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RESEARCH ARTICLE

MODELING THE SPATIAL DISTRIBUTION AND HABITAT SUITABILITY OF THE EGYPTIAN FRUIT BAT (ROUSETTUS AEGYPTIACUS) IN EGYPT

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ABSTRACT

The Egyptian fruit bat (*Rousettus aegyptiacus*) is a keystone species in the Egyptian ecosystems, providing essential services like pollination and seed dispersal. However, its role as a reservoir for zoonotic diseases poses a significant health risk. The present study aimed to investigate the current and future spatial distribution patterns of the Egyptian fruit bat and evaluate the impact of environmental factors such as bio-climatic variables, ecoregion, and land cover on their habitat suitability. Using distribution records collected from the published papers, the data collected from the field surveys, and the environmental variables, a predictive model was developed using maximum entropy (MaxEnt) modeling approach to determine its habitat suitability across Egypt. We incorporated a range of ecological covariates such as elevation above sea level, temperature, precipitation, land use, and land cover. The model output indicates that the Nile Valley, Delta, and Dakhla Oasis are highly suitable areas for *R. aegyptiacus*. The current predicted sizes of suitable habitats for *R. aegyptiacus* were 7707.37 km^2 on average, while the bat's range is expected to increase slightly by 20.1% in 2050 and by 11.5% in 2070. We found that population is the most important ecological driver of bat distribution in Egypt. The results emphasized the importance of bioclimatic variables and land cover in shaping its distribution. This knowledge can contribute to the development of effective conservation strategies, ultimately aiding in the preservation of the Egyptian fruit bat and its crucial ecological roles.

INTRODUCTION

The Egyptian fruit bat (*Rousettus aegyptiacus*) is a species of significant ecological and economic importance in Egypt. As a vital bioindicator, pollinator, and seed disperser; this bat plays a crucial role in maintaining ecosystem health and supporting agricultural productivity[1-4]. Chiropterans (bats) exhibit significant efficacy as pollinators, a function facilitated by their body mass and capacity to transport substantial pollen loads and seeds across considerable distances[3,5]. Ecosystem services, including pollination, nutrient cycling, and natural fertilization, contribute to enhanced agricultural productivity and crop quality[6,7]. However, bats can also serve as reservoirs for various parasites, posing potential threats to human health[8].

Egyptian fruit bat populations and their habitats are facing multiple threats, including habitat loss, pollution, diseases, roost destruction, habitat fragmentation, and climate change[2,3,9]. These factors have led to decline bat populations worldwide[10,11]. Fruit bats, among all bat species, are particularly susceptible to climate change and human activities[12-14]. Their access to essential resources like fruits, nectar, and water is compromised, leading to potential food shortage[15]. Furthermore, climate change contributes to shifts in seasons and temperature patterns, affecting the availability and quality of these resources[16]. These combined pressures impact various aspects of fruit bat life, including reproduction, physiology, habitat suitability, and geographical distribution, ultimately resulting in population declines[10,17,18].

The spatial distribution determination and the habitat suitability assessment for *R. aegyptiacus* are fundamental prerequisites for the development and implementation of successful conservation and management programs[9,19,20]. By identifying the factors that influence their habitat preferences and distribution patterns, conservationists can develop targeted measures to protect and enhance suitable habitats, ensuring the long-term survival of this species.

The current study aimed to (1) analyze the current spatial distribution patterns of Egyptian fruit bats (*R. aegyptiacus*), (2) identify the key environmental factors influencing their habitat suitability, and (3) predict future habitat suitability using future projections for 2050 and 2070 under two shared socioeconomic pathways (SSPs). To achieve the aims of the study, we utilized the maximum entropy (MaxEnt) modeling approach, a widely used technique for species distribution modeling.

MATERIAL AND METHODS

Bat distribution records

The current investigation was undertaken within the geographical boundaries of Egypt, a nation situated within the tropical and subtropical latitudes (22° - 31° N) and longitudes (25° - 36° E). The country exhibits a diverse topography, encompassing a broad elevational gradient that ranges from –133 meters below sea level at the Qattara Depression to 2505 meters above sea level at Mount Catherine in the Sinai Peninsula[21]

To gather bat species distribution records, we investigated the distribution records of Egyptian fruit bats in reference books, scientific articles[22-24], and online databases[25]. Enough records “104 distribution records” were collected to build robust models for *R. egyptiacus*. Prior to model fitting, occurrence points were subjected to a rarefaction process and subsequently aligned to a 1.0 km^2 raster grid resolution of bioclimatic variables. This alignment was facilitated by the utilization of SDMtoolbox version 2.5 within the ArcGIS v10.8[26]. Furthermore, all records were screened by ArcGIS 10.8 for spatial autocorrelation using average nearest neighbor analyses to remove spatially correlated data points[27,28]. Subsequent to the removal of duplicate records, a total of 82 unique occurrence points were ultimately utilized to model the spatial distribution of *R. aegyptiacus*[29] (Figure 1).

Environmental variables

We integrated 24 environmental variables, including 19 bioclimatic variables, land cover, human population index, altitude, ecoregion, and slope for creating a model of fruit bat species. The bioclimatic variables were sourced from WorldClim 2.1 at a spatial scale resolution of 30 arc seconds (~1 km^2)[30]. The topographic attributes included elevation obtained from WorldClim and slope derived from a digital elevation model (DEM), ecoregion from Morales *et al.*[31], and human population data from the humanitarian data exchange[32]. The topographic attributes, population, and ecoregion were resampled to fit a spatially resolved bioclimatic variable using ArcGIS v10.8. To assess both current and future

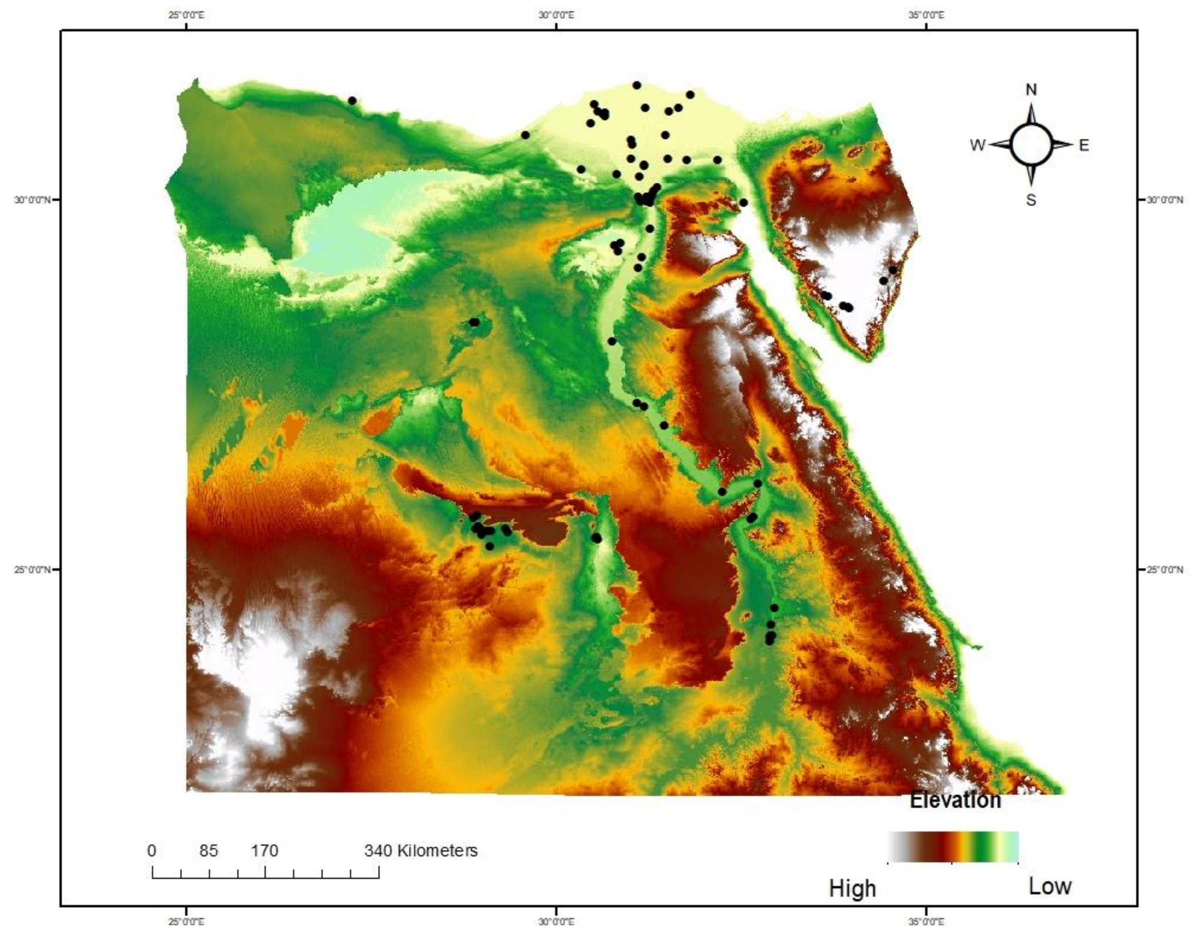

Figure 1: Map of Egypt and occurrence points of *R. aegyptiacus* (black dots) on a topographic overview of Egypt.

habitat suitability, the selected variables were utilized for baseline predictions spanning the period 1970-2000, as well as future projections for the years 2050 (2040-2060) and 2070 (2061-2080). Future projections were based on climate change scenarios generated by the UK Earth system modeling (UKESM) 1-0-LL model, developed by the UK Met Office and a consortium of UK academic institutions as part of the UKESM project. Two shared socioeconomic pathways (SSPs) were considered: SSP 4.5 (intermediate) and SSP 8.5 (worst-case).

A multicollinearity test was done using a variance inflation factor (VIF) to get rid of highly correlated predictor variables. All the variables were extracted using the remaining occurrence points to compute the Pearson correlation among the variables. By using the USDM package[33] in R version 4.1.2, the variables with VIF≤5 and correlation coefficient (r)≤|0.8| were kept for the final model establishment[34]. Ultimately, twelve environmental variables were utilized for modeling the habitat suitability for *R. aegyptiacus* (Table 1).

Habitat suitability mapping

The habitat suitability models was developed for the Egyptian fruit bat by using the maximum entropy approach implemented in MaxEnt software[35]. The MaxEnt model was run with a maximum number of iterations of 1000, a convergence threshold of 0.0001, and 10000 background points. The bootstrap method was utilized in MaxEnt, and the distribution points were randomly split into 10 folds containing equal numbers of occurrences, and the training models were created by eliminating each fold in turn. Ten replicates were utilized and an average of probability maps

Table 1: Environmental predictor variables retained for modeling the habitat of *R. aegyptiacus*, their codes, and units of measurement.

Category	Variables	Code/unit	VIF	Source
Bio climate	Isothermality (Bio2/Bio7) × 100	Bio3	1.3	https://worldclim.org/data/worldclim21.html
	Min temperature of coldest month	Bio6/^{0}C	3.9	
	Mean temperature of coldest quarter	Bio11/^{0}C	4.7	
	Precipitation of driest month	Bio14/mm	1.2	
	Precipitation of driest quarter	Bio17/mm	2.0	
	Precipitation of warmest quarter	Bio18/mm	1.2	
	Precipitation of coldest quarter	Bio19/mm	1.2	
Anthropogenic	Land use land cover	LuLc/unitless	1.2	https://cds.climate.copernicus.eu/
	Human population density	PopIndex/unitless	1.1	https://data.humdata.org/organization
Topographic	Ecoregion	Ecoreg/unitless	1.2	https://lpdaacsvc.cr.usgs.gov/appeears
	altitude	Elev (m)	2.3	https://worldclim.org/data/worldclim21.html
	Slope	Slope/unitless	6.8	

Data set problems related to collinearity were avoided by removing variables with variance inflation factor (VIF) values > 5. These variables were selected through a multi-collinearity test and were used in modeling.

for habitat suitability[36]. The MaxEnt model is preferable when the data points include presence-only with a limited number of records[37,38]. The area under the curve (AUC) of the receiver operating characteristic curve was computed in order to evaluate the resulting models' accuracy. AUC score is the dominant tool to measure the model performance, mainly due to its independence by threshold choices[37,39]; where the higher the value of AUC (closer to 1.0), the better the performance of the model[35].

RESULTS

Habitat suitability of *R. aegyptiacus* over current conditions

Our predictive models demonstrated exceptional accuracy in distinguishing suitable from unsuitable habitats for *R. aegyptiacus*. This was evidenced by robust AUC (0.98) and AUC_{Diff} (0.01) values, indicating strong discrimination capabilities. The Jackknife test revealed that population index, slope, and precipitation of the coldest quarter (Bio19) were the most influential environmental predictors (Table 2).

These variables, along with land cover, elevation, and ecoregion, significantly enhanced model performance when used individually, highlighting their crucial role in shaping bat distribution. Permutation importance analysis further underscored the significance of population, slope, mean temperature of the driest month (Bio3), and elevation (Table 2).

Table 2: Evaluation of average contribution and permutation importance of the environmental variables used in maximum entropy (MaxEnt) modeling of *R. aegyptiacus*.

Variable	Percent contribution	Permutation importance
Population index	88.1	81.2
Slope	4.8	7.5
Bio19	2	2.1
Bio3	1.2	0.9
Ecoregion	1	3.9
Landcover	0.9	0.7
Bio11	0.8	0.1
Altitude	0.6	3.3
Bio18	0.3	0.2
Bio17	0	0
Bio14	0	0
Bio6	0	0.1

The current prediction estimates a suitable habitat area of 7707.4 km² for *R. aegyptiacus*. Our maps identify the Nile Valley, Delta, and fragmented habitats in eastern and southern Egypt (primarily oases and isolated agriculture) as areas of high habitat suitability. Additionally, fragmented suitable areas were predicted in Sinai (Figure 2).

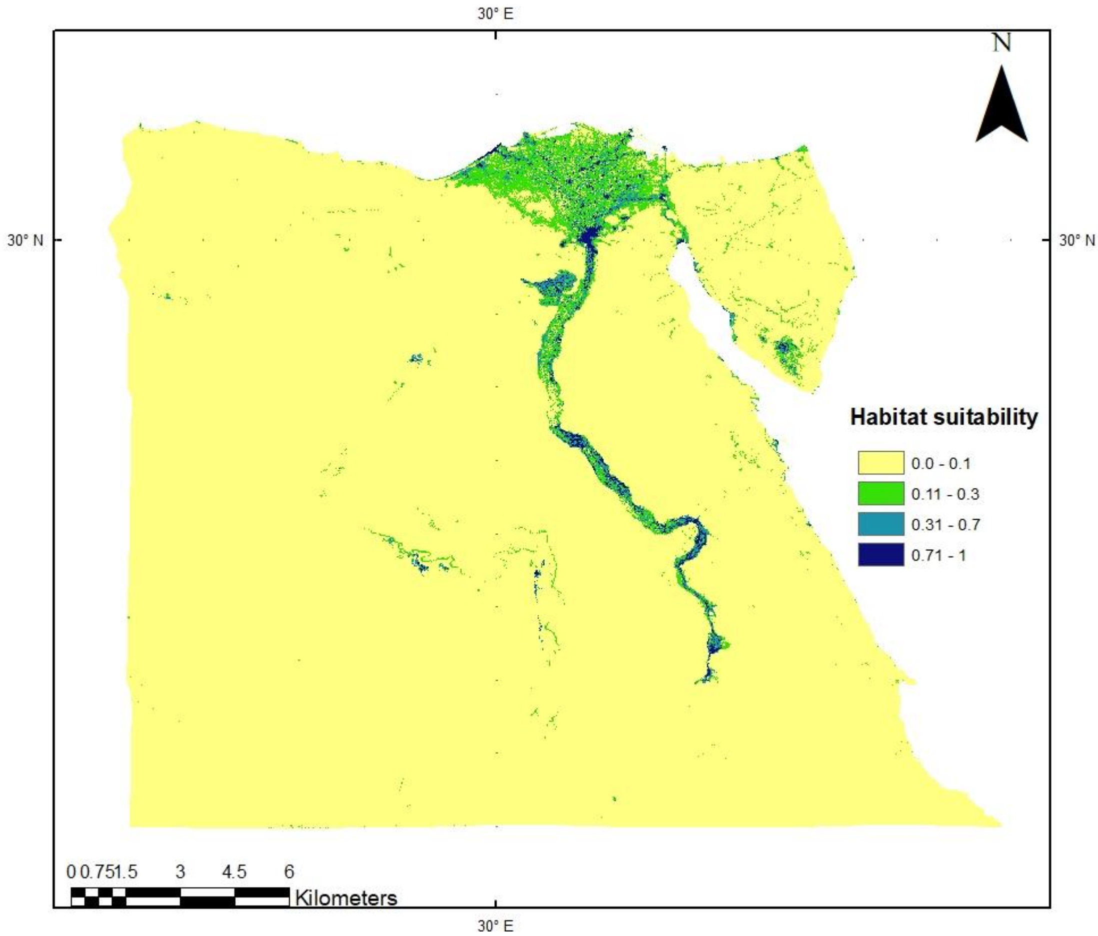

Figure 2: Map for current habitat suitability of *R. aegypticus* according to occurrence records in Egypt.

Distribution of suitable habitats of *R. aegyptiacus* under future global warming scenario

The projected climate map under UKESM model for both 2050 and 2070 scenarios resulted in an increase in the extent of suitable habitat for *R. aegyptiacus*, as compared with the potential current distribution map (Figure 3). At both socioeconomic pathways, the intermediate (SSP 4.5) and the worst (SSP 8.5), respectively, the habitat suitability would increase. By 2050, the result showed that the future projections for suitable habitat were predicted to be 9842.5 km^2 in spss4.5 and 9593 km^2 in spss8.5. By 2050, habitat suitability will increase by 21.4% and 18.9% for spss4.5 and spss8.5, respectively. For 2070, suitable habitat was predicted to be 8690.6 km^2 in spss4.5 and 9016.6 km^2 in spss8.5. By 2070, habitat suitability will increase by 9.8% and 13.1% for spss4.5 and spss8.5, respectively (Table 3).

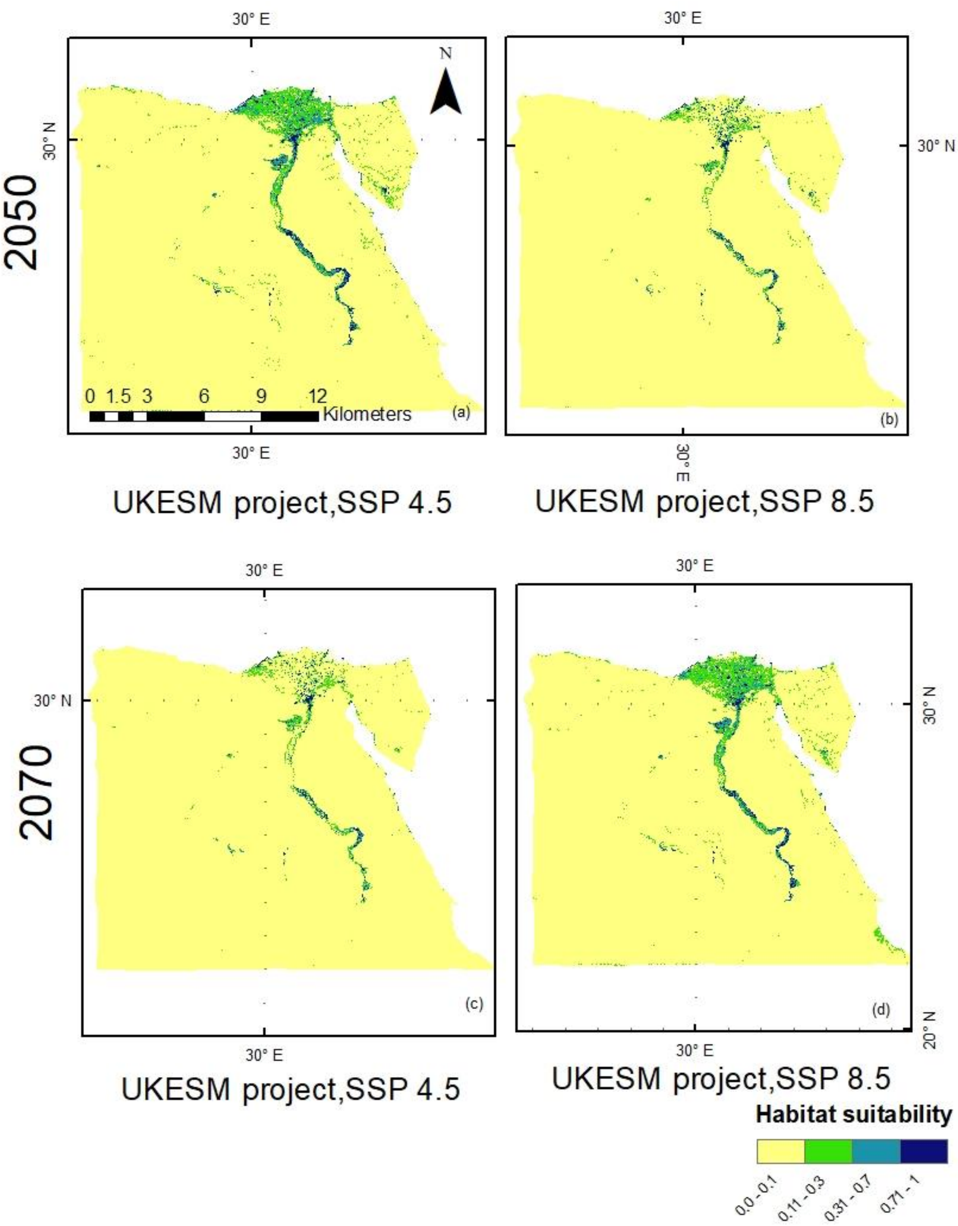

Figure 3: Map showing distribution and habitat suitability of *R. aegyptiacus* under future climate scenarios (2050 and 2070) at two pathways, the intermediate (SSP 4.5), and the worst (SSP 8.5).

Table 3: The predicted changes in suitable habitat area (km²) for *R. aegyptiacus* under two global warming scenarios (SSP 4.5 and SSP 8.5) for the years 2050 and 2070, compared with the current distribution (km²).

Predicted class	**current**	**Future scenarios**			
		2050		2070	
		SSP 4.5	SSP 8.5	SSP 4.5	SSP 8.5
Suitable habitat (0.5-1.0)	7707.4	9842.5 (+2135.2)	9593 (+1885.6)	8690.6 (+983.2)	9016.6 (+1309.3)
Unsuitable habitat (0.0-0.5)	1057150.3	1055015.2	1055264.2	1056167.1	1055841.1

Positive values indicate gains in suitable habitat (km²).

DISCUSSION

Our models demonstrated robust predictive performance, achieving an AUC of 0.975. The population index emerged as the primary driver of habitat suitability for *R. aegyptiacus*, followed by slope and precipitation of the coldest quarter (Bio19). Population dynamics significantly influence the distribution and range shifts of fruit bats. Changes in population size can impact food availability and roosting opportunities[40-42]. Human activities, such as intensive agriculture and urbanization, can further affect habitat suitability and bat behavior[20,43]. Precipitation plays a crucial role in shaping bat distribution and ecology. It influences insect abundance, roosting site conditions, and migration patterns[44,45]. Precipitation can also impact bat physiology, thermoregulation, and reproduction[30,46,47]. Additionally, precipitation can affect plant phenology, influencing the availability of fruit resources for bats[42,48]. Ecoregion, landscape, and land cover also play important roles in shaping bat distribution. These factors influence habitat quality, food availability, and roosting opportunities[20,30,41,47]. By understanding the complex interplay of these factors, we can develop effective conservation strategies to protect *R. aegyptiacus* and its vital ecological role.

The predicted maps indicated that highly suitable habitats for *R. aegyptiacus* are concentrated in the Nile Valley and Delta, with additional fragmented areas in Oases and isolated agricultural areas. These findings align with previous reports[22-24]. Under the UKESM model, the bat's range is projected to increase slightly by 20.1% in 2050 and 11.5% in 2070. However, the future maps reveal potential shifts and losses of suitable habitats in the Delta region due to climate change. Human activities and climate change pose significant threats to bat populations, impacting their distribution and the critical ecosystem services they provide, making bats more susceptible to range shifts and habitat loss[49,50]. It is crucial to implement proactive conservation measures to mitigate these threats and ensure the long-term survival of *R. aegyptiacus*.

The current study identified suitable habitats for *R. aegyptiacus* both within its established range and in regions beyond its historical distribution, suggesting a potential for range expansion. Factors like food scarcity, loss of roosting sites, and environmental stressors can influence the geographic distribution of fruit bats. Over time, fruit bats have demonstrated adaptability to changing conditions, colonizing new regions in response to food shortages and climate change[14,20,51,52]. *R. aegyptiacus* possesses a notable capacity for long-distance dispersal and exhibits a strong propensity for colonizing novel habitats[22,53]. However, these adaptations may also lead to increased vulnerability and mortality due to factors like range shifts, migration, and declining habitat quality[48,54]. By delineating and predicting species distributions and assessing habitat suitability, researchers can establish a framework for prioritizing conservation initiatives and identifying areas that warrant targeted protection efforts[14,52-56]. In conclusion, the present study can contribute to the development of effective strategies for preservation of the Egyptian fruit bat and its crucial ecological roles.

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CONFLICT OF INTEREST
The authors declare that there is no conflict of interest.

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نمذجة التوزيع الجغرافي وملاءمة الموائل لخفاش الفاكهة المصري "*Rousettus aegyptiacus*" في مصر

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يُعد خفاش الفاكهة المصري (*Rousettus aegyptiacus*) أحد الأنواع الرئيسية في النظم البيئية المصرية، حيث يقدم خدمات اساسية مثل التلقيح ونشر البذور. ومع ذلك، فإن دوره كمستودع للأمراض حيوانية المنشأ يجعله يشكل خطرًا صحيًا كبيرًا. هدفت هذه الدراسة إلى البحث في أنماط التوزيع الجغرافي الحالية والمستقبلية لخفاش الفاكهة المصري وتقييم تأثير العوامل البيئية مثل المتغيرات المناخية الحيوية، والمنطقة البيئية، والغطاء الأرضي على ملاءمة موائلها. وباستخدام سجلات التوزيع التي تم جمعها من الأبحاث المنشورة، والبيانات التي تم جمعها من المسوحات الميدانية، والمتغيرات البيئية، تم تطوير نموذج تنبؤي باستخدام نهج نمذجة "MaxEnt" لتحديد مدى ملاءمة موطنه في جميع أنحاء مصر. ولقد قمنا بدمج مجموعة من المتغيرات البيئية المشتركة مثل الارتفاع عن مستوى سطح البحر، ودرجة الحرارة، وهطول الأمطار، واستخدام الأراضي، والغطاء الأرضي. وتشير مخرجات النموذج إلى أن وادي النيل، والدلتا، والواحات الداخلة هي مناطق مناسبة للغاية لخفاش الفاكهة المصري. وقد بلغ متوسط المساحة المتوقعة الحالية للموائل المناسبة لخفاش الفاكهة المصري "7707.37 كيلومترًا مربعًا"، في حين أنه من المتوقع أن يزداد نطاق الخفافيش بشكل طفيف بنسبة "20.1%" في عام 2050 وبنسبة "11.5%" في عام 2070. وقد وجدنا أن عدد السكان هو أهم محرك بيئي لتوزيع الخفافيش في مصر. وأكدت النتائج على أهمية المتغيرات المناخية الحيوية والغطاء الأرضي في تشكيل توزيع جماعات خفاش الفاكهة المصري. ويمكن أن تساهم هذه المعرفة في وضع استراتيجيات فعالة للحماية، مما يساعد في النهاية في الحفاظ على خفاش الفاكهة المصري وأدواره البيئية الهامة.