Potential distribution of the Ocelot (*Leopardus pardalis*) in southern Sierra Madre Oriental and Sierra Negra, México

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The ocelot is one of the six species of felids distributed in Mexico. This species is threatened with extinction and thus protected by the Mexican government. Knowledge about the environmental factors that affect its presence is a crucial step in identifying key areas and designing strategies for the conservation of this species. The aim of this study was to document the presence of the ocelot to determine its potential distribution and identify important conservation areas in the southern Sierra Madre Oriental and Sierra Negra of Puebla (as part of the northern Sierra Madre del Sur). We conducted camera-trap surveys from October 2013 through January 2014, placing 63 camera-trap stations distributed in both areas. The overall sampling effort was 2,381 trap-days. The presence of the ocelot was recorded in the Sierra del Abra-Tanchipa Biosphere Reserve, in San Luis Potosi and Sierra Negra in Puebla. An estimated 78 % of the study sites hold suitable environmental conditions for the potential presence of ocelots. The variables that jointly accounted for 65 % of the potential distribution were related to precipitation, namely precipitation of the driest trimester, of the wettest month, and of the warmest trimester. Our potential distribution models suggest the existence of priority regions for ocelot conservation. This research updates the present status of the ocelot in the Sierra Madre Oriental and Sierra Negra in Puebla, sites that have been subject to high habitat encroachment by human settlements.

El ocelote es una de las seis especies de felinos que se distribuyen en México. Está especie se encuentra amenazada y por tanto protegida por el gobierno mexicano. El conocimiento sobre qué factores ambientales afectan su presencia es un paso crucial en el diseño o la propuesta de áreas de conservación para las especies. El objetivo de este trabajo fue documentar la presencia del ocelote para generar una distribución potencial e identificar sitios para su conservación en el sur de la Sierra Madre Oriental y Sierra Negra de Puebla (que es parte del norte de la Sierra Madre del Sur). Para ello, se realizó un muestreo con 63 estaciones de foto-trampeo distribuidas en ambas áreas entre octubre de 2013 y enero de 2014. En total, realizamos un esfuerzo de muestreo de 2,381 días/trampa. La presencia del ocelote se registró en la Reserva de la Biosfera Sierra del Abra-Tanchipa en San Luis Potosí y Sierra Negra en Puebla. Estimamos que el 78 % del área de estudio tiene condiciones ambientales adecuadas para la presencia potencial del ocelote. Las variables que tuvieron una contribución acumulada del 65 % para explicar su distribución potencial estuvieron relacionas con la precipitación y fueron tres: precipitación del trimestre más seco, del mes más lluvioso y del trimestre más cálido. Los modelos de distribución sugieren la existencia de sitios prioritarios para la conservación de ocelotes. Este trabajo representa un avance fundamental en la situación actual del ocelote y su área de distribución en la Sierra Madre Oriental y Sierra Negra en Puebla, sitios que han estado sujetos a presiones humanas.

Keywords: Conservation areas; camera traps; biological corridor; Maxent; ecological niche modeling.

Introduction

The ocelot (*Leopardus pardalis*) is one of six species of felids distributed in Mexico (Aranda 2005). The presence of this species in Mexico has been documented in areas ranging from semi-arid regions with xerophytic scrubs, dry tropical forests, to the coastal plains of the Pacific and Gulf of Mexico, including tropical rain forest, temperate and cloud forests, and mangroves in the Yucatan peninsula (Ahumada-Carrillo *et al.* 2013; Valdez-Jiménez *et al.* 2013; Aranda *et al.* 2014; Martínez-Calderas *et al.* 2011, 2015; Servín *et al.* 2016; Torres-Romero *et al.* 2017). Recent studies in America indicate that the ocelot is a species susceptible to habitat

loss, leading to population fragmentation and isolation, producing a low gene flow that ultimately leads to genetic divergence, reduction in population size, and lower dispersal capacity (Janecka *et al.* 2014). For these reasons, it is considered that the current anthropogenic activities in the Sierra Madre Oriental (SMO) may be acting as major barriers restraining the connectivity of wild feline populations (Grigione *et al.* 2009; Villordo-Galván *et al.* 2010; Martínez-Calderas *et al.* 2011, 2015; Dueñas-López *et al.* 2015; Torres-Romero *et al.* 2017).

The Sierra Madre Oriental is considered an important biological corridor that maintains the connection between

remnants of primary vegetation in eastern and southeastern Mexico, including those of the Sierra Negra in Oaxaca, Puebla, and Veracruz (Álvarez-Icaza 2013; Grigione *et al.* 2009; Dueñas-López *et al.* 2015). Suitable habitat patches have been found in this region, which can function as corridors for the survival and flow of different species of carnivores (Dueñas-López *et al.* 2015). However, the Sierra Madre Oriental and Sierra Negra in Puebla (SNP) are facing serious conservation problems such as land-use changes, fragmentation, and loss of vegetation cover, related to anthropic factors that could affect the presence of several felid species (Ortega-Huerta and Peterson 2008; Ramirez-Bravo *et al.* 2010; Villordo-Galván *et al.* 2010). In this sense, populations of jaguar, ocelot, cougar, jaguarundi, and their prey have been reported in regions of San Luis Potosi, which have survived given the presence of habitat patches in the region that provide coverage, food, and shelter for these species (Villordo-Galván *et al.* 2010; Martínez-Hernández *et al.* 2014; Dueñas-López *et al.* 2015; Hernández-Saint Marín *et al.* 2015).

In this regard , the generation of basic knowledge about the presence of the ocelot in an area (*L. pardalis*), a species related to landscapes with dense and broad forest coverage and little disturbance, may indicate a relatively low impact in such area and thus potential for its conservation or restoration (Aranda *et al.* 2014). For these reasons, its presence in areas with some degree of human disturbance will provide essential and useful information for the conservation of the species. An example of such areas is the southern Sierra Madre Oriental, a region that can be a biological corridor showing alterations in the landscape due to human impacts. Therefore, the objective of the present work was to record the presence of ocelot and predict, via an ecological niche modeling approach, the potential distribution of ocelot in the southern Sierra Madre Oriental and Sierra Negra in Puebla, seeking to identify and support priority sites for its conservation.

Materials and Methods

Study Area. The Sierra Madre Oriental is a mountain range spanning across 1,350 km with a width of at least 50 km and a maximum elevation of 2,500 m. This mountain complex stretches with a north-west-southeast direction, covering part of the Mexican states of Coahuila, Nuevo León, Tamaulipas, San Luis Potosi, Hidalgo, and north of Puebla (Ruiz-Jiménez *et al.* 2004). It encompasses a broad range of climatic conditions including warm, tropical, humid, temperate, and dry climates; with a mean total annual precipitation ranging from 139 to 3,377 mm (Hernández-Cerda and Carrasco-Anaya 2004). The structure of the landscape is heterogeneous, consisting of livestock and agriculture systems along with important vegetation types, including mountain cloud forests, seasonally dry tropical forests, temperate forests, humid tropical forests, and xeric scrublands. Of these, the xeric scrubland shows the most extensive distribution, while the mountain cloud forest is the most restricted (Contreras-Medina 2004; Suárez-Mota *et al.* 2017).

Sierra Negra in Puebla is a mountain range with a maximum elevation of 3,000 meters; it belongs to the physiographic province of the Sierra Madre del Sur and is located in the southern portion of the state of Puebla, bounded by Sierra Mazateca in Oaxaca and Zongolica in Veracruz (Lugo and Córdova 1992; INEGI 2009). It has a mean annual temperature ranging from 12 to 17 °C and total annual precipitation between 800 to 4,100 mm (INEGI 2009). It is home to a variety of habitats and vegetation types, including rainfed agriculture, cultivated pastures, mountain cloud forest, evergreen tropical forest, and pine forest (INEGI 2009). The study area was located in three regions, specifically the Sierra del Abra-Tanchipa Biosphere Reserve (RBSAT) in San Luis Potosi and Los Mármoles National Park (PNM) in Hidalgo; the Natural Resources Protection Area named Río Necaxa Hydrographic Basin (APRNCHRN) in Puebla; and Sierra Negra in Puebla (Figure 1).

Sampling Design. Sampling was carried out from October 2013 to January 2014 using StealthCam (Delta 8.0 Mpx®) digital camera-traps. Each camera trap was set to record wildlife both day and night during the 24-hour period, with a 3-second delay between photographic records. Each camera also recorded a 90-second video. The sampling design consisted of installing 63 simple photo-trapping stations distributed across the four sampling sites along the main roads, paths, or trails to maximize the likelihood of ocelot capture (Table 1). Trapping stations were spaced 1.5-2.0 km apart, considering the minimum area of activity of an adult female ocelot (Martínez-Meyer 1997; Torres-Romero *et al.* 2017).

Potential Distribution Modeling (MDP). Occurrence records of *L. pardalis* were obtained from fieldwork and from the scientific literature between 1990 and 2015, seeking to gather the highest number of records on the presence of ocelot in recent decades. The literature review was performed using the "ISI web of knowledge" database (https://www.accesowok.fecyt.es/). In addition, we included records of scientific collections such as the Colección de Foto Colectas Biológicas (CFB) of the Instituto de Biología
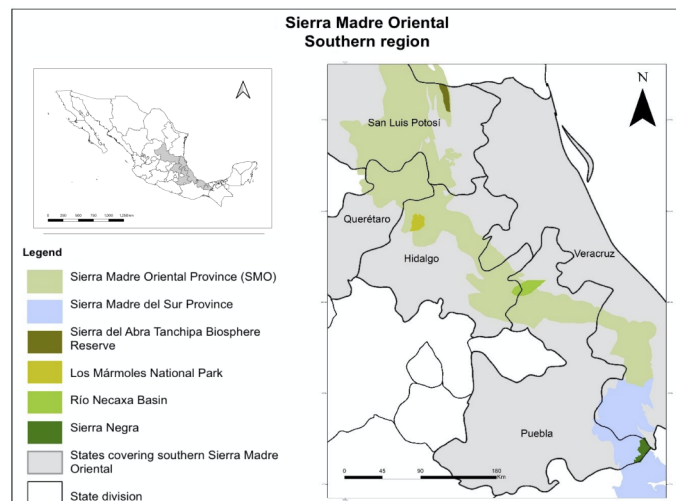

Figure 1. Study area and sampling sites of ocelot in the southern Sierra Madre Oriental.

at the Universidad Autonoma de México (http://unibio.unam.mx/collections/specimens/urn/IBUNAM:CFB:FB) and the databases: Global Biodiversity Information Facility (GBIF, www.gbif.org), Mammal Networked Information System (Manis, www.manisnet.org), Unidad Informática para la Biodiversidad (UNIBIO, www.unibio.unam.mx), and the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO, www.conabio.gob.mx). Then, occurrence records were reviewed for inconsistencies, discarding dubious and duplicate records, retaining 59 locality-unique records for analysis, nine coming from fieldwork and 50 from literature and databases.

We used the 19 digital climatic variables described for Mexico (Cuervo-Robayo *et al.* 2013). Each layer was in raster format at a 1 km^2 spatial resolution and adjusted clipped to the study region (Figure 1). We used presence records and climatic variables for modeling the potential distribution of *L. pardalis* using the maximum entropy algorithm Maxent ver. 3.3.3k (Phillips *et al.* 2006). We chose the following output settings for our models: maximum number of background points = 10,000, regularization multiplier = 1, replicates = 20, type of replication execution= bootstrap, convergence threshold = 0.00001, and maximum number of iterations = 10,000. We built models using 70 % as training data and the remaining 30 % for evaluation using the Area Under the Curve (AUC) generated by the Receiver Operating Characteristic (ROC) technique performed by the same Maxent program (Hanley and McNeil 1983). We assessed the contribution of each environmental variable with the Jackknife method implemented in Maxent. We converted the cumulative Maxent output to a binary map using the 10-percentile threshold value (Figure 2).

Next, we derived the landcover aptitude to support ocelot populations based on an analysis of the number of records of the species in land-use and vegetation classes obtained from INEGI (2011; available at: http://www.inegi.org.mx/geo/contenidos/recnat/usosuelo/; Table 1). To do so, we reclassified the land-use and vegetation classes in four categories based on the ecological requirements of

the species (Anderson *et al.* 2002), obtained from the association between the presence of the species and vegetation types, as reported by several authors throughout its distribution range (Martínez-Calderas *et al.* 2011, 2015; Valdez-Jiménez *et al.* 2013; Ahumada-Carrillo *et al.* 2013; Martínez-Hernández *et al.* 2014; Servin *et al.* 2016; Table 2), as follows: optimal (suitable habitat), suboptimal (habitat with minimum environmental conditions for its presence), marginal, and inhospitable; the latter comprises unfavorable zones with no presence of ocelots due to disturbance and anthropic activity.

Results

Ocelot Records. Photographic records of *L. pardalis* were obtained at two sampling sites: The Sierra del Abra-Tanchipa Biosphere Reserve, in San Luis Potosí, and Sierra Negra, in Puebla, with an overall sampling effort for both areas of 1,258 trap-days. We also recorded ocelot cubs in evergreen and deciduous tropical forests in both sites. By contrast, no ocelot records were obtained in Los Mármoles National Park and the Necaxa River Basin Natural Resources Protection Area with a sampling effort of 1,123 trap-days. Most phtographs (82 %) were captured below 1,000 m, with 260 m as the record at the lowest elevation, corresponding to the Sierra del Abra-Tanchipa; the record at the highest elevation was in Sierra Negra, at 1,117 m. We recorded ocelots in four types of vegetation: deciduous tropical forest (46 %), evergreen tropical forest (36 %), secondary vegetation (9 %), and riparian vegetation (9 %).

Potential Distribution and Suitable Habitat. Seventy-eight percent of the study area presented suitable environmental conditions for the presence of *L. pardalis*, while the remaining 22 % was identified as an unfavorable area (Figure 2). The unfavorable area is in the western portion of the Sierra Madre, bordering the Southern Highlands ("Zacatecano-Potosino") province and the Trans-Mexican Volcanic Belt. The mean AUC value for the *L. pardalis* distribution models was 0.825 (± 0.012). Thirteen environmental variables contributed to account for 100 % of the variation
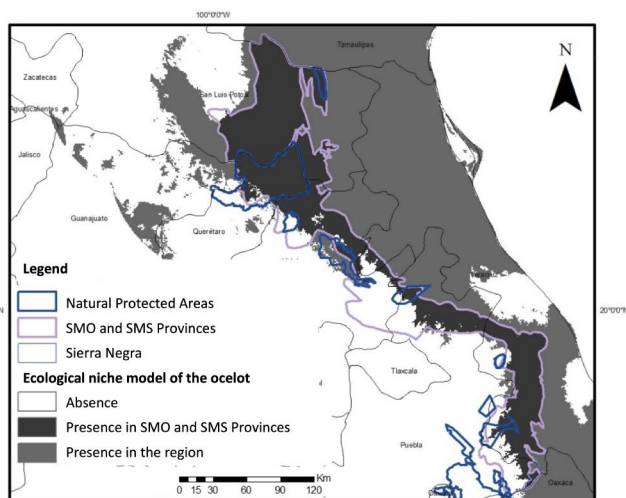

Figure 2. Potential distribution of ocelot for two areas: Study area (dark gray) and for eastern Sierra Madre Oriental (light gray).

Table 1. Sampling effort in each study site.

Study sites	Period (2013/2014)	Duration (days)	Photo-trapping stations	Trap-nights
Sierra del Abra-Tanchipa Biosphere Reserve	4 Nov. - 7 Dec. 2013	34	20	680
Los Mármoles National Park	8 Oct. - 23 Nov. 2013	47	17	799
Natural Resources Protection Area named Río Necaxa Hydrographic Basin	13 Dic. 2013 - 17 Jan. 2014	36	9	324
Sierra Negra	14 Dec. 2013 - 16 Jan. 2014	34	17	578
Total			63	2,381

in the potential distribution of ocelot (Precipitation of Driest Quarter; Bio17) , Precipitation of Wettest Month (Bio13), Precipitation of Warmest Quarter (Bio18), Precipitation Seasonality (Bio15), Precipitation of Wettest Quarter (Bio16), Temperature Seasonality (Bio04), Isothermality (BIO2/BIO7; Bio03), Min Temperature of Coldest Month (Bio06), Temperature Annual Range (Bio07), Mean Temperature of Wettest Quarter (Bio08), Precipitation of Driest Month (Bio14), Annual Mean Temperature (Bio01), Max Temperature of Warmest Month (Bio05), but only three explained 65 % of the predicted potential distribution: precipitation of the driest trimester (bio 17), precipitation of the wettest month (bio 13), and precipitation of the warmer trimester (bio 18). We obtained eight vegetation types for optimal zones, 15 for suboptimal zones, 18 for marginal, and 9 for inhospitable (Table 1). Based on this classification, 17 % of the habitat was optimal; 33 % sub-optimal, 19 % marginal, and 31 % inhospitable (Figure 3).

Discussion

Presence of the Species in the Study Areas. In the Sierra del Abra Tanchipa Biosphere Reserve and Sierra Negra, the ocelot was present with males and females, the latter accompanied by offspring. The presence of offspring in a population is worth stressing, mainly because it is indicative of recruitment and turnover of individuals. Most presence records occurred at elevations below 1,000 m (82 %), a finding consistent with Aranda (2005). In previous works, the deciduous and evergreen tropical forests were habitats with the highest incidence of ocelot records (Ramirez-Bravo *et*

Figure 3. Classification of habitat aptitude for the potential presence of ocelot and landscape connectivity in Sierra Madre Oriental.

al. 2010; Martínez-Calderas *et al.* 2011), in agreement with our findings. Interestingly, we recorded no individuals in Los Mármoles National Park or the Necaxa River. However, other studies conducted subsequently reported several carnivorous species, including ocelot, in Los Mármoles (Aguilar-López *et al.* 2016), although the analysis of the records is not specified in detail. Our modeling results suggest that Los Mármoles likely includes suitable habitat to harbor ocelot populations, or at least it can function as a corridor.

In Sierra del Abra Tanchipa Biosphere Reserve, most of the core, buffer, and use areas remain undisturbed; however, the habitat surrounding this reserve to the south is continuously transformed for use in agriculture and livestock raising. The polygon of the Reserve holds a large patch of primary vegetation that is possibly used by ocelots as a transit corridor in SMO (Table 2). It is worth mentioning that, besides the ocelot population located in the Sierra del Abra-Tanchipa (Martínez-Hernández *et al.* 2014), a second population known for eastern Mexico is located in Sierra Negra (Galindo-Aguilar *et al.* 2016). Sierra Negra is an area still covered by patches of primary vegetation and optimal and sub-optimal habitats that favor the presence of ocelots and some potential prey (Galindo-Aguilar *et al.* 2016).

Potential Distribution Models. The potential distribution model of *L. pardalis* is useful for exploring aspects related to its conservation in the study area. The results obtained are consistent with the habitat quality and connectivity models obtained for northeastern Mexico (Martínez-Calderas *et al.* 2011, 2015). Precipitation regimes are important in the distribution of various species of wild mammals such as felids and ungulates in Mexico (Carrillo *et al.* 2015; Martínez-Calderas *et al.* 2011, 2015; Ortíz-García *et al.* 2012), and rodents in Arizona, US (Morrison *et al.* 2002). In addition, tropical environments with high rainfall are usually associated with the presence of various trophic guilds (predators and prey; Di Bitetti *et al.* 2008). These results are consistent with our findings, where the potential distribution model suggests that precipitation of the driest trimester, the wettest month, and the hottest trimester contributed to explaining over 60 % of the potential distribution of ocelot in the southern Sierra Madre and Sierra Negra in Puebla.

Importance of Sierra Madre Oriental, Sierra Negra, and Human Impac. We recorded ocelot offspring in evergreen and deciduous tropical forests, which are the vegetation types with the lowest degree of human disturbance. The presence of offspring is an important attribute indicating that populations are reproductively active and the sites where offspring were recorded hold the ecological requirements for the species to reproduce and persist (Hernández-Huerta 1992; Sunquist and Sunquist 2002). This finding indicates the importance of the remaining deciduous and the evergreen tropical forests patches, as both vegetation types likely function as habitats providing shelter, food, resting sites, and security to protect their offspring from predators. The areas surroundings Sierra del Abra-Tanchipa show a high degree of fragmentation; however, there is a resident
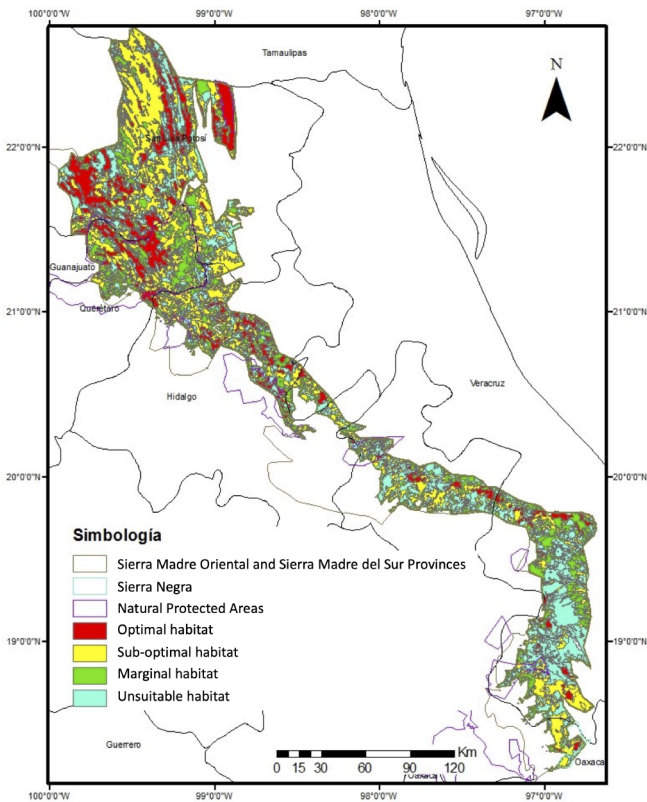
population of *L. pardalis* in the Reserve ([Martínez-Hernández *et al.* 2014](#)). Probably, ocelots and other felines use patches of vegetation that favor their mobility and dispersal to other vegetation remnants, thus promoting the recolonization of other areas ([Espinoza-Medinilla *et al.* 2018](#)).

Our results suggest that the southern portion of the Sierra Madre Oriental, specifically the State of San Luis Potosi and Sierra Negra, still maintain little disturbed areas of vegetation that, as a whole, are likely to function as a priority north-south biological corridor ([Grigione *et al.* 2009](#);

Table 2. Habitat aptitude based on the number of records of ocelot presence and the land-use and vegetation variables according to its ecological requirements.

Classification of Habitat Aptitude	Land Uses and Vegetation Types	
	Primary Vegetation	Secondary Vegetation
Optimal	Evergreen tropical forest Deciduous tropical forest Subdeciduous tropical forest Mountain cloud forest Crassicaule scrubland Microphyll scrubland Rosetophilous Scrubland Submontane scrubland	
Sub-optimal	Oak forest Pine forest Oak-pine forest Pine-oak forest Fir forest Juniper forest	Evergreen tropical forest Deciduous tropical forest Semi-evergreen tropical forest Subdeciduous tropical forest Mountain cloud forest crassicaule scrubland Microphilic desert scrubland Rosetophilous desert scrubland Submontane scrubland
Marginal	Secondary Vegetation Oak forest Pine forest Oak-pine forest Pine-oak forest Fir forest Juniper forest Mezquite woodland Gallery forest Chaparral Gallery vegetation Gallery tropical forest	Agroecosystems Cultivated and induced forest Cultivated and induced pastures Natural and induced palm-dominated forest Xerophilous halophilic vegetation Halophilic grassland Xerophilic mezquital Xerophilous halophilic vegetation
Inhospitable	Agriculture Human settlements Body of water barren land High mountain meadow Tular No apparent vegetation Halophilic hydrophilic vegetation Urban zone	

[Dueñas-López *et al.* 2015](#)). For example, ocelots have been reported in some areas of Hidalgo and Puebla ([Hernández-Flores *et al.* 2013](#); [Ramirez-Bravo *et al.* 2010](#); [Aguilar-López *et al.* 2016](#)), which may indicate the mobility of ocelots across the Sierra Madre and Sierra Negra.

High levels of anthropogenic habitat disturbance may force individuals to migrate into ecosystems with ecological or biological characteristics that are less suitable for survival ([Oliveira 1994](#)). Our results from the potential distribution model suggest that Los Mármoles and the Necaxa River did not present optimum environmental conditions for the presence of ocelots, although these may function as transit areas. In this regard, the subsequent record in Los Mármoles ([Aguilar-López *et al.* 2016](#)) suggests that the region may be used as a transit area towards the southern Sierra Madre, indicating that the ocelot is probably tolerant to certain degree of human disturbance ([Galindo-Aguilar *et al.* 2016](#)).

Based on our classification of habitat aptitude, the areas that recorded the presence of ocelot exhibited ideal conditions for them to function as biological corridors along the Sierra Madre and Sierra Negra, according to the red and yellow polygons shown in Figure 3. Therefore, we suggest implementing a systematic monitoring in areas adjacent to the study area to determine the extent to which human stressors affect the distribution of ocelots in the Sierra Madre and Sierra Negra. Besides, a molecular study should be conducted to investigate the genetic identity of this population and its relationship with the populations of Oaxaca and southeastern Mexico. Recording ocelots in adjacent areas is deemed relevant information that will enable the development of a more robust habitat connectivity model to advance better knowledge of a possible north-to-south dispersal of ocelot populations. Animal mobility is critical for preserving demographically and genetically healthy populations for conservation ([Shepard *et al.* 2008](#)). The fragmentation of the Sierra Madre, in particular, is especially worrying and is a problem that needs to be addressed strategically for the long-term conservation, not only of the ocelot, but of the biodiversity that coexist with it ([Escalante *et al.* 2005](#)).

This study contributes with basic, yet indispensable information for the conservation of the ocelot. Our results highlight that precipitation variables are related to the distribution patterns of the ocelot in the Sierra Madre and Sierra Negra.

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