Assessing the risk of *Myiopsitta monachus* (Monk Parakeet) invasion: Global perspectives and implications

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ABSTRACT
Biological invasions are major threats to ecosystems and global economies, often exacerbated by human activities, such as trade and tourism. *Myiopsitta monachus* (Monk Parakeet), native to South America, is an example of an exotic species that has established populations across North America, Europe, and other regions. This study presents a model predicting the global distribution of *M. monachus*, focusing on areas at risk of future establishment. Using 25 climatic, topographic, and anthropogenic variables along with occurrence data from eBird (2000–2023), we conducted a multivariate logistic regression to create a favorability model, with 10 variables emerging as key predictors. The model showed high discrimination capacity (AUC > 0.856) and identified areas such as New Zealand, southern Queensland and New South Wales in Australia, Bangladesh, Peninsular Malaysia, South Africa, the coasts of the Arabian Peninsula, parts of Europe, including Germany, France, the United Kingdom, Ireland, and Bulgaria, as particularly vulnerable. In the Americas, the coastal regions of Ecuador and northern Peru, northern Colombia and Venezuela, as well as most of Central America, exhibit particularly favorable conditions. Similarly, the islands of Cuba, Jamaica, and Hispaniola, along with vast areas of Mexico and the United States, present a high potential for establishment. We emphasize the need for proactive monitoring in these areas to prevent both new arrivals through international trade and potential invasions. Additionally, countries where *M. monachus* populations are still relatively small, such as Morocco, those in Central Europe, and the United Kingdom, should implement control strategies to prevent future spread. Our research highlights the importance of species distribution models in forecasting invasive spread, aiding early detection and prevention efforts. These actions are crucial for safeguarding biodiversity and reducing economic losses.

Keywords: alien species, biogeography approach, early warning, species distribution models, prevention strategies, Psittacidae

How to Cite

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LAY SUMMARY

- The spread of non-native species poses a significant threat to ecosystems and economies, a process exacerbated by global trade and tourism.
- *Myiopsitta monachus* (Monk Parakeet), native to South America, has established invasive populations worldwide.
- We developed a predictive model to assess the risk of future establishment, integrating environmental and anthropogenic variables with bird sighting data from 2000 to 2023.
- Our model identifies high-risk regions, including Australia, New Zealand, parts of Africa, and Asia, with southern Queensland (Australia), South Africa, Central Europe, and Peninsular Malaysia emerging as particularly vulnerable areas.
- By identifying these at-risk zones, our model serves as a valuable tool for informing proactive monitoring and prevention efforts, helping to mitigate both the spread of this invasive species and its introduction through international trade.
- Our findings emphasize the need for early detection and targeted management strategies to protect biodiversity and reduce economic impacts.

Evaluación del riesgo de invasión de *Myiopsitta monachus* (cotorra argentina): perspectivas e implicaciones a nivel global

RESUMEN
Las invasiones biológicas representan amenazas significativas para los ecosistemas y las economías globales, facilitadas por actividades humanas como el comercio y el turismo. La cotorra argentina (*Myiopsitta monachus*), nativa de Sudamérica, es un ejemplo de una especie exótica que ha establecido poblaciones en Norteamérica, Europa y otras regiones. Este estudio presenta un modelo que predice la distribución global de la cotorra argentina, centrándose en las áreas en riesgo de establecimiento futuro. Utilizando 25 variables climáticas, topográficas y antropogénicas junto con datos de eBird (2000-2023), realizamos una regresión logística multivariante para crear un modelo de favorabilidad, del cual 10 variables surgieron como predictores claves. El modelo mostró una alta capacidad de discriminación (AUC > 0,856) y áreas como Nueva Zelanda, el sur de Queensland y Nueva Gales del Sur en Australia, Bangladés, Malasia, Sudáfrica, las costas de la Península Arábiga y partes de Europa como Alemania, Francia, el Reino Unido, Irlanda y Bulgaria, fueron señaladas como particularmente vulnerables. En América, las regiones costeras de Ecuador y el norte de Perú, el norte de Colombia y Venezuela, así como la mayor parte de Centroamérica, presentan condiciones particularmente favorables. De igual forma, las islas de Cuba, Jamaica y La Española, junto con amplias zonas de México y Estados Unidos, muestran un alto potencial de establecimiento. El estudio enfatiza la necesidad de un monitoreo proactivo en estas áreas para prevenir nuevas llegadas a través del comercio internacional e invasiones potenciales. Además, los países donde las poblaciones de cotorra argentina aún son relativamente pequeñas, como Marruecos, las de Europa Central y el Reino Unido, deberían implementar estrategias de control para prevenir una futura propagación. Esta investigación destaca la importancia de los modelos de distribución de especies en la predicción de la propagación de especies invasoras, ayudando en los esfuerzos de detección temprana y prevención.

Palabras clave: Alerta temprana, cotorra argentina, enfoque biogeográfico, especie exótica, modelos de distribución de especies, prevención, Psittacidae

INTRODUCTION

Biological invasions represent a formidable global challenge, threatening both ecosystems and economies by disrupting ecosystem services, reducing agricultural productivity, damaging infrastructure, and increasing management costs (Wilcove et al. 1998, Pimentel et al. 2000, Blackburn et al. 2011, Bellard et al. 2017). Following Elton's (1958) foundational work, invasion biology has advanced in understanding the traits of invasive species, the ecological mechanisms underlying these processes, and the potential acceleration of successful invasions driven by global climate change (Lodge 1993, Williamson 1996, Dukes and Mooney 1999, Moran and Alexander 2014). Human activities, particularly international trade and tourism, have further amplified the diversity and scale of biological invasions (McNeely et al. 2001, Levine and D'Antonio 2003, Simberloff et al. 2013). Once established, eradicating or controlling invasive species is a challenging and costly task (Jardine and Sanchirico 2018). However, proactive monitoring and prevention, particularly in ecologically sensitive regions, represent effective strategies for mitigating their impact (Mack et al. 2000).

Many species of birds have established populations beyond their native ranges, and have thus significantly contributed to our understanding of biological invasions (Lever 1987, Hulme 2009, Simberloff 2014). Of the 75 bird species that Kark et al. (2009) identified as having established self-sustaining populations in Europe, parrots (Psittaciformes) stand out as charismatic species, as they are often perceived positively and are accepted by humans (Burger and Gochfeld 2009, Muñoz 2016). *Myiopsitta monachus* (Monk Parakeet), a highly social, medium-sized parrot native to South America (Forshaw 1989), exemplifies this phenomenon. Introduced to various regions worldwide, with its population expanding rapidly, especially in North America (Uehling et al. 2019, Huerta-Sánchez et al. 2023) and the Mediterranean basin (Domènech et al. 2003, Strubbe and Matthysen 2009, Postigo et al. 2017, Souviron-Priego et al. 2018), this parakeet is now one of the most abundant and widespread parrots in the world (Royle and Donner 2021). The proliferation of this species raises potential ecological and economic concerns, including agricultural damage and disruption to infrastructure (Newman et al. 2004, Avery et al. 2008, Van Kleunen et al. 2010, Castro et al. 2022). Additional economic impacts could arise from factors like bird strikes (Fletcher and Askew 2007) or disease transmission (Butler 2005). Typically, this species builds nests in trees using branches and twigs, but in urban areas, they may nest on communication towers or electric utility poles (Bucher and Martin 1987, Aramburú et al. 2018). In some cases, this behavior can damage these structures, causing short-circuits and power outages (Avery et al. 2002, Newman et al. 2004). Although these impacts are not widespread, they underscore the need for monitoring and management in areas where the species has become established.

Understanding the spatial distributions and dispersal patterns of invasive species is crucial for effective management and policymaking (Muñoz and Real 2006, Real et al. 2008, Paterson et al. 2015). Strubbe et al. (2013) suggested that exotic birds may occupy a different ecological niche in invaded areas compared to their native ranges, underscoring the importance of characterizing the introduction conditions that facilitate successful invasions. Species distribution models (SDMs) provide valuable insights into the environmental requirements and potential expansion of invasive species (Franklin 2010, Baquero et al. 2021). Given *M. monachus* ongoing colonization of new regions (López-Ramírez and Muñoz 2022) and the emergence of new populations due to accidental or intentional releases, identifying suitable but currently unoccupied regions is crucial for improving predictions of its future range expansion. In this study, we present a global distribution model for *M. monachus*, aiming to identify areas susceptible to future establishment and to assess the model's accuracy in predicting its spread. We also explore the potential utility of SDMs in forecasting the expansion of invasive species globally.

MATERIALS AND METHODS

Occurrence Data

Our data source was eBird (eBird 2021), a global platform that continuously compiles reports from ornithologists and birdwatchers, offering the most up-to-date and comprehensive bird distribution data available. On January 26th, 2023, we accessed all records containing geographical coordinates of *M. monachus* observations worldwide. The dataset was reviewed, and we retained only records collected between January 2000 and January 2023.

Study Area and Species Range

Here we analyzed the world's landmass, excluding Antarctica, using a global grid of 20,805 hexagonal units, each covering an area of 7,774 km^2 (Martín-Taboada et al. 2023). Georeferenced presence data obtained from eBird were processed into a binary matrix, where presences were coded as 1 and absences as 0 (Figure 1). Absence was inferred for cells with no records of the species, assuming non-detection within areas that had been sampled. This presence-absence approach reduces the risk of autocorrelation caused by spatial dependencies among nearby occurrences (Legendre and Legendre 1998), and is commonly used in large-scale ecological studies based on opportunistic presence-only data, where true absences are rarely available. Using hexagons, rather than squares, offers distinct advantages in spatial representation of both species' distributions and environmental variables. Hexagons, as Operational Geographic Units (OGUs), maintain a consistent surface area across latitudes, unlike squares, which vary in size with latitude. All spatial data, including *M. monachus* distribution and environmental predictors were projected onto this global hexagonal grid using ArcGIS software version 10.8.1 (Esri 2021), ensuring more uniform and accurate spatial analysis.

For *M. monachus* distribution data, we incorporated presence records from both its native range (410 hexagons) and non-native regions (522 hexagons) globally, resulting in a total of 932 hexagons with presence across the world (Figure 1).

Predictor Variables

To identify the factors influencing *M. monachus* invasions at the hexagonal spatial resolution used in this study, we used 25 independent explanatory variables encompassing climatic, topographic, and anthropogenic factors (see Supplementary Material Table 1). These variables have demonstrated efficacy in elucidating the environmental determinants of species distributions across large spatial scales (Pearson and Dawson 2003, García-Carrasco et al. 2024). Climatic data were obtained from Chelsa (http://chelsa-climate.org; Karger et al. 2017). Topographic variables included mean altitude (m), obtained from GTOPO30 (US Geological Survey, 1996), and slope (degrees), calculated from mean altitude using ArcGIS. Anthropogenic variables derived from data provided by the Food and Agriculture Organization of the United Nations (FAO, http://www.fao.org/geonetwork; Salvatore et al. 2005), and distances were obtained from the Digital Chart of the World (DCW, http://worldmap.harvard.edu; Harvard University, 2002).

Before constructing the model, we applied a Spearman rank correlation analysis using

IBM SPSS Statistics V25 software (IBM Corp. 2017) to address multicollinearity among variables. Specifically, when two variables within the same explanatory factor had a correlation coefficient (*r*) greater than 0.7, we retained only the variable that was most strongly associated with the distribution of *M. monachus* (Zanolla et al. 2018). As a result, several variables were removed from the analysis due to high correlation with other variables (see details in Supplementary Material Table 1).

The digitalization process of all variables to match the study's scale and resolution was conducted using ArcGIS. We used the *spatial analyst* tool Zonal Statistics in ArcGIS to calculate the average values of each variable for each hexagonal unit based on our global database.

Distribution Modelling

The variables were analyzed using multivariate forward stepwise logistic regression in IBM SPSS Statistics V25 software (IBM Corp. 2017), starting with a null model containing no explanatory variables. At each step, all remaining candidate variables were evaluated, and the one that most significantly improved model fit, according to the Akaike Information Criterion (AIC) was added. Variables were retained only if their inclusion provided a statistically significant improvement in explanatory power without compromising model parsimony. The procedure was repeated iteratively until no further improvement could be achieved. Following this, we conducted a multivariate logistic regression analysis on *M. monachus* occurrence data, based on inferred presences and absences as previously described, using the 10 predictor variables that outperformed the previously described procedure in IBM SPSS Statistics V25. From the resulting probability values, we calculated favorability values by applying the Favorability Function (Real et al. 2006, Acevedo and Real 2012):

$$\text{Favorability Function} = \frac{P/1-P}{(n_1/n_0)+(P/1-P)}$$

where P is the probability of occurrence obtained from the multivariate forward stepwise logistic regression, n_1 is the number of presences, and n_0 is the number of absences. The values of this function range from 0 to 1, with lower values indicating less suitable conditions for the species, while higher values denote environmental characteristics that favor its presence, independent of the species' overall prevalence in the dataset (Acevedo and Real, 2012). In probability functions, the initial presence/absence ratio can significantly influence the results, introducing bias. This issue is corrected by favorability values which account for the disproportionate representation of presences and absences in the dataset, a common issue in ecological modelling (Cramer 1999, Real et al. 2006, Barbosa et al. 2013). Notably, favorability values depend only on the environmental conditions of the study area and the species' distribution within it, providing an objective metric for assessing invasion risk.

We visualized favorability values using a 10-category cartographic favorability model to illustrate the potential spread and risk of *M. monachus* invasion, using ArcGIS. To identify regions at varying levels of invasion risk, we adjusted the thresholds according to the method proposed by Muñoz and Real (2006). Favorability values were classified as follows: high ($F \geq 0.8$); medium-high (values of F between 0.5 and 0.8); medium-low (values of F between 0.2 and 0.5); and low ($F \leq 0.2$).

We assessed the discrimination and classification performance of the model across our study area of 20,805 hexagonal units with presences/absences records. We evaluated the discrimination capacity of the model using the area under the curve (AUC) of the receiving operating characteristic (ROC), a metric that is independent of favorability thresholds (Hanley and McNeil 1982, Dodd and Pepe 2003). Additionally, we assessed the classification capacity of the model using 3 threshold-dependent indices: (1) sensitivity, (2) specificity, and (3) correct classification rate (CCR) (Liu et al. 2009, Zurell et al. 2020). We used Wald's test parameters to assess the relative contribution of each variable within the models (Wald 1943).

To assess the contributions of the various factors used in the *M. monachus* distribution model, we employed a variation partitioning procedure (Borcard et al. 1992, Muñoz et al. 2005). This method enabled us to quantify the proportion of variation in the favorability model explained by the combined effect of all factors, as well as the individual contributions of each factor (i.e., climate, topography, and anthropogenic). This approach provided insights into the relative influence of different environmental variables on the species' distribution.

RESULTS

Explanatory Factors and Model Assessment

The final model for the global invasion of *M. monachus* included 10 predictor variables (Table 1). Based on the Wald test values, the most influential predictors were the coefficients of variation for temperature seasonality, the range of mean diurnal air temperature and precipitation seasonality. These were followed by distance to roads. In addition to these climatic and anthropogenic variables, mean altitude was among the top six explanatory variables, together with the precipitation of the coldest quarter. Regarding the variation partitioning results (Figure 2), the anthropogenic factor explained ~54% of the observed distribution patterns, whereas climate explained almost 40% and topography accounted for 5%. The shared effect between anthropogenic and climatic factors was 6.13%, while there was an inverse shared effect of –3% between climate and topography, and –2.51% between the topography and the anthropogenic factor, indicating their contrasting influences on the species' distribution.

The model exhibited high discrimination capacity, with an AUC of 0.856. Additionally, the model showed acceptable classification performance for both presence and absence, with a sensitivity of 0.857, a specificity of 0.696, and a CCR of 0.703. Notably, the model exhibited slightly higher prediction accuracy for presence (sensitivity) compared to absence (specificity). The model also displayed a high overprediction rate (0.883), indicating its ability to identify unoccupied regions that possess favorable conditions for invasion, along with a low underprediction rate (0.009).

Identifying Favorable Territories for *Myiopsitta monachus* Invasion

The global favorability model accurately predicted a significant portion of territories currently occupied by *M. monachus* (Figure 3). The model successfully identified countries with the highest favorability, where invasion has been extensively documented, including regions in Europe and the Americas, such as Spain, Central and South America, the United States, Canada, and Mexico. Furthermore, the model identified areas with medium-high favorability values ($0.5 \leq F < 0.8$) and high favorability ($F \geq 0.8$), where the species is not currently present. Medium-high favorability countries include Colombia, Peru, Madagascar, Ivory Coast, and India, while Australia, New Zealand, Bangladesh, Peninsular Malaysia, Ireland, Austria, Switzerland, and several countries of Eastern Europe, including Serbia and Bulgaria, the Maghreb region, southern Africa, and Cuba, exhibited the highest favorability.

DISCUSSION

Preventing the Colonization of Highly Favorable, Unoccupied Areas

Myiopsitta monachus, extending beyond its native range, poses an emerging threat as a potentially invasive species in several countries worldwide. Our model predicts a high potential risk of invasion in the Pacific region of Australia and New Zealand, where wild breeding records have not yet been reported. Despite the implementation of robust preventive measures (Hoffmann and Broadhurst 2016) and eradication plans for invasive species (Cromarty et al. 2002), the risk of *M. monachus* establishment remains high. Notably, there have been escape incidents involving this species along the east coast of Australia, particularly between Brisbane and Melbourne, and the parakeet is among the most frequently reported non-native caged-bird species listed on missing animal websites (Vall-llosera and Cassey 2017). However, the higher diversity of birds, particularly parrots in Australia (Rogers and Kark 2020), may naturally control the establishment of this species through competition. Our model identified regions with high environmental favorability for *M. monachus* colonization, spanning from southern Queensland to South Australia, including Victoria and New South Wales. The areas identified by Csurhes (2016) in Australia as climatically suitable for the species are also captured by our model, which additionally identifies the western part of the country as favorable. Given these findings, it is imperative to implement stringent prevention measures, especially in areas highlighted by our models as having the highest favorability values.

We have also identified highly favorable areas for *M. monachus* in Asian countries, including Oman, Yemen, Bangladesh, Peninsular Malaysia, Vietnam, and Thailand, despite the absence of official sightings of the species to date. Oman and Yemen, in particular, are flagged as potential invasion sites due to reported sightings of escaped individuals in the United Arab Emirates (Aspinall and Porter 2011). In this scenario, *M. monachus* could potentially disperse naturally from the United Arab Emirates to Oman, which also features areas with high favorability ($F > 0.8$) for the species to establish. However, this process may be gradual, given that the average distance travelled by *M. monachus* in other countries where they have become invasive is 33.2 km yr^{-1} (Borray-Escalante et al. 2023). While there is considerable distance between recorded sightings in the United Arab Emirates and Asian countries with high favorability values, such as Bangladesh and Thailand, the potential for natural arrival remains low. However, *M. monachus* has been reported to be sold at a Bangkok market (Chng and Eaton 2016), hinting at potential future introductions. Escapes or releases of the species could lead to established populations in these favorable environments. Therefore, monitoring and intervention are crucial to prevent *M. monachus* establishment in these regions.

In Africa, the potential risk of *M. monachus* invasion differs significantly between the north (mainly Tunisia and Algeria) and the south (including South Africa, Namibia, and Angola) (Figure 3). While the northern part of the continent features areas of high favorability, *M. monachus* has only been recorded in Morocco (Calzada Preston et al. 2021). This information is significant, as there is a real risk of the species expanding its range from Morocco to Algeria and Tunisia. Both countries have northern regions with high favorability values ($F > 0.8$), rendering them susceptible to potential *M. monachus* invasion. We anticipate that it is only a matter of time before this species establishes itself through natural dispersal in Morocco's neighboring countries, such as Algeria. However, the likelihood of the species naturally reaching areas with high favorability in the southern part of Africa, such as South Africa or Angola, is extremely low. Nevertheless, it is important not to disregard the potential risk of individuals arriving in these regions through international trade. Ultimately, if the species were to arrive in South Africa, where nearly the entire territory exhibits very high favorability values, our model suggest that the risk of establishment would be very high. The current risk increases if we consider the high number of *M. monachus* legally imported to and exported from South Africa in the first 2 decades of the present century: ~4,600 and 98,000 individuals, respectively (https://trade.cites.org/en/cites_trade). This indicates that if the species is bred in captivity in South Africa and is already present there, individuals could potentially escape and get established in the wild.

Although *M. monachus* is already breeding in parts of Europe, the threat of further invasion remains. Despite the high favorability values ($F > 0.8$) for Ireland, the presence of this parrot has not yet been detected. However, given Ireland's geographical proximity to the United Kingdom, where the species is established and breeding (Calzada Preston et al. 2021), and the intercontinental traffic from Europe, Ireland appears susceptible to unintentional introduction. Concern about the expansion of *M. monachus* is lower in Scandinavian countries, where the climate may limit its spread (Braun 2021), nevertheless authorities must be prepared to develop and implement proactive monitoring and prevention plans for this species. To this end, the proposed preventive cartography tool could aid in territorial decision-making.

In the Americas, our model identifies extensive areas with high environmental suitability for *M. monachus* colonization, despite the species not yet being present in many of these regions. Notably, the coastal regions of Ecuador and northern Peru, northern Colombia and Venezuela, as well as most of Central America—excluding northern Guatemala—, exhibit particularly favorable conditions. Similarly, the islands of Cuba, Jamaica, and Hispaniola, along with vast areas of Mexico and the United States, present a high potential for establishment. This is of particular concern given that *M. monachus* is already established in Puerto Rico (Falcón and Tremblay 2018) and across extensive areas of the southern United States (Uehling et al. 2019) and Mexico (Huerta Sánchez et al. 2023), which could facilitate via physical connectedness its natural dispersal into currently unoccupied yet highly suitable environments. Given these factors, proactive monitoring and the implementation of preventive measures are essential to mitigate the risk of further expansion.

Natural Dispersal from Favorable Invaded Areas and Control Strategies.
Based on the results from the model, prevention plans can be designed to deter the spread of *M. monachus* in high-risk regions, such as Australia, New Zealand, South Africa, or Ireland. Additionally, the findings support the formulation of control and eradication strategies in areas where the species is already established and the zone is highly favorable. In Morocco, the United Kingdom, France, or Germany, where invaded areas are still relatively small but favorable areas are considerably larger, it is crucial to promptly initiate control measures (see Figure 3). Various control methods have been employed to manage invasive parakeet populations, including chemical control agents, such as fertility control through oral contraceptives (Yoder et al. 2007, Avery et al. 2008, Lambert et al. 2010, Anderson et al. 2023), trapping, and shooting (Tillman et al. 2004, Saavedra and Medina 2020). However, all these measures are controversial, mainly because public perception of parakeets is often positive, which can lead to opposition against control efforts (Ribeiro et al. 2021). While each approach presents advantages and challenges, further research is needed to assess their feasibility and effectiveness in different contexts before implementation. In the case of Morocco, one reason for this urgency may stem from the recent

onset of the invasion (Bergier et al. 2015), with its presence limited to the coastal areas in the north of the country. Similarly, the parakeet's presence is primarily confirmed in the southern regions of England, but the favorable area spans the entire United Kingdom, indicating potential widespread invasion. While *M. monachus* in France has been detected in only two locations, almost the entire country exhibits high favorability values ($F > 0.8$). In Germany, the species has been observed in the northwest, near the Netherlands, but the western region of the country is highly favorable for species invasion. It is imperative in these countries to prevent further spread throughout the nation. Early intervention is critical, as it is easier to control and eradicate an invasive alien species in the initial stages of its invasion, thereby reducing control costs (Ahmed et al. 2022).

Distribution Models as a Tool for Prevention and Identification of Control Areas. Among the potential applications relevant to conservation, distribution models play a crucial role in predicting species presence in understudied areas (Romero et al. 2021), in forecasting species responses to environmental changes (López-Ramírez et al. 2024), and in predicting the spread of introduced species (Bellisimo et al. 2024). Including information related to the trade of the species could enhance the predictive accuracy of distribution models and help identify high-risk areas. However, tracking trade routes and distinguishing between legal and illegal breeding and commerce remains challenging. In the case of *M. monachus*, its widespread presence in the pet trade further complicates management efforts. The species is already legally and illegally bred in several countries, facilitating its continuous introduction into new areas. Understanding the role of the pet trade in the invasion dynamics of *M. monachus* could provide key insights for improving preventive measures (Souviron-Priego et al. 2018), particularly in countries or regions previously identified as highly suitable for its establishment. Recognizing the threat posed by invasive alien species to biodiversity, habitats, ecosystems, and the economy is a fundamental step in invasion management.

When combined with detailed knowledge of a species' biology and ecology, distribution models can serve as valuable tools, offering a spatial and biogeographical perspective to invasive species management (Araujo et al. 2019, Liu et al. 2022). However, invasive species, such as *M. monachus* pose unique challenges for management. Naturalized parrots are not like typical invasive species, which is particularly true for *M. monachus*. Human perception of parakeets is generally positive, even in cases, where they have been identified as invasive (Crowley 2021). This phenomenon is not unique to *M. monachus*; other parrot species, such as *Psittacula krameri* (Rose-ringed Parakeet), which has established invasive populations across Europe (Pârâu et al. 2016), *Psittacara erythrogenys* (Red-masked Parakeet), widely introduced in North America, and *Ara ararauna* (Blue and Yellow Macaw) also benefit from public support in urban areas like Brooklyn, San Francisco, and Caracas due to their charismatic appearance and association with urban green spaces (Kiacz and Brightsmith 2021). In Spain, a successful eradication effort was carried out in the city of Zaragoza, which resulted in the removal of a population of ~1,800 *M. monachus* (https://www.zaragoza.es/contenidos/medioambiente/InformeCotorraArgentina.pdf). As of today, the area remains free of *M. monachus*. However, there have been many failed attempts, where control and other management actions were halted by citizen associations due to the positive perception of the species (Parrot 2013), which is further reinforced by the generally favorable public attitude towards parrots as charismatic and socially engaging birds (Anderson 2003). In some invaded areas, particularly in Europe and the United States, this perception is reinforced by the fact that *M. monachus* is often the only or one of the few parrot species present, which generates considerable public interest and support (Crowley et al. 2019). Our model showed that over 54% of the explanation for the species' invasion is linked to human activity. Therefore, the success of our management strategies, including efforts to raise environmental consciousness, will largely depend on how we manage the impact of activities, such as urban development, agriculture, and transport, as well as educating the public about the issues associated with biological invasions.

We recommend focusing monitoring and prevention efforts on areas identified as highly suitable for *M. monachus* but where the species has not yet been detected. This proactive approach aims to facilitate early detection and intervention. This model identifies environmentally favorable areas for the species, regardless of whether its introduction occurs through natural dispersal or international trade. By pinpointing high-risk zones, it enables a more efficient use of resources by preventing its establishment. Implementing such a strategy can significantly reduce the financial costs associated with post-invasion eradication efforts (Ahmed et al. 2022).

While our model effectively identifies areas with a high probability of *M. monachus* establishment, it is important to acknowledge that certain factors potentially influencing the species' distribution could not be considered, partly due to methodological constraints inherent to working at a global scale and coarse resolution. Even when specific variables—such as those related to trade regulations (e.g., CITES)—are recognized as ecologically or socially relevant, limited data availability often precludes their consistent inclusion across all hexagonal units, countries, or regions. Moreover, the model reflects current environmental and anthropogenic conditions, yet it remains subject to the inherently dynamic nature of biological invasions. This is particularly relevant for an expanding species such as *M. monachus*, whose range is still evolving across many parts of the world. Ongoing monitoring of its spread will be essential to refine model outputs and update risk assessments as new introduction and establishment patterns emerge. We also recognize that the model operates at a relatively coarse spatial resolution (~7,700 km^2 per hexagon), which limits its applicability for site-specific management but enhances its value as an early-warning tool. It serves to highlight broad regions where the species could potentially establish, whether through human-mediated transport or natural dispersal.

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Ethics statement
This study did not involve any experimental procedures with animals and therefore did not require ethical approval. The authors declare that they have no conflicts of interest.

Author contributions
A.R.M. and A.M.T. conceived the study; A.R.M. and D.R. designed and supervised the research; A.M.T. performed the data analyses under the supervision of A.R.M. and D.R.; A.R.M led the manuscript writing, and all authors contributed to text editing; final editing was carried out by A.R.M.

Data availability
Analyses reported in this article can be reproduced using the data provided by Martín-Taboada et al. (2024).

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Table 1. Climatic, topographic and anthropogenic variables included in the model, ordered according to their entry sequence. Listed are the standard errors (SE), Wald test values, significance level (*P*), and the coefficient (β), along with its multiplying factor for the variable in the logit of the multivariate logistic regression, as estimated by the model.

Variable	**SE**	**Wald**	***P***	**β**
Temperature seasonality	0. 000015	365. 808376	1. 5306 *e*−81	–0. 000280
Precipitation seasonality	0. 000162	305. 538320	2. 0474 *e*−68	–0. 002831
Mean monthly precipitation of the coldest quarter	0. 000024	134. 769870	3. 7074 *e*−31	–0. 000281
Mean diurnal air temp. range	0. 001747	309. 867990	2. 3334 *e*−69	0. 030744
Population density	0. 000108	63. 996763	1. 2462 *e*−15	0. 000866
Distance to roads	0. 000008	145. 379177	1. 7745 *e*−33	–0. 000091
Mean monthly precipitation of the warmest quarter	0. 000016	48. 145452	3. 9575 *e*−12	0. 000109
Mean altitude	0. 000118	98. 913155	2. 6382 *e*−23	–0. 001172
Mean slope	0. 027265	51. 263619	8. 0759 *e*−13	0. 195212
Mean daily temperature of the warmest quarter	0. 000959	12. 486503	0. 000410	–0. 003389

Figure 1. The current global distribution of *M. monachus*, using hexagonal units. Territories with confirmed presence of the species, based on data from the eBird database (https://ebird.org/spain/home, consulted until January 2023), are shown in black. The native range of the species is depicted in green, following BirdLife International and the Handbook of the Birds of the World (2017). The map was created using ArcGIS (Environmental Systems Research Institute. Inc., Redlands, CA, USA).

Figure 2. Variance partitioning showing the proportion of *M. monachus* invasion explained in the global model by each factor (climatic, topographic, and anthropogenic) separately, and the shared effects and interactions between them.

Figure 3. Favorability values for *M. monachus* are represented using a color gradient, ranging from dark red (highest favorability values) to pale yellow (lowest favorability values).

Figure 1

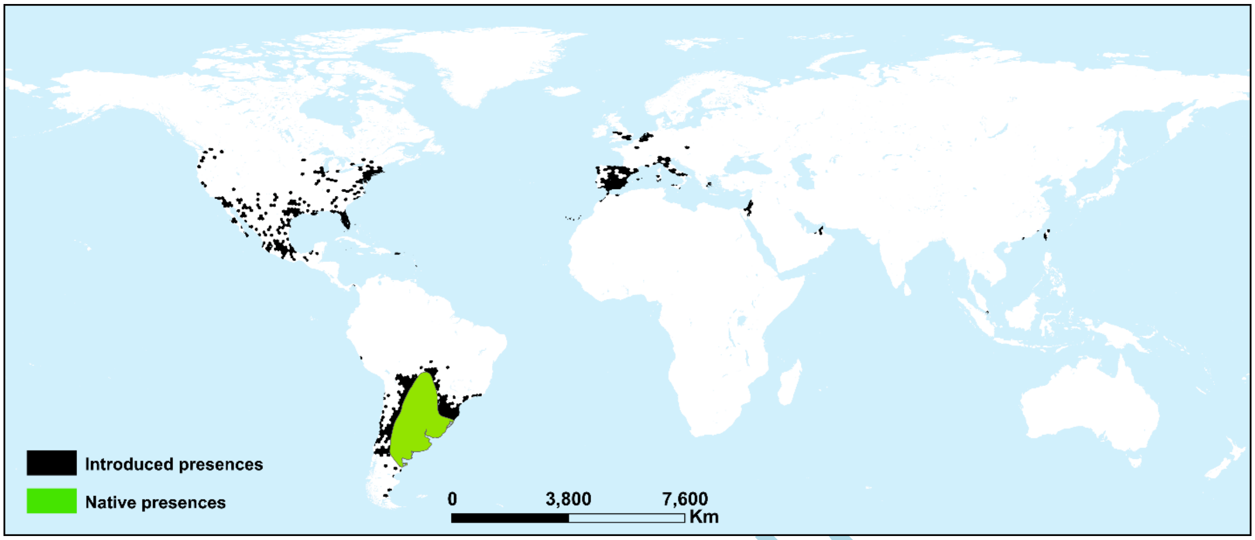


Figure 2

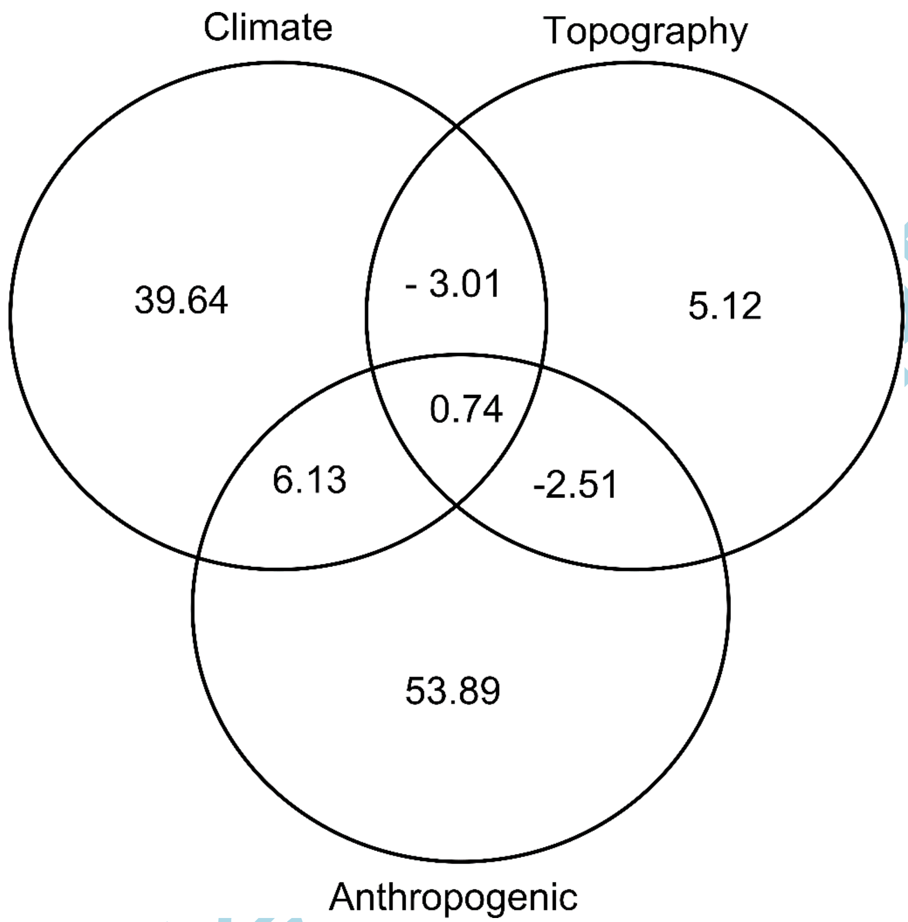
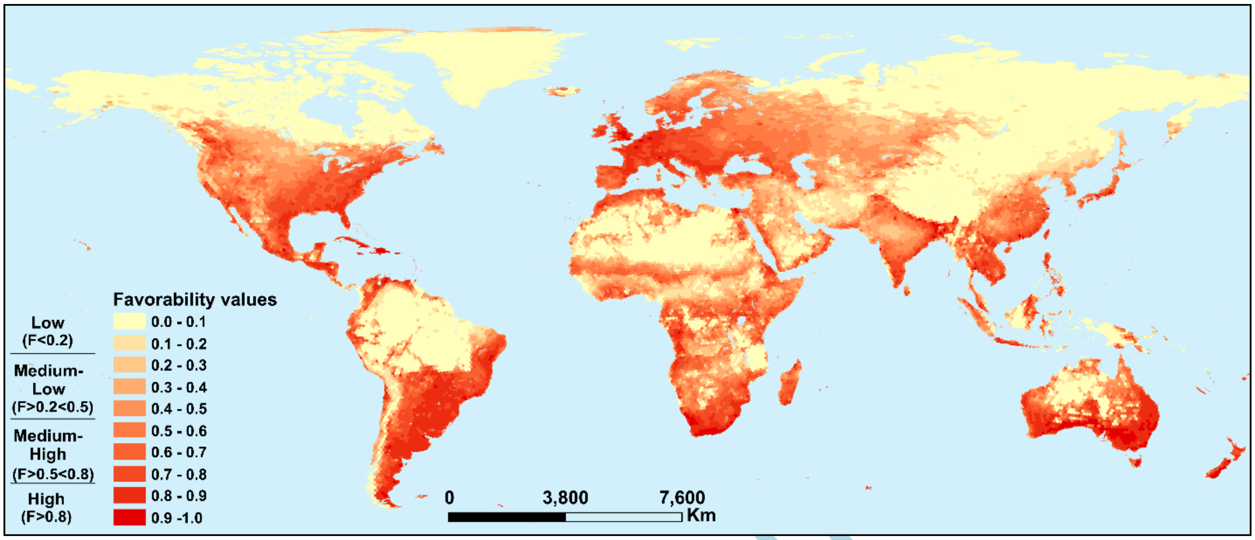

Climate
Topography
39.64
- 3.01
5.12
0.74
6.13
-2.51
53.89
Anthropogenic

Figure 3


Favorability values
Low
(F<0.2)
Medium-
Low
(F>0.2<0.5)
Medium-
High
(F>0.5<0.8)
High
(F>0.8)
0.0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 -1.0
0
3,800
7,600
Km