ROC curve (Receiver Operating Characteristics, Hanley and McNeil, 1982) on IDRISI Selva 17.0. We chose the models with AUC > 0.7 (moderate to high performance) (Manel *et al*., 2001) to develop the ensemble model (Marmion *et al*., 2009). We calculated two AUC for each model, the first based on 70% of the records (internal $AUC=AUC_i$) and the second based on the 30% (external $AUC=AUC_e$). We chose the models, to generate the ensemble model (Figure 2), using the external AUC and we calculated the ensemble (in the IDRISI calculator) using the weighted average formula which considers the internal AUC: $\Sigma(M_i \times AUC_i)/\Sigma(AUC_i)$ (M_i=model ith; AUC_i=internal AUC) (Marmion *et al*., 2009).

ENFA also calculated marginality, specialization and tolerance coefficients (Segurado and Araújo, 2004; Hirzel *et al*., 2004; Franklin, 2009).

2.5 High suitability areas and NPAs

We assessed the high suitability areas (Figure 3) by reclassifying the ensemble model (each pixel contains a probability value from 0 to 100) using a 50% probability threshold (Liu *et al*., 2005) and thus obtaining a binary map with two suitability classes (low <50% and high >50%).

We calculated on ArcMap 10.0 (ESRI, 2010): the total high suitability area; the percentage it occupies in the whole country; the percentage of high suitability areas in each province; the NPAs total area and the percentage of high suitability areas included in it.

3. Results

We assessed 501 total records and used 183 after filtering them (Figure 1).

We used ENFA (Median) (AUC= 0.86) and ED (AUC= 0.78) to generate the ensemble model (Figure 2), because of the better performance (AUC>0.7) obtained (Table 2) (Marmion *et al*. 2009).

ENFA calculated a global marginality of 0.63, a specialization global coefficient of 9.01 and a global tolerance of 0.11. Marginality was moderate, which means that the optimum state for the species doesn't differ very much from the environmental profile of the study area. Specialization is high and tolerance very low, indicating that the niche amplitude of the species is narrow (Hirzel *et al*., 2004).

The variables that contributed most to the ENFA model were: grasslands, with a marginality coefficient of 0.74 and tree cover percentage, with a coefficient of – 0.40.

The AUC of the ensemble model was 0.93 indicating a high performance.

The high suitability areas (Figure 3) spans 304,889.22 km^2, representing 16% of the country and 17% of the study area. These areas are located in 17 biogeographic provinces of Mexico (Table 3). A greater proportion was predicted in some provinces (Table 3): Altiplano Norte, Sonorense, Altiplano Sur, Tamaulipeca, Baja California, California, Eje Volcánico. The total high suitability area consists of 36,635 continuous areas. The largest continuous area is situated mostly in the Altiplano Norte (Chihuahuense) and partly in the Altiplano Sur (Zacatecano-Potosino) covering 21,255.09 km^2. Most of the areas (21,652) measure 1 km^2 and are spread all along the study area indicating great habitat fragmentation.

Just 8% of the high suitability area is within NPAs (Figure 3).

4. Discussion

Little is known about the historic distribution of the Golden Eagle in Mexico (Rodríguez-Estrella, 2002; Eccardi, 2008). In this study we found that the actual potential distribution occupies 16% of the country, and just 8% of the suitable habitat is located in NPAs (Figure 3). The number of nests, in NPAs, increased (from 117 to 317) during the period 2010-2016 (CONANP, 2016), however a much greater proportion of the population is likely to be found outside NPAs, where the species and its habitat are not subject to other types of protection.

The ensemble model (Figure 2) shows the range of habitat suitability in the study area in the form of percentage probabilities. This map will be a good source of information for further studies and highlights the importance of appreciating ecological variation across the range (Liu *et al*., 2013) while the binary map gives the possibility to prioritize conservation areas (Mendoza-González *et al*., 2016) and it helps stakeholders to focus on establishing protected areas or in species reintroduction programs (Manel *et al*., 2001; Liu *et al*., 2005). Furthermore, the Golden Eagle is a large raptor that displays long distance dispersal (Soutullo *et al*., 2006) so observations responsible for low suitability areas in the model could lead to misinterpretation. On the contrary, the determination of well-defined high-suitable areas helps to identify potential foraging, nesting or stopover habitat.

The most suitable and continuous areas present arid and semiarid climates, xeric shrublands, grasslands, and conifer and oak forests (Espinosa *et al*., 2008; INEGI, 2014). The Eje Vólcanico presents every type of Mexican vegetation with a predominance of conifers (31%) and oaks (28%) (Espinosa *et al*., 2008) but also grasslands and shrublands (Espinosa *et al*., 2008; INEGI, 2014). These habitat features appear to be important factors in predicting Golden Eagle presence and determining the ecological niche for the species. The ENFA results also confirm that the most important variables are presence of grasslands and low tree vegetation cover (as in grasslands and shrublands areas).

Various studies confirm the presence of the species in the areas that are predicted by this model.

Some of the main breeding areas are in the Altiplano Norte and Sur, as in the state of Aguascalientes, where nine nesting and sighting sites are estimated (Lozano-Román, 2008), and in Chihuahua, where Bravo *et al*. (2015) registered 12 nests (5 active and 7 inactive) and studied the diet of the Golden Eagle. In this area, large populations of rodents and lagomorphs, considered the main prey for the Golden Eagle in Mexico, are registered (Lozano-Román and Villalobos-Sánchez, 2003; Bravo *et al*., 2015). In these regions we found the biggest continuous area of suitable habitat which we consider of priority for conservation.

In the Sonorense province the species is common in almost 5 localities (Sonora) and this is reported as a breeding area (Rodríguez-Estrella, 2002).

The Tamaulipeca province includes the state of Nuevo León where the observation of two individuals was reported in 1996 and *Cynomis mexicanus*, the prairie dog (prey of Golden eagles according to Manzano-Fischer *et al*., 1999 and Behrstock and Eubanks, 1997).

Different studies carried out in the Baja California province have been published about distribution and nesting sites of the Golden Eagle (Rodríguez-Estrella *et al*., 1991; Rodríguez-Estrella, 2002; Ruiz-Campos *et al*., 2005; Jiménez-Pérez *et al*., 2009; Guerrero-Cárdenas *et al*., 2012).

In the Eje the presence of the species has been registered in Llanos de Ojuelos (NE of Jalisco), an area with grasslands and nopales (*Opuntia sp*.) subject to cattle and sheep overgrazing, which has affected natural grasslands and many rodent and lagomorph species (Ex.: *Lepus californicus*) (Jiménez-Pérez *et al*., 2009).

Part of the Sierra Madre del Sur is included in the state of Oaxaca, where some authors report that the Golden Eagle has lived and reproduced in the past (Friedmann, 1950; Winker *et al*.,

1992) and recent studies reported a breeding area in the Biosphere Reserve of Tehuacán-Cuicatlán (Luis Felipe Lozano-Román, personal communication, May 2016).

The presence of Golden Eagle is also reported in some states within the Sierra Madre Occidental (Durango, Chihuahua, Zacatecas, Sonora) (Rodríguez-Estrella, 2002).

The percentage of high suitability areas in the other provinces (Depresión del Balsas, Oaxaca, Costa del Pacífico, Los Altos de Chiapas, Del Cabo, Soconusco) is minimal as would be expected due to the predominant vegetation types in these areas being deciduous forests, cloud forests, evergreen forests.

In some areas, the model identifies potential suitable habitat, where there are no recent records of the species, or its presence has never been registered. This could be due to lack of studies in these areas, model bias or high anthropic disturbance. It would be worthwhile to focus new studies in the south-central potential area of distribution of the Golden Eagle in Mexico, like Jalisco and Michoacán in the Eje Volcanico, a breeding area of Oaxaca/Puebla (Biosphere Reserve Tehuacán-Cuicatlán) and part of Morelos in the Depresión del Balsas and Veracruz in the Gulf of Mexico. This would allow verification of the predictive models as well as a more complete understanding of the state of this species to plan better management and conservation measures.

Unfortunately, an obvious feature of the identified high suitability areas is strong fragmentation; most of them have very limited area for expansion and are dispersed (Figure 3).

The loss of grassland or shrubland habitat is the main threat to the survival of the species in the country, especially because it affects the populations of the main prey of the Golden Eagle (Ex.: *Lepus californicus*) and consequently it can limit reproductive success (Kochert *et al*., 1999). In Idaho (United States) it has been shown that the successful breeding of the Golden Eagle depends on the abundance of its main prey, the Black-tailed Jackrabbit (Steenhof *et al*., 1997), which is found in grasslands and shrublands. These habitats are easily disturbed by human activity which is detrimental to prey density (Knick and Dyer, 1997).

Natural grasslands were once one of the most widespread biomes in the world and are now among the most disturbed and least protected (Manzano-Fischer *et al*., 2006). This type of vegetation occupies 6% of the Mexican territory, while xeric shrublands occupy 30%. Both types of vegetation have been degraded to different degrees, due to overgrazing (CONABIO and SEMARNAT, 2009). In Mexico, almost all grasslands, natural or induced, are used for livestock production, generally at high intensity. Overgrazing affects 95% of the natural grasslands of the country (SEMARNAT, 2013). The loss and degradation of this habitat affects many species of mammals, such as rodents and lagomorphs, and other birds species. An example is *Cynomis mexicanus* in areas like Janos Casas Grandes in north-western Baja California, where the species is declining because of overgrazing and use of pesticides, such as carbofuran (Manzano-Fischer *et al*., 2006). This species is extremely important because it creates and maintains a mosaic of different priority habitats for predators and other species (including birds) (Manzano-Fischer *et al*., 2006).

The selection of habitat, foraging areas and prey, by Golden eagles varies subject to anthropogenic disturbances and consequently home ranges can become concentrated in areas with greater availability of suitable habitat and prey (Marzluff *et al*., 1997). Golden eagles have been shown to adapt to alternative habitats and preys, particularly during the breeding season (Steenhof and Kochert, 1988; Marzluff *et al*., 1997) but in these cases, it is likely that breeding success is reduced (Steenhof *et al*., 1997).

One of the main reasons that have motivated the direct persecution of the species is the mistaken belief that the Golden Eagle is a predator of cattle and sheep and that it would be able to lift a small child. After 30 years of study Gordon (1955) reported only three cases of depredation of calves and Arnold (1954) found that this species has a high preference for carrion, so in all diet studies that have reported remains of large mammals, including cattle and sheep, and based on analysis of stomach contents, without observation of predation, it cannot be assumed that the cattle have been really preyed; on the contrary there is a high probability that the eagle has eaten a cattle carrion. There are no reported cases of child predation.

The most important parameters that determine the presence and density of the species are the availability of suitable habitat, with limited or absent anthropic disturbance, prey availability, and appropriate rules to control human activities such as hunting and pesticide use (Rodríguez-Estrella, 1991). Likewise, the species conservation could be promoted through environmental education programs specifically targeted towards children and those communities that use the species or parts of it (feathers for example) for magical-religious ceremonies or medicinal use (Eccardi, 2008).

One of the biggest problems in Mexico is the lack of studies, particularly in regions like Eje Volcanico, Depresión del Balsas, Sierra Madre Occidental, Sierra Madre del Sur and Golfo de México, where suitable habitat is available, but few records are reported. There are also few publications about the mayor threats affecting the species in most of its range. Therefore, even if it seems obvious, it is important to underline the most urgent actions to carry out, like to improve research and fieldwork in those areas and sensitize people in the priority areas for conservation we identified, so we propose:

1. Raising awareness and sharing information in communities involved in legal or illegal activities concerning the use and/or sale of the species and/or its parts, in the priority areas we identified in the current study. A good example is the sensitization and monitoring activities CONANP has been doing, particularly in breeding areas like Aguascalientes (Lozano-Román, 2013).

2. Creating solutions to mitigate the impact of overgrazing like livestock management and improving control of poaching and illegal trade at least in priority areas. During fieldwork in the Altiplano sur it was possible to observe that livestock had access even to protected areas where Golden Eagle's nests are present.

4. Coordinating efforts to study the species across its range, sharing scientific information among researchers to develop more comprehensive information and to carry out specific projects or long-term studies.

In addition, the acquisition of a more complete understanding of the ecology of the species in Mexico, both for conservation and research should be prioritized. Subjects to focus further research include: the size of the national population, the size and routes of the migratory population, and the identification of wintering areas.

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Legends to figures

Figure 1. Study area and filtered records (183) of *Aquila chrysaetos*.

Figure 2. Ensemble model of the Golden Eagle's potential distribution in Mexico. The values, going from 0 to 100 %, represent the probability of habitat suitability for the species in the study area.

Figure 3. High suitability areas for *Aquila chrysaetos* in Mexico and Natural Protected Areas (NPAs) (federal, state and municipal) occurring in the study area.

Table 1. Environmental and anthropogenic variables that influence the species distribution.

Variables		**Source**	**Scale**
Topographic	Altitude Slope Aspect	USGS (2007)	1:1,000,000
Hydrographic	Water bodies (distance) Rivers (distance)	INEGI (2000)	
Vegetative	Tree vegetation cover (%)	Global Land Cover Facility, De Fries *et al*. (2000)	
	Agriculture Grassland Temperate forest Deciduous forest Evergreen forest Aquatic vegetation Arid vegetation	INEGI (2014)	
Anthropogenic	Human population density	Centre for International Earth Science Information Network – CIESIN (2015)	
	Paved roads (distance)	INEGI (2012)	

Table 2. Internal and external AUC of each model obtained by different algorithms.

Algorithms	**AUC_{ext}**	**AUC_{int}**
ENFA (Median)	0.86	0.76
ED	0.78	0.99
GARP with Best Subsets new openModeller implementation	0.69	0.82
ANN	0.59	0.18
SVM	0.54	0.93
Maxent	0.43	0.94
GARP with Best Subsets DesktopGARP implementation	0.27	0.75

Table 3. High suitability areas (HSA) in each biogeographic province (km^2); biogeographic provinces areas (km^2); percentage of HSA proportional to the area of each province; total high suitability area and total biogeographic provinces area (study area).

Province	HSA (km^2)	Province area (km^2)	% HSA in each province
Altiplano Sur (Zacatecano-Potosino)	64,282.62	197,768.37	32,50
Sonorense	46,894.42	171,397.73	27,36
Altiplano Norte (Chihuahuense)	87,643.39	338,751.69	25,87
Tamaulipeca	25,022.33	98,698.44	25,35
Baja California	24,352.87	102,067.62	23,86
California	4,097.08	18,616.54	22,01
Eje Volcánico	19,845.09	119,539.53	16,60
Sierra Madre del Sur	3,349.59	56,746.08	5,90
Golfo de México	10,241.57	174,823.86	5,86
Sierra Madre Occidental	12,158.00	210,660.82	5,77
Sierra Madre Oriental	2,526.00	45,232.49	5,58
Depresión del Balsas	1,939.58	64,128.87	3,02
Oaxaca	164.72	10,349.69	1,59
Costa del Pacífico	2,231.39	172,243.52	1,30
Los Altos de Chiapas	121.10	14,463.12	0,84
Del Cabo	18.64	8,855.88	0,21
Soconusco	0.83	9,031.20	0,01
Total	**304,889.22**	**1,813,375.44**	**16,81**

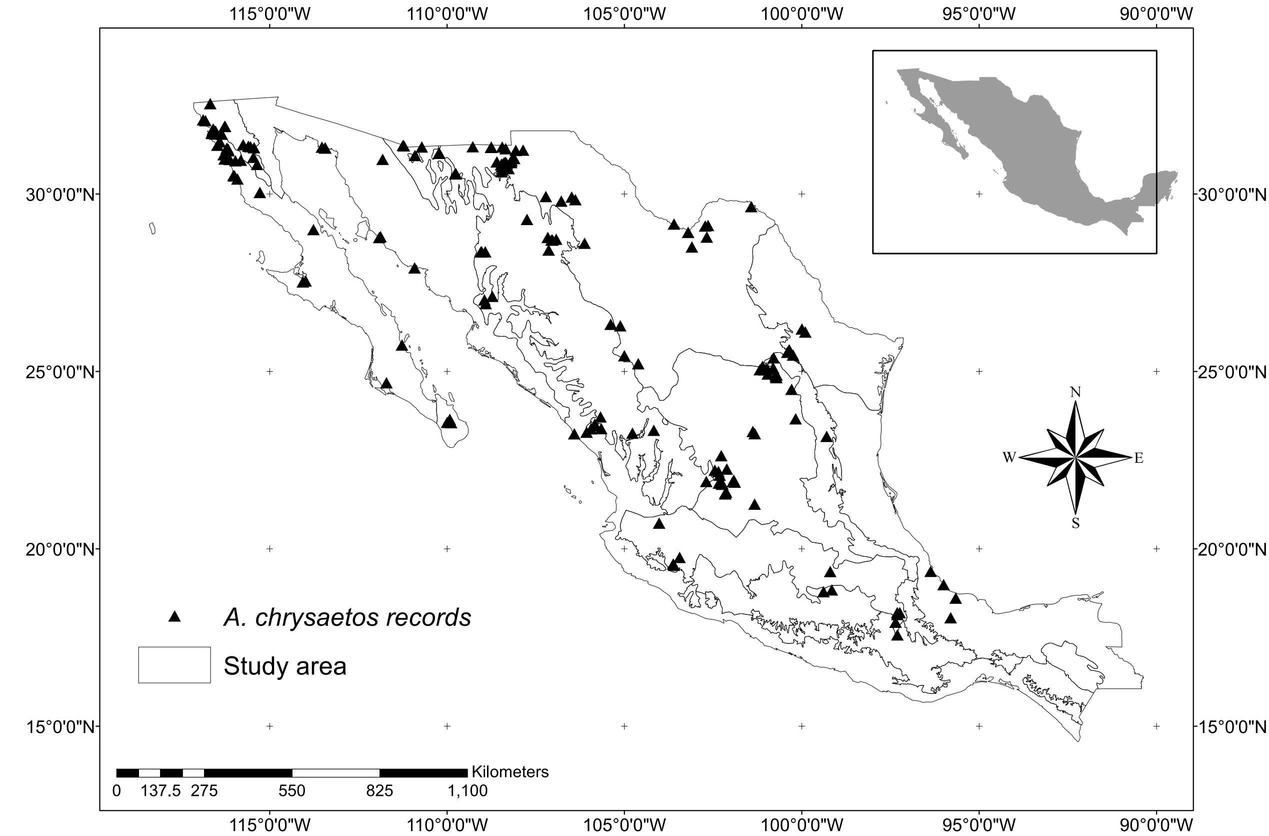
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Figure 1

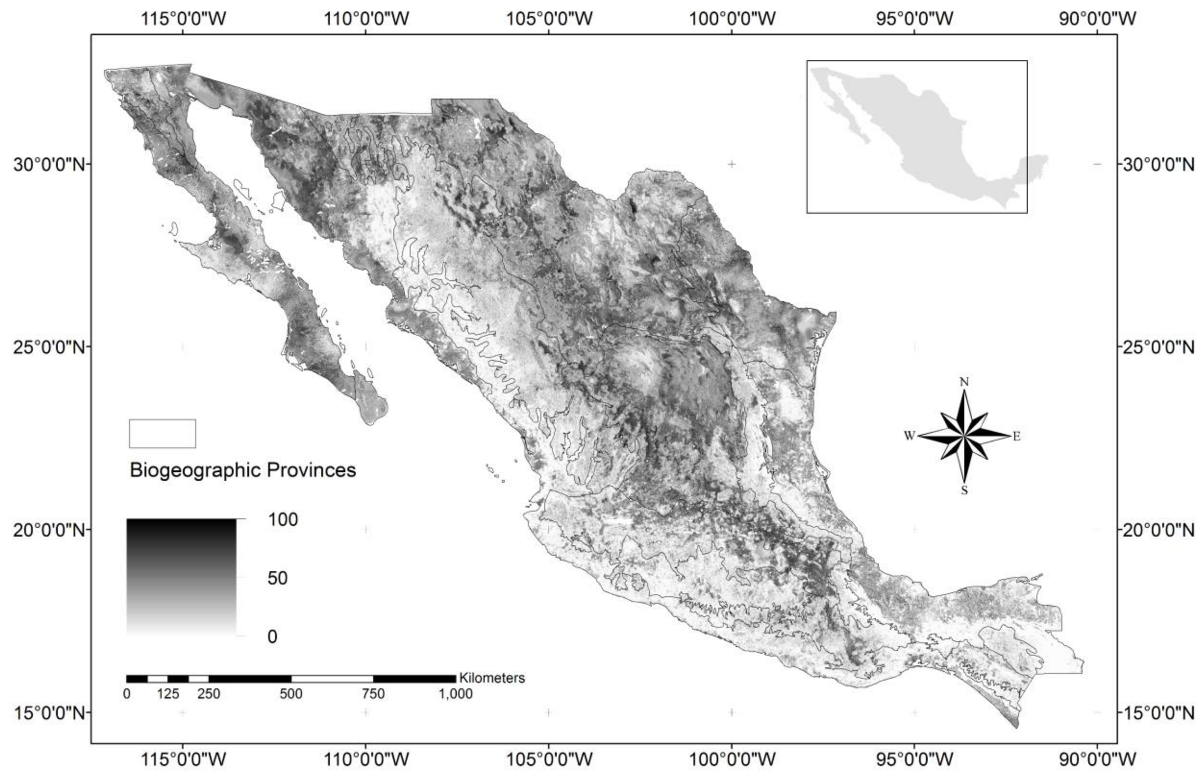
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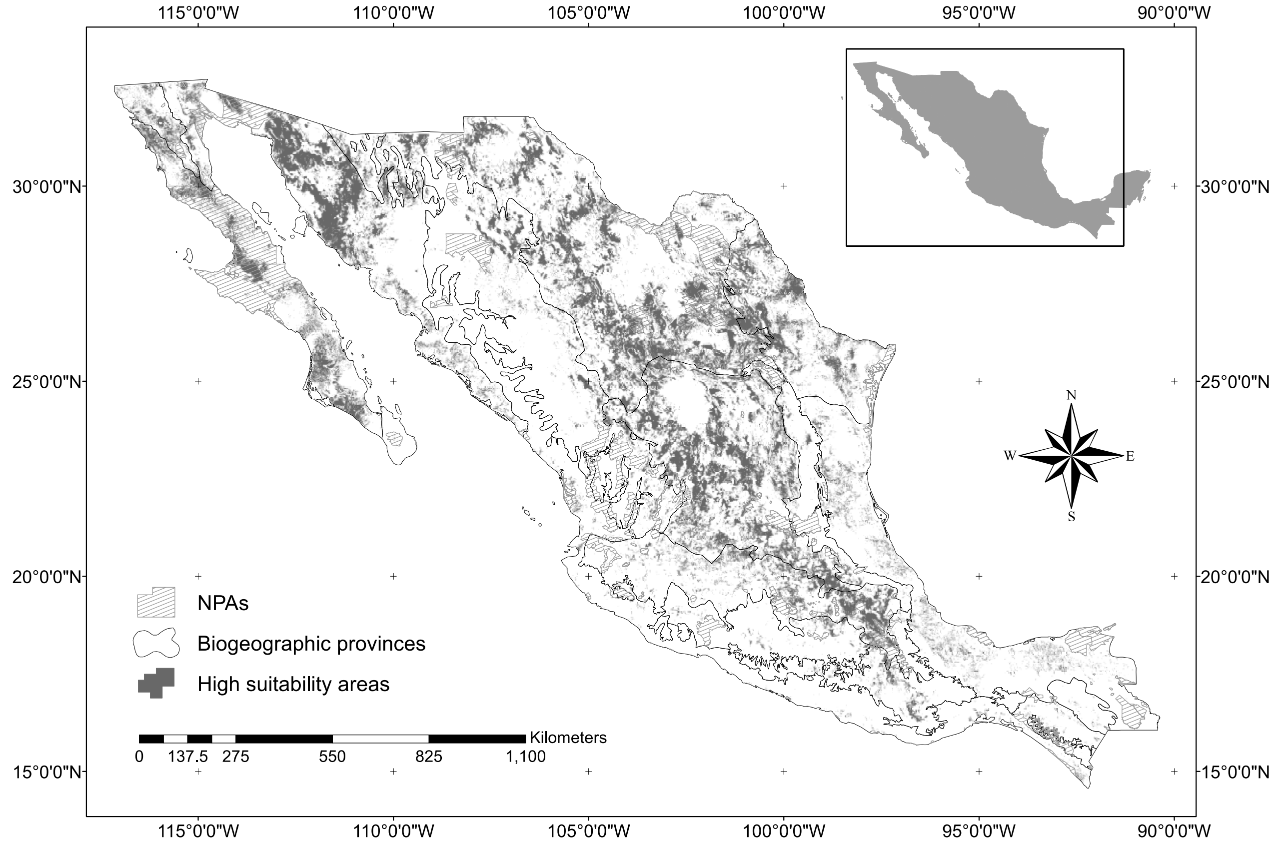
Figure 2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30°0'0"N
25°0'0"N
20°0'0"N
15°0'0"N
N
S
W
E
NPAs
Biogeographic provinces
High suitability areas
Kilometers
0
137.5
275
550
825
1,100

Figure 3

IV. SEGUNDO ARTÍCULO

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Priority areas for the conservation of three neotropical raptors in Mexico

Áreas prioritarias para la conservación de tres aves rapaces neotropicales en México

Page-header title: Distribution of neotropical raptors in Mexico

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Authors contributions

Maristella D'Addario: Study conception, formal analysis, investigation (performed the experiments, data/evidence collection), writing/manuscript preparation (writing the initial draft, visualization/data presentation).

Octavio Monroy-Vilchis: Study conception, resources, writing/manuscript preparation (critical review, commentary or revision), supervision, project administration.

Martha Mariela Zarco-González: Study conception, resources, supervision, project administration.

Summary

Neotropical raptors are a poorly studied group that is strongly affected by habitat loss and fragmentation throughout their distribution, of which Mexico is the northern limit. The target species of this study are *Spizaetus ornatus*, *Spizaetus tyrannus* and *Sarcoramphus papa*, three neotropical raptors labeled as endangered by the Mexican government. We determined the potential distribution of these species in Mexico using seven algorithms to develop different individual ecological niche models and the weighted average ensemble method to obtain the final prediction. We also determined the common high suitability area which we consider a priority for these species' conservation. We found out that the distribution of the three raptors is mainly connected to evergreen rainforest, tree cover percentage and water bodies closeness, and according to our results the biggest continuous suitable shared area in the country is in the Petén province. The results suggest that Natural Protected Areas are not sufficient to preserve the three species' populations. Moreover, according to the results and to recent observations, the King Vulture (*S. papa*) is distributed in areas where it is considered extinct according to the IUCN, so we suggest reviewing the official published map.

Resumen

Las rapaces neotropicales son un grupo de aves poco estudiadas y al mismo tiempo muy afectadas por problemas como la pérdida y fragmentación de su hábitat a lo largo de su distribución, de la cual México representa su límite norteño. Las especies objeto de este estudio son: *Spizaetus ornatus*, *Spizaetus tyrannus* y *Sarcoramphus papa*, consideradas en peligro de extinción por el gobierno mexicano. En el presente estudio se determinó la distribución potencial de las tres especies en México usando siete algoritmos para desarrollar diferentes modelos de nicho ecológico y el método ensamble de la media ponderada para obtener la predicción final. Se determinó también un área común de alta idoneidad que se considera prioritaria para la conservación de estas especies y que se encuentra en la provincia

biogeográfica del Petén. Los resultados sugieren que la distribución de estas especies está principalmente relacionada con la presencia de selva perennifolia y con la cercanía a ríos o cuerpos de agua y que las actuales áreas naturales protegidas en México no son suficientes para preservar sus poblaciones. De acuerdo con los resultados y con recientes observaciones el Zopilote Rey (*S. papa*) se encuentra en áreas donde está considerado extinto por el IUCN, así que se sugiere una revisión de los mapas oficiales publicados.

1. Introduction

The life history of most Neotropical birds of prey, as well as the main threats they face, are poorly known (Del Hoyo *et al*., 1994; Bierregaard, 1995; Trejo, 2007). Abundance, richness and diversity of these raptors have been demonstrated to be sensitive to habitat transformation and fragmentation (Carrete *et al*., 2009), making them important indicators of anthropogenic disturbance (Bierregaard, 1995; Carrete & Donázar, 2005). Moreover, they require large areas to live, so they can be considered very good umbrella and flag species to establish protected areas in Neotropical forests (Thiollay, 1989; Canuto *et al*., 2012) or to regulate their size but at the same time it is complicate and expensive to study them.

Knowing the potential distribution of species and the habitat suitability in certain geographic areas is required for further studies, and to establish new conservation and management strategies (Franklin, 2009). One way to do this in a relatively short time, with few resources and working on more than a species at the same time (Hernandez *et al*., 2006; Pearson et al., 2007; Marmion *et al*., 2009) is using Ecological Niche Modelling. Predictive modelling has been used for many applications, like: conservation planning (Corsi *et al*., 1999), epidemiology (Peterson & Shaw, 2003) and invasive-species management (Peterson & Robins, 2003), particularly to work at big scales (Guisan & Thuiller, 2005). It’s been used recently in Mexico to study the potential distribution of big mammals like the jaguar (*Panthera onca*) (Rodríguez-Soto et al., 2011), the American black bear (*Ursus americanus*)

(Monroy-Vilchis *et al*., 2015) or reptiles like the lizard subspecies *Barisia imbricata imbricata* in the Mexican biogeographic province named Eje Volcanico (Sunny *et al*., 2017), to improve the knowledge about them and the effectiveness of the existing protected areas, and to give the basis for new conservation strategies.

This means, most of the time, using records already collected by other researchers, available on online databases, literature or from museums (Farrand *et al*., 2011; Monroy-Vilchis *et al*., 2015) that can be improved by some personal fieldwork. We investigated on data availability about neotropical eagles and vultures of Mexican tropical forests, that are considered important species to study as top predators of this ecosystem, one of the most endangered in the world and in the country (Geist & Lambin, 2002; Rodríguez-Soto *et al*., 2017). According to the amount of data we found, we focused the study on the distribution of three diurnal species (better sampled): two eagles – *Spizaetus ornatus* (Ornate Hawk-eagle) and *Spizaetus tyrannus* (Black Hawk-eagle) – and a Vulture – *Sarcoramphus papa* (King Vulture), which have been poorly studied in Mexico. The three species are enlisted "under risk of extinction" in Mexico (SEMARNAT, 2010), although, *S. tyrannus* and *S. papa* are categorized as "Least Concern" and *S. ornatus* as "Near Threatened" in the IUCN red list (Birdlife International, 2016a, b, c).

S. ornatus mainly inhabits dense tropical evergreen forests (Howell & Webb, 1995; Piana *et al*., 2010; Phillips & Hatten, 2012) up to 1,500 m.a.s.l. (Ferguson-Lees & Christie, 2006) but occasionally higher (Ferguson-Lees & Christie, 2006; Aranda *et al*., 2009). In Mexico, it has been observed in tropical rainforests, deciduous forests, cloud forests and occasionally pine-oak forests (Iñigo-Elias *et al*., 2000; Aranda *et al*., 2009). It's been proved that the Mexican population of the Ornate hawk-eagle declined during the last 50 years, mainly because of habitat loss and fragmentation as well as poaching (Aranda *et al*., 2009), in fact this species is sensitive to habitat perturbation and anthropogenic disturbance (Canuto, 2008) and prefers primary undisturbed forest (Thiollay, 2007). *Spizaetus tyrannus* inhabits forests and secondary woodlands, from 0 to 1,500 m.a.s.l. (Ferguson-Lees & Christie, 2006) and it is moderately tolerant to habitat perturbations (Thiollay, 2007). *Sarcoramphus papa* needs large areas to establish a viable population, and it generally inhabits wet tropical forests, near rivers and far from urban areas (Reyes-Martínez, 2008; Haenn *et al*., 2014). The main reasons leading these species to a worrying population decrease are deforestation of tropical forests (Thiollay, 2007; Aranda *et al*., 2009; Bird *et al*., 2011) capture and poaching (Albuquerque, 1995) and their populations are declining globally (Birdlife International, 2017) so it is important to improve the knowledge about them and to establish new conservation priorities as soon as possible.

It is reported that they range from northern/central Mexico to northern Argentina (Howell and Webb, 1995; Birdlife International, 2016a, b, c). Moreover, these species are territorial, and their populations are widely distributed in low densities, so that studying them requires high sample efforts (Bierregaard, 1995; Thiollay, 2007). This is the reason why we choose using Ecological Niche Modelling to determine their potential distribution in Mexico.

The objectives of the present study were: 1) to determine the potential distribution of the three species in Mexico; 2) to identify the high suitability areas for the species and the percentage of it that is included in Natural Protected Areas (NPAs); and 3) to propose priority areas for the species' management and conservation.

2. Materials and methods

The study areas include the neotropical portion of Mexico and they are divided in specific biogeographic provinces (CONABIO, 1997) for each species. They were established considering the known distribution (from literature and reported records) of the raptors and the provinces characterized by suitable habitat for each species and following a biological criterion. The provinces are: Costa del Pacífico, Eje Volcánico, Sierra Madre Oriental (SMO), Golfo de México, Oaxaca, Depresión del Balsas, Sierra Madre del Sur (SMS), Soconusco, Los Altos de Chiapas, Yucatán and Petén for *Spizaetus ornatus* (Figure 1a); Costa del Pacífico, SMS, Oaxaca, Golfo de México, Soconusco, Los Altos de Chiapas, Yucatán, and Petén for *Spizaetus tyrannus* (Figure 1b); Costa del Pacífico, Oaxaca, SMO, Golfo de México, Soconusco, Los Altos de Chiapas, Yucatán, and Petén for *Sarcoramphus papa* (Figure 1c).

We obtained the species' records from: a) literature, b) online databases (GBIF, VertNet, Naturalista of CONABIO) and c) field work; we verified and depurated the records choosing the most reliable georeferenced ones from 1990 to 2015. 70% of the records was used to process the models and 30% to evaluate them (Guisan & Zimmerman, 2000). We found 267 records of *Spizaetus ornatus*, 322 of *Spizaetus tyrannus,* and 370 of *Sarcoramphus papa*. We obtained five field records in a Wildlife Management Unit (UMA)[1] in Laguna de Términos (Campeche, Mexico) March the 29th, 2015: three of Ornate Hawk-eagle, one of Black Hawk-eagle and one of King Vulture. We also observed a King Vulture in the Biosphere Reserve El Cielo (Gómez Farías, Tamaulipas) on June 2013. After depuration, we obtained 92 records of *Spizaetus ornatus*, 103 of *Spizaetus tyrannus* and 124 of *Sarcoramphus papa* (Appendix 1). The depuration consisted in eliminating multiple records of the same individual, untrustworthy data, data without geographic coordinates or without the year of the record. Furthermore, we processed the records layer to obtain one datum for each pixel at a 1 km resolution.

We identified 15 variables that influence the target species' establishment, survivorship and reproduction, considering the scientific literature about their ecology, and downloaded them in raster format from different sources at a 1:1,000,000 scale (Table 1). All the layers were processed to work at a 1 km resolution and we used WGS84 as coordinate system. The maps of the vegetation types have been downloaded in raster binary format from the INEGI website where 0 indicated the absence and 1 the presence of a vegetation type. Each map was processed to obtain continuous values using a moving window of 25 km^2 (Rodríguez-Soto *et al*., 2011). We choose three topological predictors, seven vegetation types, tree cover percentage, distance to rivers and water bodies, and three variables representing human disturbance (Table 1). These environmental conditions, resources and biotic environment factors represent two groups of variables that determine the limits of species distributions (Soberón, 2007).

We choose to use machine learning methods (artificial neural networks, genetic algorithms, maximum entropy and support vector machines) because they perform better with noisy and or sparse information, like in the case of species only-presence data from museums and other digital databases (Elith *et al*., 2006). We used the algorithms: ENFA (Hirzel *et al*., 2002) in Biomapper4 (Hirzel *et al*., 2009); Maximum Entropy Species Distribution Modelling 3.3.3k (https://www.cs.princeton.edu/~schapire/maxent/) (Phillips, Dudik & Shapire, 2004); Artificial Neural Network (ANN) (Gevrey *et al*., 2003; Pearson *et al*., 2004), Environmental Distance (ED) (Hirzel & Arlettaz, 2003), Genetic Algorithms for Rule-set Production (GARP with Best Subsets–new openModeller implementation y DesktopGARP implementation) (Stockwell & Peters, 1999), Support Vector Machine (SVM) (Cristianini & Scholkopf, 2002) in openModeller 1.1.0 (http://openmodeller.sourceforge.net/index.html). Hence, starting from the geographic space (the geographic coordinates of the occurrences and raster maps of the variables), the algorithms relate the records of the species with the predictive variables in an environmental space and the result is proyected to the geographic space to obtain a potential distribution (Martínez-Meyer & Sánchez-Cordero, 2006; Peterson & Soberón, 2012). In this way we obtain the areas where biotic and abiotic conditions are suitable for the species (part of the fundamental niche) in the established study area (Peterson & Soberón, 2012). Before running the correlation between variables was calculated by Biomapper4 (Hirzel *et al*., 2009).

We evaluated the models obtained using an external group of data (30%) in the ROC module of IDRISI Selva 17.0, obtaining an AUC value (external AUC=AUC_e) which indicates the models' performance. We chose the models with a moderate to high performance (AUC>0.7) (Manel *et al*., 2001) to generate an ensemble model. We also calculated the AUC with the modelling data (70%) (internal AUC=AUC_i) to obtain the ensemble model by the weighted average equation: $\Sigma(M_n \times AUC_i)/\Sigma(AUC_i)$ in the IDRISI calculator (M_n=n Model adecuation; AUC_i=internal AUC). It's been demonstrated that single algorithms don't fit perfectly in all cases (Hernandez *et al*., 2008) while this consensus method gives a different weight to the prediction of each individual model obtained by different algorithms by using their predicting performances (AUC) (Marmion *et al*., 2009).

We used Maxent to determine the most important variables influencing the species distribution because this is the only software (between the ones we choose to model) that calculate accurately, and by using different statistics, the relative contribution of the variables. We considered the percent contribution values (relative variables contributions) calculated by Maxent and the response curves of the most contributory variables (also calculated by Maxent) choosing the plots that reflect eventual correlations between variables (the second ones displayed in the Maxent html output) (Phillips *et al*., 2006).

We determined the high suitability areas reclassifying the ensemble model (where each pixel of the raster represent a probability of suitability from 0 to 100%), in a binary map (Figure 2a,b,c) considering areas with a 50% to 100% to be high suitability areas (Liu *et al*., 2005). Then we calculated the extension of high suitability areas, of each species including those in NPAs (Figure 2a,b,c), as well as the high suitability common area for the three species and the NPAs included in them (Figure 2d).

3. Results

No significative correlation was found between variables (<0.7, De Pando and Peñas De Giles, 2007). The algorithms with AUC>0.7 used in the ensemble formula were seven (Table 2) for *S. ornatus*. The external AUC of the ensemble model was 0.94. The most important variables for *S. ornatus*, according to Maxent, were decreasingly: tree cover percentage (the habitat suitability is higher in areas were tree cover percentage is from 60% to 90%), evergreen forest presence (positive relationship), slope (positive relationship when slope>60°) and distance to rivers (from 10 to 40 km). The high suitability area is of 212 959 km^2 and 18% of it is included in NPAs.

In the case of *S. tyrannus,* the algorithms used for consensus were five (Table 2) and the external AUC of the consensus model was 0.95. The most important variables influencing the distribution of *S. tyrannus* were: evergreen forest presence (positive relationship), distance to water bodies (the habitat suitability is higher near water bodies) and slope (positive relationship when slope >60°). The high suitability area is 122 538 km^2 and the 20% of it is included in NPAs.

We used six algorithms to obtain the ensemble model of *S. papa* (Table 2), and the external AUC of the latter was 0.99. We also found that the most important variables for the species were: evergreen forest presence (positive relationship), tree cover percentage (from 60 to 85%), absence of agriculture and distance to rivers (the habitat suitability is higher near the rivers). The high suitability area is 80 795 and 26% of it is included in NPAs. In all cases the high suitability area occurred with different extensions in all the provinces. The shared high suitability area occupies the provinces of Petén, Golfo de México, Soconusco and Costa del Pacífico and it ranges 59 783 km^2 (Figure 2d). The Natural Protected Areas included in the common suitable area cover 15 732 km^2, approximately 26% of it (Figure 2d).

4. Discussion

Mexico is a marginal portion of these species' range since they are mostly distributed in south and central America (Ferguson-Lees and Christie, 2006). However, they have become rare in many regions mainly due to deforestation (Bierregaard, 1998; Drummond *et al*., 2008). This does not mean that Mexico is not important for their populations, on the contrary, the marginal parts of a species' range are subject to edge effect extinction and decrease of genetic variability (Harrison & Bruna, 1999; Fahrig, 2003; Vucetich & Waite, 2003; McMinn *et al*., 2017) making them relevant for preservation, to avoid high population decreases or regional extinctions. These species also have a low reproductive rate, which makes them more sensitive to habitat loss and fragmentation (Quesnelle *et al*., 2014) and requires larger habitats for population persistence (Vance *et al*., 2003).

According to our results, Petén is the province with the largest high suitability area for all three species. Moreover, this is where we found the most continuous and extended patches of suitable habitat and a shared extended suitable area (Figure 2d). Tropical evergreen wet forests dominate this region (Espinosa *et al*., 2008; INEGI, 2014). This vegetation type and the presence of water are very important variables determining the occurrence of the three raptors, as has been found by other authors (Puebla-Olivares *et al*., 2002; Phillips & Hatten, 2012; Sánchez-Soto *et al*., 2013). This suggests that the area should be a priority for the conservation of the target species as well as for tropical forests themselves. These ecosystems are hotspots, rich in endemic species and biodiversity, but they are also among the most affected by fragmentation and habitat loss (Myers *et al*., 2000; Brooks *et al*., 2002).

Several neotropical raptors, such as the target species of this study, are strongly associated to forests, and are consequently severely affected by habitat degradation (Zurita & Bellocq, 2007).

Even if *Spizaetus ornatus* is cited as the most dependant of the three to pristine primary forests (Thiollay, 2007) with higher tree cover percentage, its range resulted to be the most extended. This species can in fact be found in both types of tropical forests occurring in Mexico (evergreen and deciduous) (Grosselet & Burcsu, 2005; Monroy-Ojeda *et al*., 2014) as described for other areas of its distribution (Canuto *et al*., 2012). *S. ornatus* and *S. papa* reach the north of the country in the east-coast (Tamaulipas, SMO province) and many of the overall observations of this area, we found in the databases (Appendix 1), occurred in the Biosphere Reserve El Cielo.

Balancing the percentage of high suitability areas in each province and the size of continuous patches, the most important areas for the Ornate Hawk-eagle are included in the provinces of: Petén, Gulf of Mexico, Soconusco, Oaxaca and Los Altos de Chiapas, which are dominated by the presence of evergreen rainforest and a warm humid climate; Yucatán, SMS and Pacific coast, where deciduous wet forest and sub-humid climate dominate; SMO, where the climate is humid and the dominant vegetation is template forest (Espinosa *et al*., 2008; INEGI, 2014). *S. tyrannus* and *S. papa* are found (in Mexico) mainly in areas with evergreen rainforest like the provinces of Petén, Gulf of Mexico, Soconusco, and, for *S. tyrannus*, Oaxaca.

Rainforests in Mexico originally occupied 9.2% of the country, but now they have decreased to 4.7% (http://www.biodiversidad.gob.mx/ecosistemas/selvaHumeda.html). They are mainly distributed on the Atlantic side of the country and are more abundant in the Yucatán peninsula followed by the Sierra Madre of Chiapas, the SMS, and Oaxaca and Guerrero on the Pacific coast (http://www.biodiversidad.gob.mx/ecosistemas/selvaHumeda.html). These regions are where we found the most important suitable areas for the three raptors.

These target species are also characterized by different levels of tolerance to human presence and activities. Some raptor species are favoured by human activities and infrastructure (Rodríguez-Estrella, 1998), but this is not the case of those with preference for preserved forests far from human presence (Reyes-Martínez, 2008) like the Ornate Hawk-eagle and the King Vulture. Our results show that absence of agriculture is an important factor for the King Vulture. Only the Black Hawk-eagle can tolerate moderate anthropic disturbance (Thiollay, 2007). Meanwhile, the population density of both *S. ornatus* and *S. tyrannus* has been proved to be lower in fragmented areas (Canuto *et al*., 2012), suggesting that habitat fragmentation affects all three species. Habitat connectivity and patch size are very important factors to prioritize along the whole distribution range of either species, especially for those most specialized and those less tolerant to human presence, as confirmed by other authors (Zurita & Bellocq, 2007).

The most important and extended NPAs occupying part of the high suitability shared area are: the Biosphere Reserve La Sepultura, Zona de Protección Forestal Territorios Municipios La Concordia, Ángel Albino Corzo, etc., Reserva de la Biósfera El Triunfo and Pico El Loro – Paxtal, which together sum a continuous protected territory of 4 045.79 km^2 Selva El Ocote (1 015.22 km^2), the Biosphere Reserve Montes Azules (3 235.34 km^2) and the Biosphere Reserve Lacantún (602.82 km^2), the Cañon del Usumacinta (445.63 km^2), and the reserve Los Tuxtlas (1 481.13 km^2) in the Golfo de México province. Two reserves in the Petén province form a large continuous patch of protected primary forest (11 248.46 km^2), Balam-Kú and the Biosphere Reserve Calakmul, which is the biggest tropical reserve of Mexico (http://calakmul.conanp.gob.mx). Meanwhile, Sian-Ka'an and Uaymil just protect a little part of the high suitability area in the south-east of the Petén province. Most of the Petén province, where we found the most extended suitable patch of habitat for the three species, is not protected. The Natural Protected Areas established in Mexico are not sufficient and do not cover many of the important areas of suitable habitat for these top predator species. As top predators they need thousands of hectares to maintain their breeding populations and their loss in fragmented areas can influence the structure of entire communities and the persistence of many other species (Terborgh, 1992). Moreover, legal timber extraction and poaching represent additional threats also in protected areas or buffer zones (Sanvicente-López *et al*., 2010; Monroy-Ojeda *et al*., 2014). It is worth to mention the presence of good examples of sustainable economic development, like the coffee plantation of Arroyo Negro (Chiapas), which has been recognized as a natural corridor between two important protected areas, where just 100 over 1600 ha of the property are cultivated with organic coffee and healthy and reproductive populations of *S. ornatus* can be found in addition to the registered presence of *S. tyrannus* and *S. papa* (Orantes-Abadía & Navarra, 2011; Monroy-Ojeda *et al*., 2014).

The King Vulture has the biggest high suitability area included in NPAs of the studied species, although it is also the one with the least extended total suitable area. This could be because the species is achieving better survival in protected areas than in the rest of its potential distribution range. In fact, as is stated above, this species prefers forest areas far from human activities and urbanization and it is severely affected by poisoning (organophosphates) and poaching (Sanvicente-López *et al*., 2010). Two of the three optimal conservation areas in Mexico are affected by serious deforestation levels; these are the Lacandona forest (Chiapas) and Los Tuxtlas (Veracruz), where these species have been extracted (Winker, 1997) but were still observed in 2005 (GBIF, Naturalista).

The observation of King Vultures in two areas where it is listed as extinct by IUCN–Gulf of Mexico coast and Pacific–is noteworthy (Birdlife International, 2016a). This is backed both by the prediction of potential distribution, but also because of the records in these areas (GBIF, 2004, 2006; Appendix 1; obs. pers., 2013). Moreover, it occurs in areas not even considered from the IUCN like the Biosphere Reserve El Cielo (Tamaulipas) and El Palmar (state reserve) in Yucatán (Appendix 1), so we strongly recommend a revision of the IUCN official published distribution range in Mexico.

The available information about many aspects of these species' life history is poor in Mexico, particularly regarding the relative abundance, the nesting populations and their home ranges, which is critical to determine their conservation status. It would be important to conduct further studies in Mexico and to develop new conservation strategies.

[1] An UMA (Unidad de Manejo para la conservación de la vida silvestre: wildlife management unit) is a public Mexican political instrument. This denomination is given to a land or facility where sustainable use of fauna and flora and conservation are combined. This frame depends on the LGVS (Ley General de Vida Silvestre: general law for wildlife) and its regulations (SEMARNAT, 2000, 2006).

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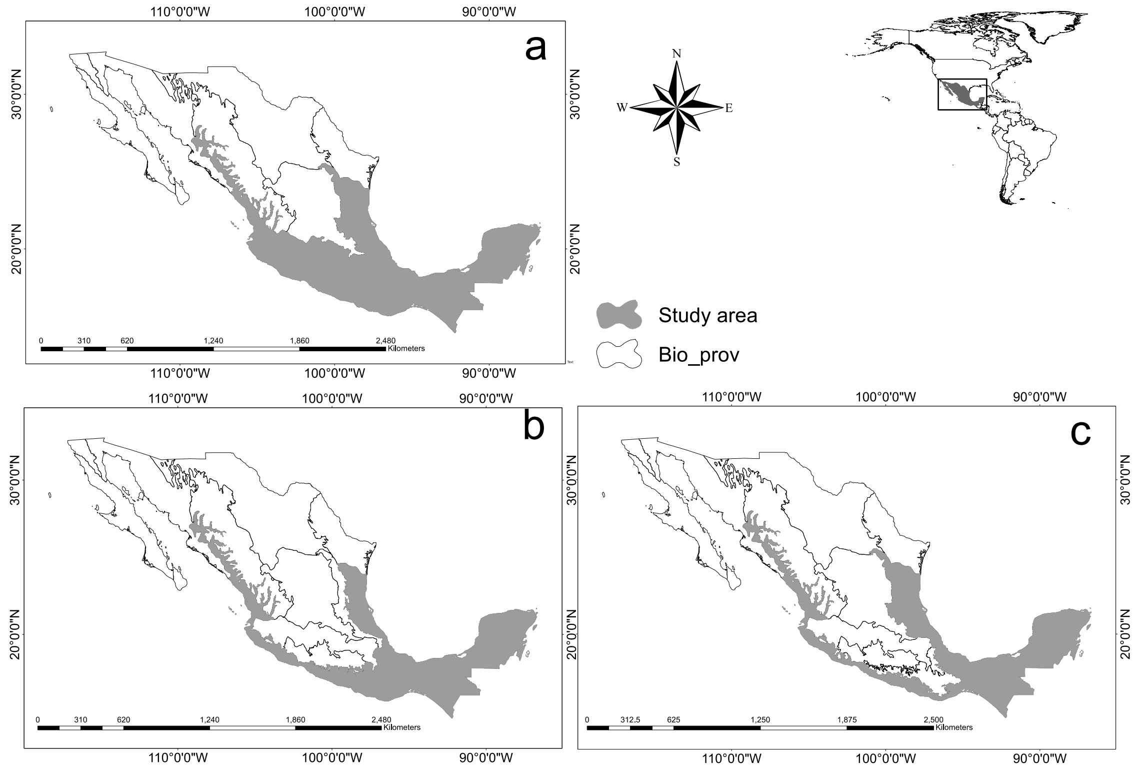

Figure 1. Maristella D'Addario. Distribution of neotropical raptors in Mexico.

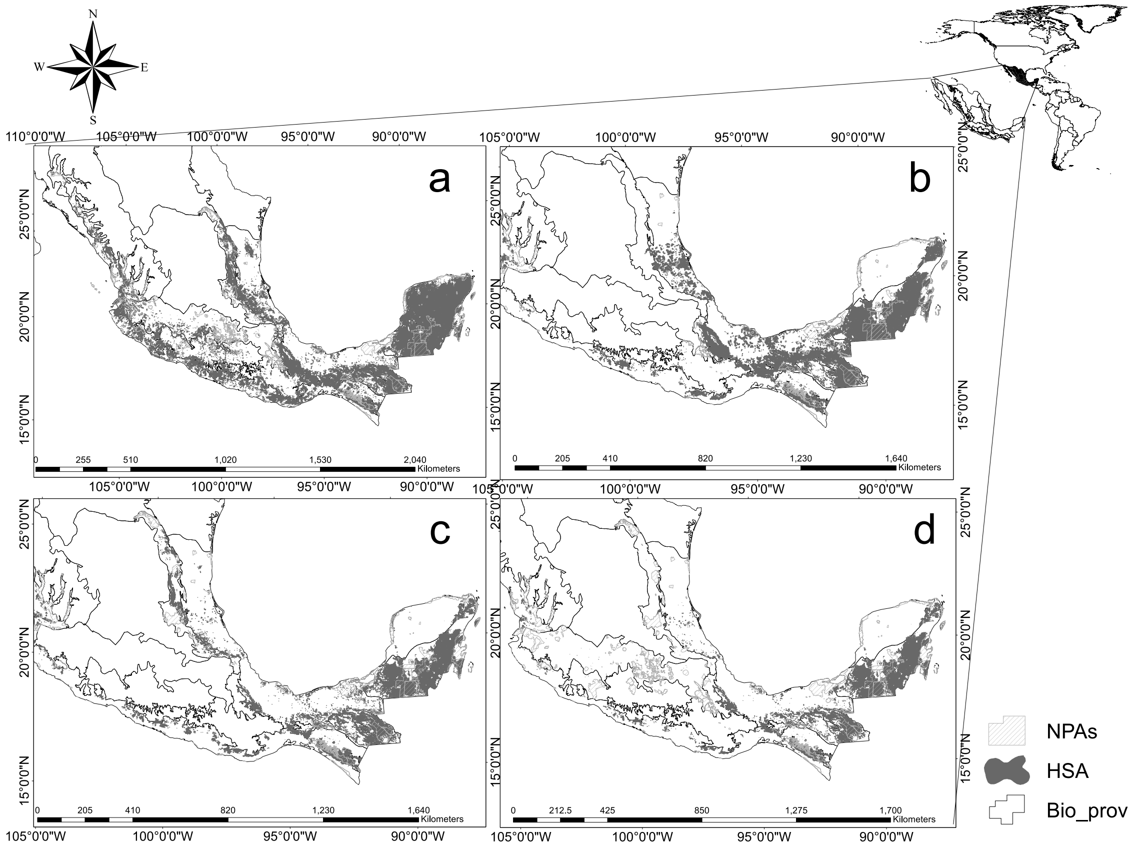

Figure 2. Maristella D'Addario. Potential distribution of four neotropical raptors in Mexico.

Legends to figures

Figure 1. Study areas of *Spizaetus ornatus* (a), *Spizaetus tyrannus* (b) and *Sarcoramphus papa* (c). Bio_prov = Biological provinces.

Figure 2. High suitability areas (HSA) of *Spizaetus ornatus* (a), *Spizaetus tyrannus* (b) and *Sarcoramphus papa* (c), and the high suitability area shared by the three species (d). In light grey we can see the Natural Protected Areas (NPAs) included in the study area. Bio_prov = Biological provinces.

Table 1. Predictive variables.

Variables	**Source**
Altitude (m)	USGS (2007)
Slope (degrees)	USGS (2007)
Aspect (degrees)	USGS (2007)
Distance to water bodies (km)	INEGI (2000)
Distance to rivers (km)	INEGI (2000)
Tree vegetation cover (%)	Global Land Cover Facility, De Fries *et al.* (2000)
Agriculture	INEGI (2014)
Grassland	INEGI (2014)
Temperate forest	INEGI (2014)
Deciduous forest	INEGI (2014)
Evergreen forest	INEGI (2014)
Aquatic vegetation	INEGI (2014)
Arid vegetation	INEGI (2014)
Human population density	Centre for International Earth Science Information Network (2015)
Distance to paved roads (km)	INEGI (2012)

Table 2. AUC values for each species and algorithm, and the final external AUC values of the ensemble models (AUC_i=internal AUC; AUC_e=external AUC). GARP1= GARP with Best Subsets–new openModeller implementation. GARP2= DesktopGARP implementation.

	S. ornatus		***S. tyrannus***		***S. papa***	
Algorithms	**AUC_i**	**AUC_e**	**AUC_i**	**AUC_e**	**AUC_i**	**AUC_e**
ENFA (median)	0.94	0.84	0.75	0.20	0.71	0.93
Maxent	0.85	0.90	0.99	0.90	0.98	0.99
ANN	0.48	0.77	0.75	0.68	0.89	0.86
ED	0.99	0.89	0.99	0.87	0.99	0.99
GARP1	0.93	0.76	0.82	0.77	0.68	0.60
GARP2	0.89	0.86	0.88	0.78	0.85	0.81
SVM	0.60	0.87	0.91	0.92	0.92	0.93
Ensemble		**0.94**		**0.95**		**0.99**

Supplementary material: Appendix 1

- File name: Appendix 1
- File format: .xlsx
- Title of data: *S. ornatus, S. tyrannus, S. papa*
- Description: database of the species' georeferenced records

V. DISCUSIÓN GENERAL

México representa el límite sur de la distribución de *Aquila chrysaetos chrysaetos* y el límite norte de la distribución de las otras tres especies, siendo una zona de transición entre climas neárticos y neotropicales. Las áreas marginales de distribución de las especies son las más sujetas a pérdidas de variabilidad genética y como consecuencia a extinciones locales o a fuertes disminuciones de sus poblaciones (Harrison & Bruna, 1999; Fahrig, 2003; Vucetich & Waite, 2003; McMinn *et al*., 2017), eso significa que México es una zona clave para la conservación de estas especies.

El área de alta idoneidad que se obtuvo para el águila real (ver primer artículo) resulta muy fragmentada y fuertemente relacionada a la presencia de pastizal y matorral, características típicas de su hábitat en México (Rodríguez-Estrella, 2002). Una de las áreas prioritarias para la conservación del águila real, por su tamaño y continuidad, se encuentra en el Altiplano norte y parcialmente en el Altiplano sur, además en esta zona ya se encuentran importantes áreas de anidación de la especie (Lozano-Román, 2008; Bravo *et al*., 2015) y grandes poblaciones de sus principales presas (Lozano-Román & Villalobos-Sánchez, 2003; Bravo *et al*., 2015). La principal amenaza para esta especie, en México, es la pérdida y fragmentación de su hábitat, causada principalmente por sobrepastoreo bovino y ovino, que afecta también muchas otras especies, incluso en algunas ANPs (Manzano-Fischer *et al*., 2006; Jiménez-Pérez *et al*., 2009). El pastizal representaba en el pasado uno de los biomas más difundidos en el mundo mientras ahora es uno de los más amenazados y menos protegidos (Manzano-Fischer *et al*. 2006). En México pastizal y matorral presentan diferentes niveles de degradación debido sobre todo al sobrepastoreo (CONABIO & SEMARNAT, 2009). Para esta especie propusimos dar prioridad a su conservación en las áreas de alta idoneidad que coinciden con las áreas de anidación más importantes como Baja California, Sonora, Chihuahua, Coahuila Aguascalientes, Zacatecas, Durango, Guanajuato, Jalisco (CONANP, 2018). Además, propusimos: actividades de sensibilización en sitios, como en Zacatecas, donde algunas comunidades usan partes de las águilas para ceremonias y rituales mágico-religiosos y mayores medidas de control de pastoreo, sobre todo en áreas de anidación protegidas o alrededor de estas, donde es importante mantener la vegetación natural (pastizal y matorral) y todo el ecosistema relacionado.

Las tres especies neotropicales estudiadas (*S. ornatus*, *S. tyrannus* y *S. papa*) están consideradas raras en muchas regiones debido sobre todo a la deforestación (Bierregaard, 1998; Drummond *et al*., 2008) y están caracterizadas por tasas reproductivas bajas, lo cual las hace más sensibles a la pérdida y fragmentación de su hábitat (Quesnelle *et al*., 2014). Los resultados del presente estudio (ver segundo artículo) muestran que el hábitat más idóneo para las tres especies está caracterizado por la presencia de selva húmeda tropical (selva perennifolia en las variables elegidas) y la cercanía a cuerpos de agua, mencionado en estudios locales (Puebla-Olivares *et al*., 2002; Phillips & Hatten, 2012; Sánchez-Soto *et al*., 2013). Estos ecosistemas representan hotspots de biodiversidad, ricos de especies endémicas y al mismo tiempo muy afectados por la deforestación (Myers *et al*., 2000; Brooks *et al*., 2002). Las áreas más idóneas para las tres especies se encuentran en las provincias biogeográficas de: Petén, Golfo de México, Soconusco y Costa del Pacífico, sobre todo en el Petén, donde encontramos las áreas potencialmente idóneas más continuas y extensas, dominadas por selva tropical perennifolia. Nosotros propusimos sobre todo el área de alta idoneidad que se encuentra en la provincia del Petén como prioritaria para la conservación de las tres especies (ver segundo artículo). Además, propusimos la inclusión de algunas áreas de distribución del Zopilote rey en el mapa oficial de IUCN (ver segundo artículo).

Otro alcance importante de este estudio fue evidenciar que el zopilote rey (*S. papa*) se encuentra en México en una zona donde es considerado extinto por la IUCN (International Union for Conservation of Nature), en las costas del Pacífico y del Golfo de México y en un área no reportada por la misma fuente, en la Reserva de la Biósfera El Cielo, en Tamaulipas. Esta evidencia se debe no sólo a los resultados del modelado sino también a observaciones recientes publicadas en GBIF (2004, 2006) y a una observación en campo de nuestro equipo de trabajo en el 2013. Por lo tanto, sugerimos la revisión del mapa publicado en el sitio del IUCN relativo a la distribución del zopilote rey.

Las aves de presa grandes necesitan de amplias áreas de hábitat idóneo para que sus poblaciones puedan persistir a largo plazo (Vance *et al*., 2003) por lo cual es prioritario, para establecer nuevas estrategias de conservación, considerar la importancia de la conectividad entre áreas naturales protegidas, o el tamaño de estas, en particular para las especies más especializadas y menos tolerantes a los cambios o al disturbio antrópico (Zurita & Bellocq, 2007).

Se necesitan todavía numerosos esfuerzos y más estudios enfocados a investigar o mejorar el conocimiento de aspectos básicos de su ecología para poder establecer con más precisión su estado de conservación y planear estrategias de manejo y conservación adecuadas. Se necesita sobre todo una más eficiente colaboración entre investigadores para poder obtener resultados a gran escala y a largo plazo.

VI. REFERENCIAS

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