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Geographic distribution prediction of an invading species in Mexico: the case of the monk parakeet (*Myiopsitta monachus*)

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ABSTRACT

Objective: To determine the potential distribution of the monk parakeet (*Myiopsitta monachus*) in Mexico.
Design/methodology/approach: The study generated the model with confirmed presences of the species, the MaxEnt algorithm, and bioclimatic and elevation information. The evaluation, calibration and selection were carried out with the kuenm package in R. The model generated was projected to the geographic space of Mexico.
Results: The model estimated the most favorable areas for the species in Mexico, based on the similarity of the climate and elevation conditions of the sites with its natural distribution. The most favorable sites for the species are distributed in the central-southern regions of the country. Variables influencing its distribution are derived from temperature, precipitation and elevation.
Limitations on study/implications: The model can contribute to the planning of management and monitoring strategies that mitigate the invasion of this species.
Findings/conclusions: The areas in Mexico where there is a high risk of invasion by the monk parakeet were identified.

Keywords: Exotic species, invasive species, invasion risk, biodiversity loss, MaxEnt.

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INTRODUCTION

Most of the invading species in Mexico have been introduced due to human activities related to trade (CONABIO, 2010). In the case of birds, their traffic has experienced a constant increase (Ribeiro *et al.*, 2019) and their liberation or escape into other environments represents a significant risk. This is because their propagation can cause economic losses, damage to biodiversity, and harmful effects for native species (CONABIO, 2010).

Although not all the exotic species manage to establish self-sustainable populations in the places where they are introduced, the risk increases significantly when the climate conditions are similar to those of their places of origin (Liu *et al.*, 2020). Therefore, the

spatial identification of sites that are more favorable for their propagation can be essential in the management of their local populations, in addition to promoting an early reaction against unwanted initial colonies.

In Mexico, out of the 348 species recognized as invaders, at least 16 bird species have been established and reproduced successfully (DOF, 2016). The monk parakeet (*Myiopsitta monachus*, Boddaert 1783), originally from South America (Salgado-Miranda *et al.*, 2016), was introduced as an ornamental bird since 1970 and has become one of the invading parrots with highest distribution in Mexico, confirming its presence in different states of the south (Pablo, 2009), center (Pineda and Malagamba, 2011), and north (Guerrero-Cárdenas *et al.*, 2012) of the country.

Although the monk parakeet is widening its distribution and can be abundant locally, the species has received scarce attention in Mexico. In addition, considering the importance of increasing its study, due to the damage that it generates in its environment (Hernández-Brito *et al.*, 2020; Castro *et al.*, 2022; Briceño *et al.*, 2023), the objective of this study was to model the potential distribution of the monk parakeet in Mexico, with the aim of determining the favorable zones for the species and estimating its possible expansion. An approach of such broad scale can help to elucidate some of the factors responsible for the increase in population and the distribution area of this potentially harmful species.

MATERIALS AND METHODS

Study area and records of presence

The study area corresponds to the Mexican Republic, which covers a continental surface of 1 959 248 km^2 and includes the totality of the physiographic provinces (INEGI, 2021). The coordinates of presence of the monk parakeet were obtained from the Global Biodiversity Information Facility platform (GBIF, 2021; 239 594 points) and field records (30 points). The spatial correlation between coordinates decreased considering a buffer circular area of 1.22 ha between each record, in function of the home range of this species (Senar *et al.*, 2021). The points that were outside this threshold were eliminated and the coordinates duplicated with spThin (Aiello-Lammens *et al.*, 2015) and *remove.duplicates* (Bivand *et al.*, 2013; R Core Team, 2021) packages, respectively.

Bioclimatic variables and calibration area

Bioclimatic variables generated from the interpolation of data from monthly meteorological stations were used, considering the average values covering from 1970 to 2000 (WorlClim, version 2.1; Fick and Hijmans, 2017), with a spatial resolution of 30 seconds of arc ($\sim$1 km^2). From the set of variables downloaded (n=19), the average temperatures of the most humid (BIO 8) and driest (BIO 9) trimester were excluded, as well as the amount of rainfall in the warmest (BIO 18) and coldest (BIO 19) trimester, due to the uncertainty that is generated when combining information about temperature and precipitation in the same raster (Escobar *et al.*, 2014). The variables were selected based on their coefficient of correlation (Pearson, $r \geq 0.8$) and biological importance (Avery *et al.*, 2012). The delimitation of the calibration area was fundamental in the modelling of niches and distribution of species, as well as in the generation of the model

(Soberón *et al.*, 2017). This site (Figure 1) was defined as the original distribution area of the monk parakeet and it was generated using the centroid of the presences and the minimum convex polygon.

Execution and evaluation of the model

The calibration, construction and evaluation of the model were carried out using the kuenm package (Cobos *et al.*, 2019), within the R Core Team environment (2021). The adjustment of the model was determined through the partial ROC analysis (operative curves characteristic of the receptor), the omission rate and the complexity of the model (Akaike information criterion). The exit format adopted was the logistic, where the maps represented values of environmental suitability in a range of 0 to 1, for the monk parakeet. The type ASCII file generated by the software was projected to the geographic space of the study area through QGIS (version 3.16; QGIS, 2021).

RESULTS AND DISCUSSION

Presence data and distribution model

The coordinates of presence were refined and reduced to 10862 single ones and spatially non-correlated. In the study, 1433 models and 85 sets of environmental variables were evaluated. The model selected was constructed with refined records (7603 for training and 3259 for execution) and the set of bioclimatic variables: isothermality (BIO 3), maximum temperature of the warmest month (BIO 5), annual temperature interval (BIO 7), mean temperature of the coldest quarter (BIO 11), annual precipitation (BIO 12), precipitation of the driest month (BIO 14), precipitation of the driest quarter (BIO 17), and elevation. The final model presented a satisfactory adjustment, with AUC rates of 0.96, omission rates of 0.01%, and partial ROC value of 0.

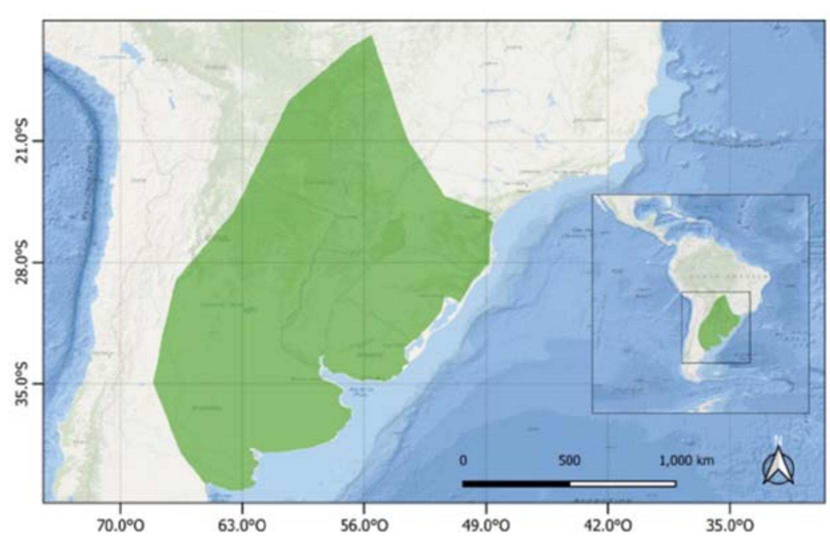

Figure 1. Calibration area (original distribution) used for the potential distribution model of the monk parakeet (*Myiopsitta monachus*).
Source: Prepared by the authors.

Bioclimatic variables

The bioclimatic variables selected through the Jack-knife process allowed identifying the climate spaces where the species groups together. These sites are characterized by having a partially fresh climate, whose temperature fluctuates between 3 and 14 °C in the coldest month and between 15 and 20 °C in the warmest month (Table 1).

Potential distribution of the monk parakeet in Mexico

The model projected zones of high climate suitability in the entire territory, especially highlighting regions in the center and southwest of Mexico (Figure 2).

These areas include the states of Jalisco, Michoacán, Puebla, Guanajuato, Guerrero and Oaxaca in areas where the species has not been recorded.

Table 1. Percentage contribution of the bioclimatic variables to the potential distribution model of the monk parakeet (*Myiopsitta monachus*) in Mexico.

Bioclimatic variables	Contribution (%)
Mean Temperature of Coldest Quarter (BIO 11)	61.2
Elevation	25.7
Precipitation of Driest Quarter (BIO 17)	4.7
Isothermality (BIO 3)	3.9
Maximum Temperature of Warmest Month (BIO 5)	1.8
Temperature Annual Range (BIO 7)	1.4
Precipitation of Driest Month (BIO 14)	1.2
Annual Precipitation (BIO 12)	0.1

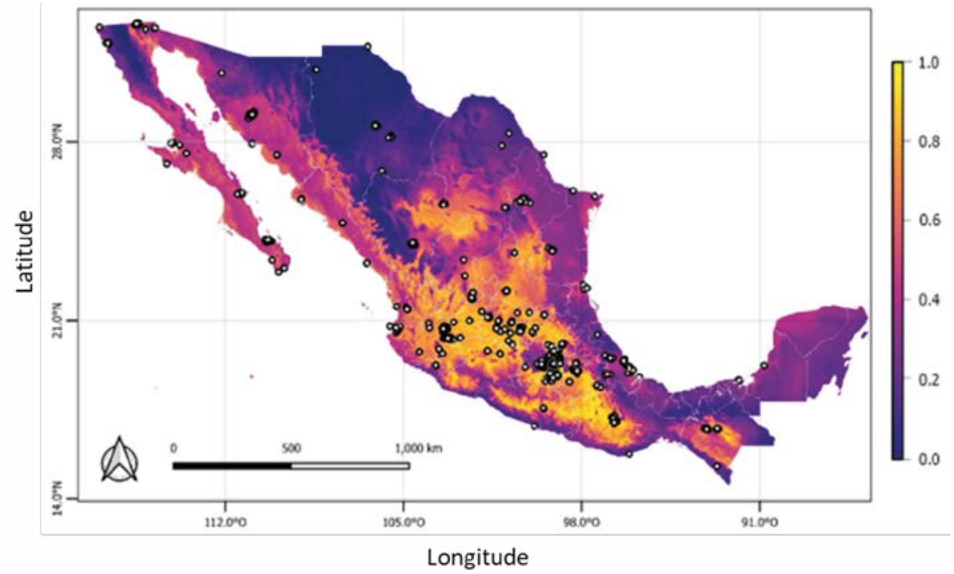

Figura 2. Potential distribution model for the monk parakeet (*Myiopsitta monachus*) in Mexico. The map indicates the continuous logistic estimation with lighter areas (values close to 1) that contain greater bioclimatic suitability. The circles indicate known presences of *M. monachus*.

DISCUSSION

The invasion anticipated by the model

The distribution of invading species can be modelled using environmental information from their region of origin (Thuiller, 2005). This study has been built to estimate the distribution of the monk parakeet in Mexico. It was developed with a limited set of bioclimatic and elevation variables that could influence its possible invasion. The predicted areas extend on most of the territory, especially in the zones of warm and temperate climates of the central portion of the country.

One of the most desirable characteristics of this model is that it classifies as favorable areas some sites where the species is absent. This could be explained by taking into account that the monk parakeet has invaded Mexico for some years (CONABIO, 2015) and that the colonization process is probably not over. Although the speed of dispersion of this species is low and there is no evidence that it conducts long-distance movements (>10 km, Borray-Escalante *et al.*, 2023), it is likely that the settlement of the sites estimated as favorable by the model is slow. Especially considering that these sites have continuity with those that have presence recorded and with favorable or intermediate favorable characteristics (>0.6). In these sites, the populations could be well established and act as sources from which monk parakeets disperse toward nearby favorable areas. However, the dispersion of the species observed during recent years has been fast and extensive (Da Silva *et al.*, 2010; Dawson *et al.*, 2021; Borray-Escalante *et al.*, 2023). This phenomenon has been attributed to this species being a broadly traded parrot, whose success in colonization and establishment increases notably with the rate of escape (Duncan *et al.*, 2003), which is why the model generated could be modified by including this factor.

As an exotic species, the demographic growth and of dispersion ends around 30 years after its phase of establishment (Shigesada and Kawasaki, 2002) and perhaps this invading species needs to surpass some other factors and biological interactions before occupying its potential distribution. However, if the establishment of the monk parakeet in Mexico was in an expansion phase (CONABIO, 2015), it would probably imply that demographic growth will continue in the zones with potential distribution, especially considering that its reproductive capacity increases in invaded areas (Senar *et al.*, 2019).

Need for monitoring

Once the exotic and invading species are established, their control or eradication is costly and difficult to carry out (Beever *et al.*, 2019). The monk parakeet can be considered exotic and invader in Mexico and its establishment has taken place successfully, since its presence is reported in most of the country (Zuria *et al.*, 2017).

Without adequate management, the expansion and demographic growth and of dispersion of this species could continue due to its adaptability to urban environments (Dickinson *et al.*, 2023), because its diet is nearly omnivorous of anthropogenic origin (Mazzoni *et al.*, 2021), and due to its high reproductive capacity (Senar *et al.*, 2019). This phenomenon has been documented in other countries (Hernández-Brito *et al.*, 2022) and at the same time, it has been accompanied by other potential damages in agricultural areas (Castro *et al.*, 2022), since it competes over nesting sites with native birds (Hernández-Brito *et al.*, 2020) and it can transmit zoonotic diseases (Briceño *et al.*, 2023); therefore, without a doubt they are factors that should be taken into consideration while monitoring the zones with potential for distribution.

CONCLUSIONS

The areas in Mexico where there is a high risk of invasion by the monk parakeet have been identified. Although it is clear that some variables not included in the model, such as climate change, the influence of human activities, or the biotic relationships with native fauna, can influence the dispersion of this species, the map generated can contribute to the planning of management and monitoring strategies. Likewise, the estimation can be considered as a first step toward a future expansion and invasion in Mexico, which justifies a close tracking of the populations of this species, especially in the areas detected as favorable by the model.

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