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ORIGINAL ARTICLE

Mapping the Indian crested porcupine across Iraq: the benefits of species distribution modelling when species data are scarce

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Abstract

Species distribution modelling (SDM) is a key technique used to explore the spatial distribution and habitat suitability of a population, species, or community. SDM is particularly advantageous when species data are scarce, and extrapolation into un-surveyed, potentially inaccessible areas is necessary. Iraq is one such place, where due to the ongoing conflict and political situation, species data are limited and there is neglect of, or even sometimes active destruction of biodiversity and ecological knowledge. The Indian crested porcupine *Hystrix indica* is a widely distributed mammal that, despite its overall global conservation status of Least Concern, is thought to be heavily threatened by overharvesting in the Middle East, including Iraq. Nevertheless, the lack of data and research in this geographical area limits the conservation of this potentially declining species. We use occurrence records collected from previous literature and expert observations in the field to fit distribution models and map the current distribution of the Indian crested porcupine, with the aim of addressing the knowledge gap about this species in Iraq. We also examine the extrapolation potential of the models across Iraq using multivariate environmental similarity surfaces (MESS). The Indian crested porcupine distribution is strongly influenced by soil type and slope, with the most suitable areas towards the north-east of Iraq, as well as a small vegetated area in the south-east, and along the banks of the Euphrates and Tigris rivers. MESS maps suggest that the extrapolation ability of the SDMs appears high, with high similarity and few novel environments across Iraq, providing extra confidence in our distribution predictions. This study provides the most current overview and new baseline of the current Indian crested porcupine distribution across Iraq. Our study highlights the benefits of using SDM to address ecological research questions in areas such as Iraq where species data and knowledge are sparse.

Keywords Arid environment · Habitat suitability · Indian crested porcupine · Iraq · Mammals · Species distribution modelling

Introduction

Effective conservation relies heavily on having a sufficient knowledge and understanding of the distribution of the target population, species, or community (Lawler et al. 2011; Kaky et al. 2022). Species distribution modelling (SDM), which quantitatively associates species occurrences with environmental characteristics to infer about habitat suitability and the distribution of a species, is an important and widely used conservation approach (Phillips and Dudík 2008; Elith and Leathwick 2009; Alatawi et al. 2020). SDM outputs are commonly applied during conservation planning and management to aid decision-making authorities (Guisan et al. 2013), and are also highly useful in predicting impacts of climate change and range shifts (Chen et al. 2011; Kaky and Gilbert 2020). As a result of the popularity of SDM, distribution maps are

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considerably more available and improved for many taxa around the world (Lessmann et al. 2014; Fois et al. 2015; Kaky and Gilbert 2016; Alatawi et al. 2020; Hameed et al. 2020; Kaky 2020). One major benefit of SDM is that it can provide an opportunity for scientists and conservationists to study and predict species distributions in highly remote, inaccessible locations where there is considerably less effort and resources dedicated to conservation (Kaky 2020).

Information and data about the distribution and conservation status of biodiversity in Iraq are extremely scarce. Iraq is a unique country in the Middle East in terms of its high biological diversity of flora and fauna, as well as its natural resource availability, compared to other countries in the southern Arabian Peninsula (Al-Sheikhly et al. 2015). There are a variety of highly productive habitat types in Iraq stemming from the fertile soils around the Tigris and Euphrates rivers that run through the country, and their surrounding valleys, delta, and marshlands. There are also spectacular high and steep mountains with dense vegetation cover in the north of Iraq (Al-Sheikhly et al. 2015) which experience snow cover in the winter, contrasting some of the more arid, dry areas in the south. However, the unstable political situation over the past 4 decades has resulted in large gaps in the amount of available information regarding wildlife in Iraq (Raza et al. 2011). Furthermore, there have been instances of the destruction of valuable preserved specimens in the "Biological Research Centre of Baghdad" (Al-Sheikhly et al. 2015). This highlights the urgent need to address the lack of knowledge about biodiversity in Iraq, as well as the immediate implementation of conservation strategies, and possible ways to increase conservation awareness going forward.

Recent, slight improvements in the political situation have resulted in a few studies being conducted, revealing interesting information about wildlife in Iraq (Raza et al. 2012; Al-Sheikhly et al. 2015, Kaky et al. 2022). One such study by Al-Sheikhly et al. (2015) produced a systematic checklist consisting of 93 wild mammal species in Iraq, which is now considered one of the most comprehensive checklists in Iraq. On this list is the Indian crested porcupine *Hystrix indica* (Kerr 1792), a large, elusive, nocturnal rodent that lives in a burrow system, and survives on a generalist herbivorous diet, feeding on both natural and wild plants and cultivated crops (Mushtaq et al. 2010; Khan et al. 2014; Mukherjee et al. 2017). The Indian crested porcupine has a wide global distribution across various habitats and climates from the eastern Mediterranean through to southwest and central Asia (Amori et al. 2021). The porcupine is considered to be a serious economic pest across large parts of its range as it causes significant damage to both traditional and non-traditional crop species (Mushtaq et al. 2010; Hafeez et al. 2011; Mukherjee et al. 2017; Amori et al. 2021). For example, in Pakistan, the porcupine is a source of high concern due to its significant damage of plants communities (Safeer et al. 2018), and different measures have been taken to control this pest such as aluminium phosphide fumigation (Khan et al. 2016). The global conservation status of the Indian crested porcupine is listed as Least Concern on the International Union for Conservation of Nature (IUCN) red list (IUCN 2012), with a stable condition and no major threats (Amori et al. 2021). However, it is thought that the conservation situation of the Indian crested porcupine in the Middle East, and especially Iraq, is completely different.

The Indian crested porcupine has been recorded in numerous regions in Iraq, particularly around the Tigris and Euphrates River and streams banks, and in the Kurdistan areas (Kadhim 1997; Raza et al. 2011, 2012; Al-Sheikhly et al. 2015). However, unlike throughout the rest of its range where it is considered primarily a pest species, the porcupine is greatly hunted and trapped for other purposes in Iraq and surrounding countries, including local market selling, consumption, exportation, and traditional medicine practices (Raza et al. 2011; Al-Sheikhly et al. 2015), all of which are increasingly threatening the conservation of this species. As a result, where more data are available, the porcupine has been classified as Vulnerable in Jordan (Eid et al. 2020) and Near Threatened in Turkey (Yürümez and Ulutürk 2016); such classifications in countries where these practices, pressures, and threats also occur indicate that it is likely the species is similarly threatened in Iraq. Kadhim (1997) carried out one of the few long-term ecological studies in Iraq on the Indian crested porcupine, and even at this time, reported declining population trends. However, due to the overall lack of data and more recent studies, it is impossible to accurately assign the true conservation status of the Indian crested porcupine without further investigation into its potential current distribution. For example, common citizen-science species databases including Global Biodiversity Information Facility (GBIF) and iNaturalist only list two records of the species throughout the whole of Iraq. Therefore, SDM, which can be applied remotely and with relatively few species occurrences (Breiner et al. 2016), provides an ideal opportunity to examine the current distribution of the Indian crested porcupine in Iraq.

With the increasing popularity of SDM and a high demand for efficient, quick and easy applications within ecological and biogeographical research, a variety of new SDM methods have emerged. Many different platforms, software, and R packages can be selected to manipulate and run distribution models quickly and conveniently (Kaky et al. 2020). Variations in accuracy and performance among different methods are expected (Marmion et al. 2009), but Maximum Entropy (MaxEnt) is the most widely applied and is highly effective (Phillips et al. 2009). Nevertheless, other well-known techniques such as random forest (rf), generalised linear or additive models (GLMs/GAMs), and other classification machine-learning methods have been shown to produce highly accurate distribution maps and predictions (Guillera-Arroita et al. 2014). Applying alternative algorithms and investigating differences in their spatial and temporal predictions of habitat suitability can increase the reliability of the predicted distribution maps (Marmion et al. 2009).

Our overall aim of this study was to investigate the current distribution of the Indian crested porcupine across Iraq using SDM. We apply a variety of alternative SDM algorithms in relation to potential environmental variables, including temperature, precipitation, and topography characteristics that we hypothesise are likely determinants of the Indian crested porcupine ecological niche. We predict that SDM will be a reliable method for predicting distributions of species with very few occurrence records, and, with some additional consideration of the likely error in geographical extrapolation, can produce highly accurate distribution maps, which are currently inaccessible in Iraq due to ongoing political issues. Such a study is highly important because of the scarcity of the available data and the unknown consequences of the continuous pressures from hunting and trapping. Therefore, all information, mapping, and analysis of the distribution or environmental preferences of the Indian crested porcupine will further our understanding of this species, to support the need for the implementation of effective conservation and monitoring programs.

Methods

Study area and species records

The study area comprises the whole country of Iraq in Western Asia, covering a total land area of 437,831 km^2 (UNEP-WCMC 2019) (Fig. 1). Iraq is bordered to the south by Saudi Arabia and Kuwait, with Jordan to the west, Syria to the west and north-west, Turkey to the north, and Iran to the east. Iraq is located between a latitude of 29.97 to 37.15 and longitude of 40.29 to 48.47, and has a general subtropical semi-arid climate, with a more Mediterranean climate in the north and north-east, and more arid in the south. The day temperature varies from about 16 °C in winter to 43 + °C in summer, and the mean annual precipitation is ~ 220 mm, but has wide geographic variations: annual mean precipitation can reach up to 1200 mm in the north, but can be less than 100 mm in the south depending on season (FAO 2008). The less arid, Mediterranean climate towards the north is the result of the higher elevation in the north and north-east compared to the arid lowlands, plains, and deserts in the south.

A total of 83 individual records of the Indian crested porcupine (*Hystrix indica*) were collected across the study area from various sources (Fig. 1). Records sourced from previous literature include 14 occurrences from Al-Sheikhly et al. (2015) and 23 occurrences from Kadhim (1997, published online in 2013). The other 46 records were compiled from expert observations and additional field work. Specific targeted field work was carried out over the years of 2019–2020 around the vicinity of three cities (Kirkuk, Diyala, and Sulaymaniyah), in the northern part of Iraq, and other observations of Indian crested porcupine were collected from experts in this field throughout Iraq. We acknowledge that the collected data are incomplete, and the species is likely to be present in many other areas across Iraq. Nevertheless, owing to the issues regarding data shortages and lack of surveys from the ongoing war and conflict in Iraq, these records are the most comprehensive available in this country on this species.

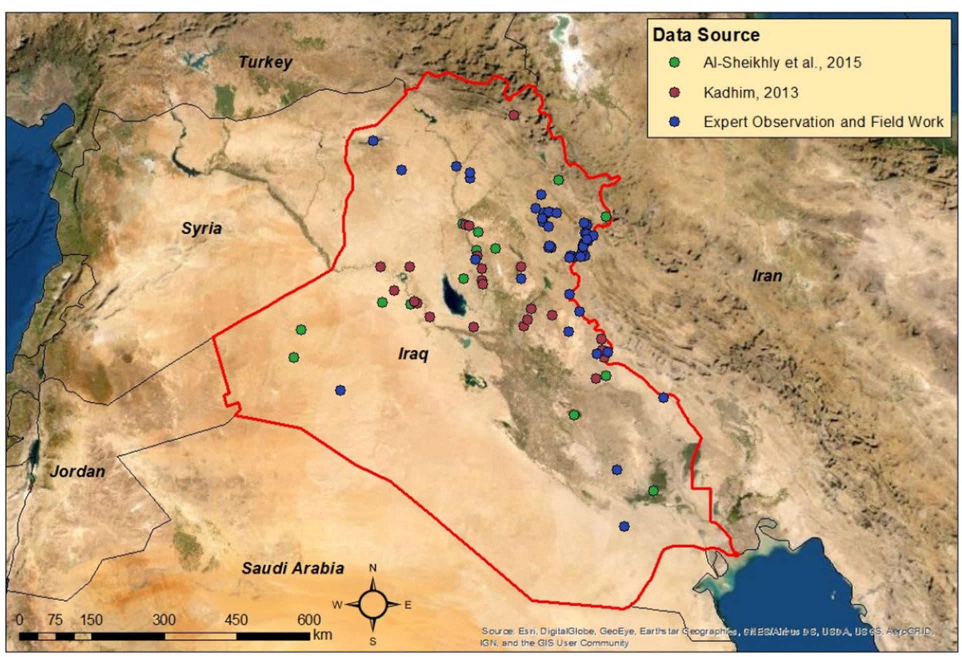


Fig. 1 Geographical locations of the 83 records of Indian crested porcupine (*Hystrix indica*) collected across Iraq. Records sourced from previous literature include 14 occurrences (green dots) from Al-Sheikhly et al. (2015) and 23 occurrences (red dots) from Kadhim (1997, published online in 2013). The other 46 records (blue dots) were compiled from expert observations and additional field work (see "Methods" section for more information)

Environmental predictors

A total of 11 environmental or land-use predictors were considered for modelling the distribution of Indian crested porcupine across Iraq, nine of which were continuous and two were categorical (Table 1; Fig S1). We selected these predictors as potential determinants of the Indian crested porcupine distribution based on our own knowledge of the species, other studies on Indian crested porcupine, and also studies on a close relative, the crested porcupine *Hystrix cristata:* see Table 1 for full justifications for the inclusion of each predictor. Six of these predictors relating to the climate (aspects of temperature and precipitation) and two relating to topography (slope and elevation) were extracted from WorldClim climate dataset averaged across the time period 1950–2000 (Hijmans et al. 2005). The final continuous variable was the Landsat Normalized Difference Vegetation Index (NDVI), (Didan 2015), a measure of vegetative greenness and productivity across the landscape with wide-ranging uses in assessing vegetation density and condition. NDVI was extracted using AppEEARS software (AppEEARS team 2020) for the years of 2015 to 2019 (24 raster layer maps per year), and maps were averaged to produce the final NDVI map using ArcGIS version 10.4 (ESRI 2018) (Fig. S1).

The two categorical predictors included land cover across Iraq, extracted from the MODIS Land Cover types (Sulla-Menashe et al. 2019), and soil type across Iraq, extracted from the Food and Agriculture Organization of the United Nations (FAO) Digital Soil Map of the World (Table 1; Fig. S1). There are 48 different independent soil types across Iraq, so the top nine most common were retained, and all others assigned as 'other' to aid model fitting, resulting in 10 independent soil types (Fig. S1). All predictors were scaled to a resolution of 30 arc-seconds (~ 1 km) to match that of the WorldClim data (Fick and Hijmans 2017).

Collinearity reduction between predictors was carried out in R (R Core Team 2018), using Variance Inflation Factor (VIF) (package: 'usdm' (Naimi 2015) and pairwise Pearson's correlation coefficients. Strong pairwise correlations ($r > 0.7$) were seen between Bio3 and Bio12, and Bio8 and elevation, and all four of these predictors produced VIF values greater than two. Following the removal of Bio8 (Mean temperature of wettest quarter) and Bio12 (Annual precipitation), all VIF values fell on or below two and no strong pairwise correlations (based on a threshold of 0.7) were present.

Modelling and analysis

Species distribution models were fitted for the 83 Indian crested porcupine occurrence records in relation to the nine environmental predictors. Five alternative modelling algorithms were implemented and evaluated: maximum entropy (MaxEnt) (Phillips et al. 2006), random forest (rf) (Breiman 2001), boosted regression trees (brt) (De'ath 2002), a generalised additive model (GAM) (Guisan et al. 2002; Hastie and Tibshirani 2004), and a generalised linear model (GLM) (McCullagh 2019). MaxEnt is the most commonly used method, and has been shown to be robust when using presence-only data and small sample sizes (Phillips et al. 2006; Elith et al. 2006; Wisz et al. 2008). Rf and brt are decision tree-based machine-learning methods, that have also performed well in many SDM studies (Becker et al. 2020; Kaky et al. 2020), particularly in predicting in under-sampled areas (Mi et al. 2017). All models were fitted in R (R Core Team 2018), using the package 'sdm' (Naimi and Araújo 2016). Models were fitted using 10,000 randomly selected pseudo-absence background points across the study area, 1000 iterations, regularization multiplier = 1, and specifying a logistic output. All other parameters were set to the default options (Naimi and Araújo 2016).

Models were evaluated using K-fold cross-validation, using tenfold for each model: input data are split into ten random, equal-sized groups, with each group subsequently used as the test data for the remaining nine groups. Models were then evaluated using mean area under the curve (AUC) for both training and testing data, and the mean true skills statistic (TSS) across the tenfold. AUC is a threshold-independent statistic and measures a model's predictive power based on its ability to correctly classify observations in relation to the probability of presence (Fielding and Bell 1997; Lobo et al. 2008). AUC ranges from 0 to 1, with scores above 0.7 generally indicating a high performing model (Swets 1988). Although it has been critised as overinflating model performance when fitting spatially auto-correlated species data (Lobo et al. 2008; Peterson et al. 2008), it is one of the most widely used SDM evaluation metrics. TSS is a threshold-dependent statistic (Allouche et al. 2006) that ranges from -1 to $+1$, with scores approaching 1 indicating a good model, and scores closer to, or less than zero indicating a model that performs no better than random.

Following SDM fitting and evaluation, an additional step to increase confidence in model predictions and inference is to test whether model performance is significantly better than would be expected if based on chance (Olden et al. 2002; Raes and ter Steefe 2007). We fitted a series of null models based on randomly sampled points across Iraq of equal sample size ($n = 83$) to the Indian crested porcupine occurrence records. Null models were fitted for the five algorithms using the same parameters as the species model and were evaluated also using tenfold CV and AUC. Frequency histograms of AUC values were generated by running the null models 350 times, and the significance of the position of the observed Indian crested porcupine AUC values for each model algorithm was assessed using a one-sided 95% confidence interval of the null model frequency histograms to see if the species model performs significantly better than

Table 1 All environmental predictors considered for modelling the distribution of Indian crested porcupine (*Hystrix indica*) across the study area, Iraq

Predictor	Description (units)	Type	Justification as a predictor	Dataset source
Bio3*	Isothermality (°C)	Continuous	Neither the crested or Indian crested porcupine hybernate, so are limited by low temperatures and have been found to prefer warmer annual temperatures (between 15 and 17 °C) (Mori et al. 2021). Torretta et al. (2021) also found annual mean temperature to be a driving factor of crested porcupine distribution	Worldclim dataset (1950–2000), (see Hijmans et al. 2005 for more information) http://www.worldclim.org
Bio7*	Temperature annual range (°C)	Continuous		
Bio8	Mean temperature of wettest quarter (°C)	Continuous		
Bio12	Annual precipitation (mm)	Continuous	Crested porcupine *Hystrix cristata* were found to prefer intermediate precipitation levels between 600 and 1200 mm (Mori et al. 2021), with low precipitation areas deemed unsuitable (Mori et al. 2013). It is likely the Indian crested porcupine shares a similar rainfall tolerance	
Bio15*	Precipitation seasonality (mm)	Continuous		
Bio18*	Precipitation of warmest quarter (mm)	Continuous		
Elevation*	Topography—elevation (m)	Continuous	High mountainous areas have been found to be unsuitable for porcupine (Mori et al. 2013) due to the colder climates and lower availability of food and vegetation sources. Crested porcupines have also been shown to prefer steep slopes for denning (Monetti et al. 2005)	
Slope*	Topography—slope (m)	Continuous		
NDVI*	Normalized Difference Vegetation Index	Continuous	Crested porcupine *Hystrix cristata* are known agricultural pest and show associations to certain habitat and vegetation types (Fattorini and Pokheral 2012; Mori et al. 2021), including grassland, cover of cultivation, broad-leaved and mixed woodlands and shrublands (Torretta et al. 2021)	Landsat Normalized Difference Vegetation Index: 1km_16_days_NDVI. http://www.usgs.gov https://lpdaacsvc.cr.usgs.gov
Land cover*	Classification of land cover/use in Iraq	Categorical		MODIS Land Cover type (MCD12Q1) (Sulla-Menashe and Friedl 2018). http://www.usgs.gov
Soil type*	Classification of FAO soil type in Iraq	Categorical	As (Indian) crested porcupines excavate and inhabit underground caves or burrows, as well as dig for underground root crops, e.g., bulbs and tubers, soil type is likely to play a major role in burrow site selection, foraging and habitat preferences (Monetti et al. 2005; Mukherjee et al. 2017)	The Digital Soil Map of the World Version 3.6 (2003). Land and Water Development Division, FAO, Rome. http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/

A total of 11 climate, topography, and land classification predictors were considered, nine of which were continuous and two were categorical. The final nine variables used to fit the distribution models following collinearity reduction analysis are indicated using a * in the first column chance (Raes and ter Steefe 2007). Although initially recommended to run the null model 999 times (Raes and ter Steefe 2007), the results from the null models stabilised before this number was reached, so additional model runs beyond 350 were deemed unnecessary.

Response curves of the probability of species presence in relation to the environmental predictors, and variable importance were then analysed to provide insight into the most influential environmental determinants of the Indian crested porcupine distribution. Variable importance is calculated through two model-independent methods: (1) a cross-validation procedure of sequential removal of each variable to measure comparative model performance based on AUC when excluding or including that variable and (2) a randomised technique whereby the correlation between model predictions and predictors are randomly permutated. If variable importance is high, then permutations will result in low correlations. Therefore, variable importance can be represented as 1—correlation (Thuiller et al. 2009; Naimi and Araújo 2016).

Exploring the extrapolation abilities of the SDMs

Due to the data shortage of many species, including Indian crested porcupine, across Iraq, any SDM fitted is likely extrapolating across a large geographical area, leading to potentially higher levels of error and uncertainty in predictions and therefore reducing the ecologically and conservation value of such models. Thus, estimating the similarity of the environment in the areas containing the majority of model training data (occurrence records), and the environment in the largely un-sampled projection areas across Iraq could provide valuable insight into novel types of environments in which model predictions may have higher levels of uncertainty (Elith et al. 2010). We computed multivariate environmental similarity surfaces (MESS) based on the methods by Elith et al. (2010) using the package 'dismo' (Hijmans et al. 2017) in R. Surfaces were computed for each individual continuous predictor (i.e., except soil type and land cover), and for all continuous predictors combined. Each map produced is at the same resolution as the predictors (30 arc-seconds), and calculates the extent of the difference in climate or environmental feature between the locations of the occurrence records of the Indian crested porcupine and all other pixels across the study area.

Currently, the analysis of categorical variables within the MESS surface is not supported in the 'dismo' package, so we carried out additional manual exploration of the frequency of the variables 'soil type' and 'land cover' across the study area in relation to the number of occurrence points. We first calculated the expected number of species occurrences in relation to the area covered by each particular soil or land-cover type, and compared this to the observed number of occurrence records actually present within this soil or land-cover type. The final output is two additional surface maps depicting for each pixel the difference in actual and expected number of occurrences of Indian crested porcupine for each land or soil type.

Results

Model performance and variable importance

All five SDMs performed well (AUC > 0.7) when modelling the distribution of Indian crested porcupine across Iraq (Fig. 2, Table 2). The best-performing model based on both AUC and TSS was the rf SDM, followed by the brt SDM which performed similarly well (Table 2). The MaxEnt model also performed relatively well, but neither the GLM or GAM models were able to match the performance of the other three models (Fig. 2, Table 2). All five SDMs performed significantly better than chance based on a significance level of 0.05 (using a 95% one-sided CI) when compared to the AUC frequency histograms of the null models (Fig. S4).

Evaluation of variable importance showed high similarity between the results produced using either AUC or correlation tests to measure predictor contributions (Fig. 3). Soil type proved to be the most influential predictor in four out of five models (GLM, rf, GAM, and brt) based on AUC, and three out of five (GLM, rf, and GAM) based on correlation tests (Fig. 3). All other models (MaxEnt and brt) listed slope as the most important predictor. The soil type suggested to be linked to the highest habitat suitability is 1303 (Fig. 4a), which represents a calcic xerosol soil with a lithic phase type and no permafrost (Table S.1), found predominantly towards the north of Iraq (Fig. S.1). The response curves for the predictor 'slope' across all models show in general very low habitat suitability across the majority of values, with a sudden peak around 80 m (Fig. 4b). The MaxEnt model also shows a slightly higher suitability at lower slope values than other models.

Other influential predictors that generally were ranked within the top three or four variables for most models included NDVI, land cover, bio 3 (Isothermality), and bio 7 (Temperature annual range) (Fig. 4). Peak habitat suitability for the Indian crested porcupine was seen at around NDVI values of 0.5 and at bio 3 values of around 37 °C, as well as gradual decreases in suitability as bio 7 temperature range values increased from 30–40 °C (Fig. 4b). Additionally, habitat suitability for the Indian crested porcupine was generally highest on land classified as savanna, croplands or other, and lowest on open shrublands or grasslands (Fig. 4a). Variables linked to precipitation (bio 15 and bio 18) as well as elevation had relatively little influence on the Indian crested porcupine habitat suitability across Iraq (Figs. 3, 4b).

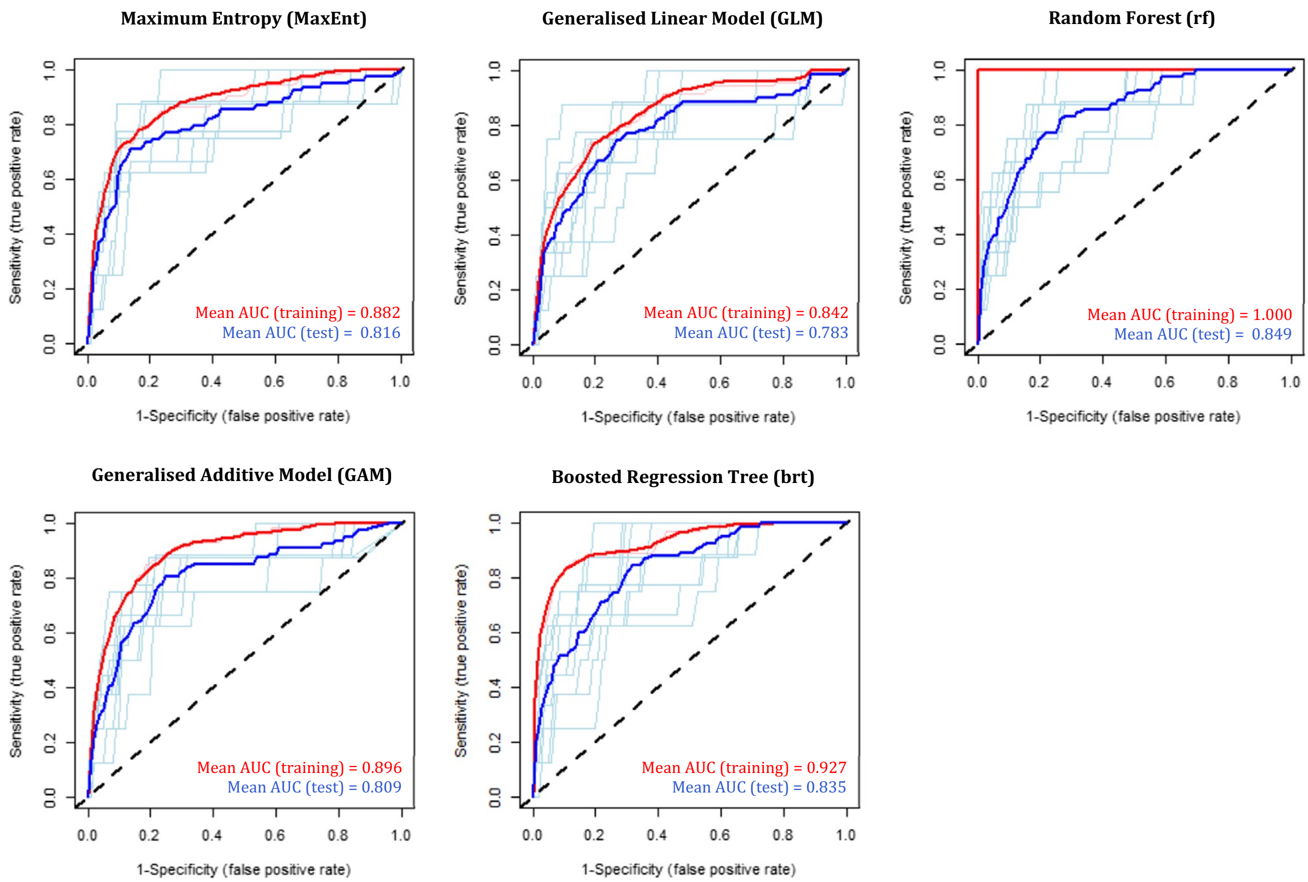


Fig. 2 Receiver-operating characteristic curve (ROC) curves for the five species distribution models: maximum entropy (MaxEnt), generalised linear model (GLM), random forest (rf), generalised additive model (GAM), and boosted regression tree (brt). Mean training (red lines) and testing (dark blue lines) area under the curve (AUC) values are shown across the ten cross-validation folds (light blue lines)

Table 2 Mean area under the curve (AUC) and true skill statistic (TSS) for the ten cross-fold evaluation of each species distribution model of Indian crested porcupine (*Hystrix indica*) in Iraq

Model	Mean AUC (±SE)	Mean TSS (±SE)
MaxEnt	0.816 (±0.026)	0.600 (±0.042)
GLM	0.783 (±0.025)	0.548 (±0.030)
rf	0.850 (±0.013)	0.629 (±0.030)
GAM	0.807 (±0.021)	0.588 (±0.039)
brt	0.841 (±0.016)	0.628 (±0.032)

Predictions of habitat suitability are evaluated for five different models: maximum entropy (MaxEnt), generalised linear model (GLM), random forest (rf), generalised additive model (GAM), and boosted regression tree (brt)

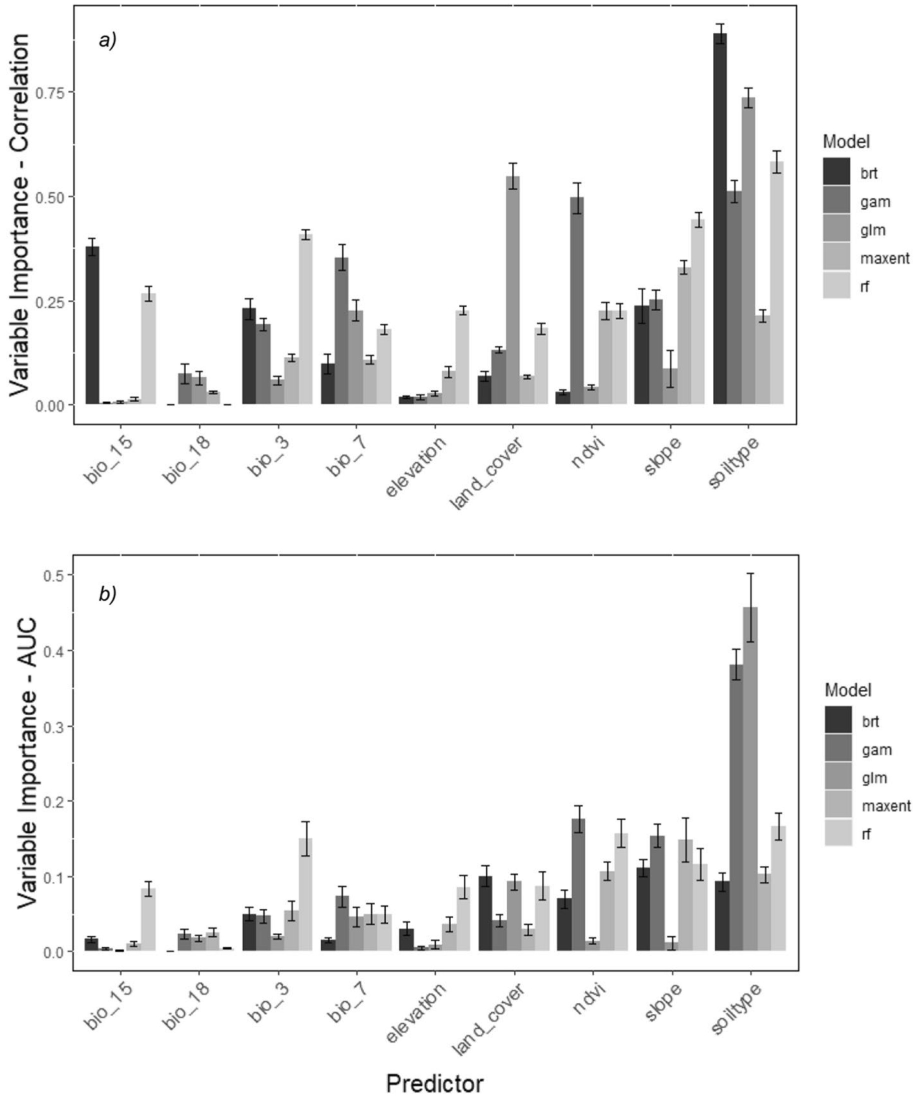
Habitat suitability prediction maps

The MaxEnt model showed the largest variability in habitat suitability across Iraq, which can be seen in both the variable response curves and prediction maps (Figs. 4, 5). All other distribution models showed relatively low habitat suitability across Iraq with little variation (Fig. 5), but showing some areas with slightly higher suitability towards the north-east. The MaxEnt prediction map showed areas with much higher suitability and more variation, although this map similarly suggests that habitat suitability is highest in the north-east. In addition, high habitat suitability was seen in a relatively small, productive vegetative area in the south-east on the border with Iran, and an area to the east near the border with Syria which experiences slightly lower temperatures than surrounding areas (Fig. S1). A high proportion of other suitable habitat is situated along the banks of the Euphrates and Tigris rivers, running from the north-west and north, respectively, down towards the Persian Gulf in the south-east (Fig. S2).

Multivariate environmental similarity surfaces

MESS surfaces were computed for two sets of predictors based on the previous variable importance results: (1) the top four continuous predictors (slope, NDVI, bio3, and bio7), and (2) all continuous predictors. The majority of the

Fig. 3 Variable importance of the nine environmental predictors used to model the distribution of the Indian crested porcupine (*Hystrix indica*) across the study area, Iraq. Mean variable importance (± SE) from the test data across the ten cross-validation folds was evaluated using **a** correlation tests or **b** area under the curve (AUC) test (see "Methods" section for how these were calculated). Results are shown for each of the five species distribution models fitted: maximum entropy (MaxEnt), generalised linear model (GLM), random forest (rf), generalised additive model (GAM), and boosted regression tree (brt)



environment across Iraq was shown to be similar to that of the reference occurrence points for the four most important predictors of Indian crested porcupine (Fig. 6). Novel environments (represented as negative values where the predictor values are outside the range of the environments of the occurrences) were characterised by bio3 in a large area to the west of Iraq, bio7 in some smaller areas in the north, and NDVI in several areas to the south-east (Fig. 6b). The overall MESS map shows that the majority of the area (93% of all pixels) across Iraq falls within the environmental range of the occurrence points, with the exception of the novel areas mentioned previously in relation to the individual predictors (Fig. 6b). MESS maps computed from all continuous predictors also show high similarity across Iraq to the reference points (Fig. S3), with some additional novel environments seen in the far north (driven by bio18 and elevation), and in the south-east (driven by elevation and bio15). On the whole, the extrapolation ability of the SDMs appears high, particularly in the central areas of Iraq, with high similarity and few novel environments seen across Iraq, suggesting that we can be confident in our overall model predictions of habitat suitability despite the low sample size.

Analysis of the categorical variables across the study area show that the majority of Iraq is covered by land class types where the number of observed occurrences is much lower than expected (Fig. 7a). These areas are located primarily towards the south and west sides of Iraq. Areas where the number of occurrences is actually higher than expected in relation to the area covered by each land-cover type are particularly towards the north and east parts of Iraq. Despite the higher number of observed occurrences than expected on the land-cover type found especially in the middle and east of Iraq, this area still showed relatively low habitat suitability in the prediction maps (Fig. 5). Soil type similarly showed a high coverage across Iraq of soil types where the expected occurrence number was higher than observed (Fig. 7b), especially towards the south of the

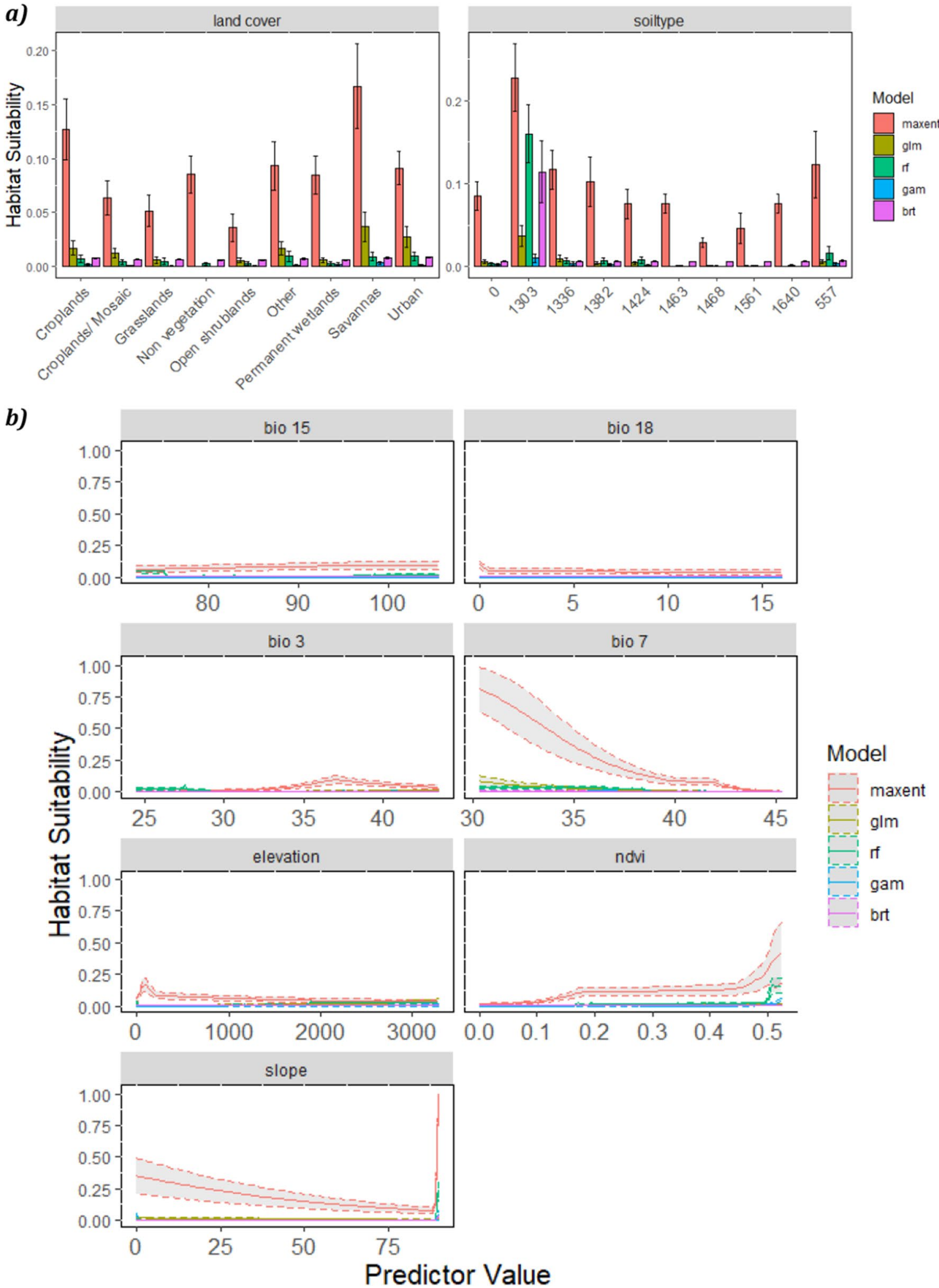


Fig. 4 Response bar plots and curves from **a** the two categoric predictors and **b** the seven continuous predictors used to model the distribution of the Indian crested porcupine (*Hystrix indica*) across Iraq. Each curve or bar plot portrays how habitat suitability, averaged across the ten cross-validation folds (± standard deviation) changes across the range or categories of the environmental predictor. Results are shown for each of the five fitted distribution models: maximum entropy (MaxEnt), generalised linear model (GLM), random forest (rf), generalised additive model (GAM), and boosted regression tree (brt)

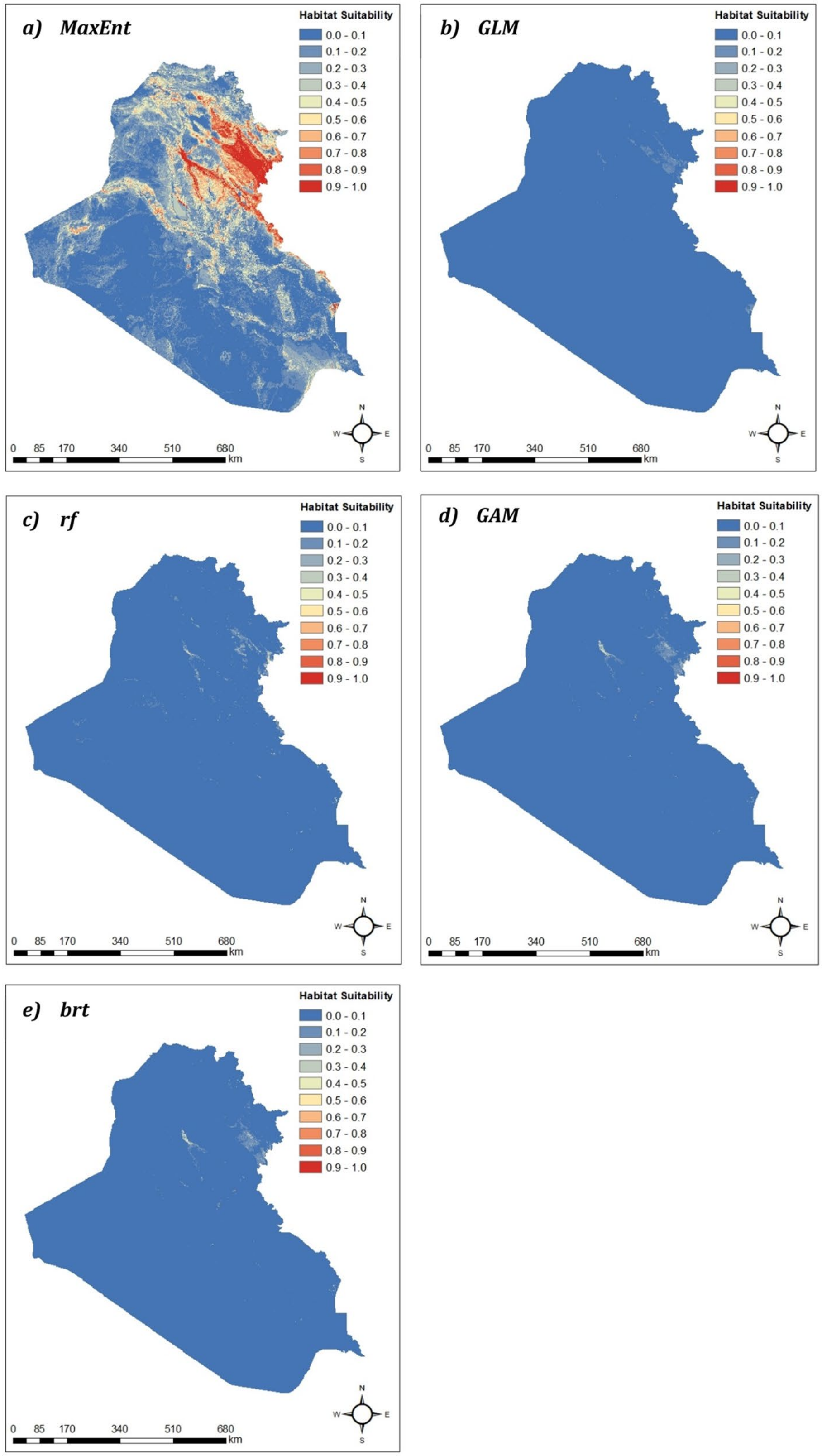


Fig. 5 Predicted habitat suitability maps for the Indian crested porcupine (*Hystrix indica*) across the study area, Iraq from **a** maximum entropy (MaxEnt) model, **b** generalised linear model (GLM), **c** random forest model (rf), **d** generalised additive model (GAM), and **e** boosted regression tree model (brt). Suitability ranges from highly suitable (1: red) to low suitability (0: blue)

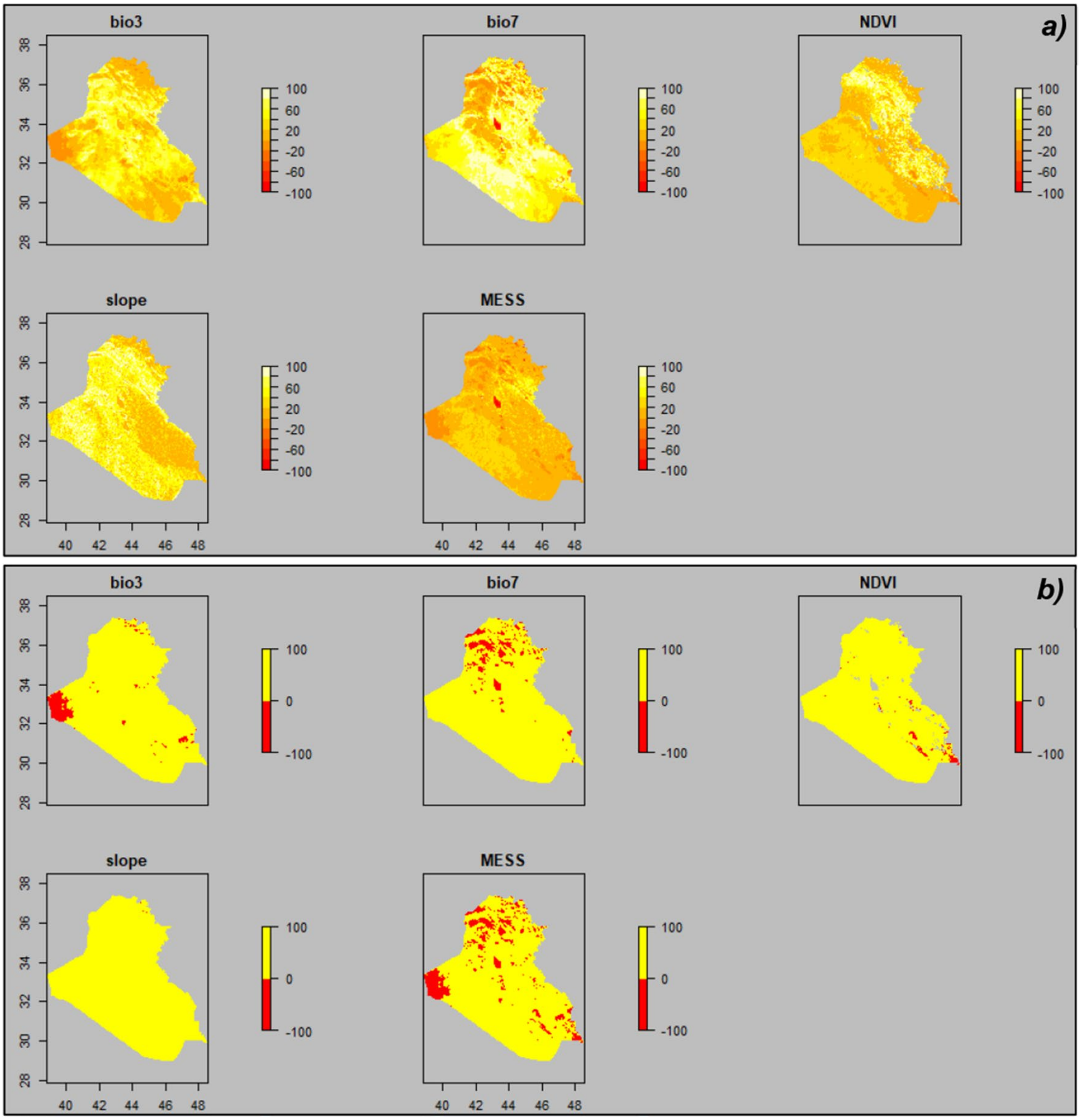


Fig. 6 Multivariate Environmental Similarity Surfaces showing the extent of environmental difference for the top four most importance continuous predictors (bio3, bio7, slope, and NDVI) separately and combined (shown as MESS), between the pixels containing occurrence records of the Indian crested porcupine (*Hystrix indica*), and each other pixel across the study area, Iraq. Plot A shows a continuous scale of similarity ranging from highly similar (positive values, yellow) to highly dissimilar (negative values, red). Plot B shows the same maps but categorised singularly as either similar (yellow) or dissimilar (red)

country. The specific soil type (1303) deemed most important from the SDMs and is highly suitable in the prediction maps is highlighted here as the soil type most likely to contain more occurrence records than expected relative to the area it covers.

Discussion

The Indian crested porcupine has a wide global distribution, is listed as of 'Least Concern' on the IUCN red list (IUCN 2012), and is considered an agricultural pest in many countries (Amori et al. 2021). However, it is thought to experience much higher levels of threats and anthropogenic pressure in Iraq and other parts of the Middle East, where a few studies conducted in these areas report that the population has undergone a noticeable decline over the past few decades due to excessive (and often illegal) hunting and trapping (Raza et al. 2011; Alsheikly et al. 2015). Confirming these findings is difficult, as the lack of species occurrence data, surveys, record curation, or research studies in Iraq is limited by the political climate. Our study, made possible through the use of SDM and its ability to

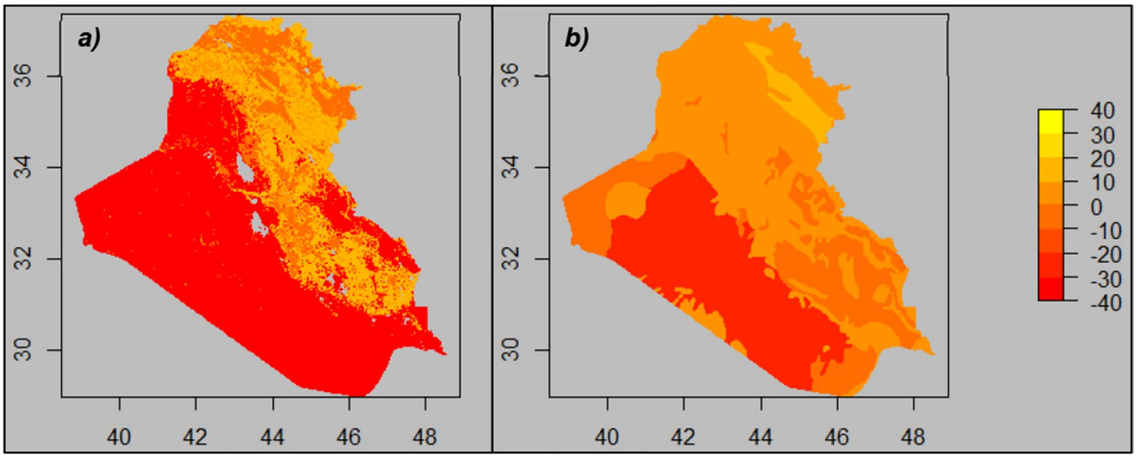


Fig. 7 Categorical predictor surfaces showing the difference in the expected and observed number of occurrence records of the Indian crested porcupine (*Hystrix indica*) across Iraq, within each particular category of **a** land cover and **b** soil type. Negative values (red) indicate pixels belonging to a category where the observed occurrence number is much lower than expected, whereas positive values (yellow) indicate pixels belonging to a category where the observed occurrence number is higher than expected

model limited species occurrences, presents the first baseline distribution map of the Indian crested porcupine across Iraq and highlights potential areas of habitat suitability and also important environmental drivers of its distribution. We propose that our findings can inform future systematic and targeted surveys to properly evaluate the conservation status of the Indian crested porcupine and to avoid sudden population declines.

The Indian crested porcupine shows great adaptability and an impressive tolerance to living in many different environments, from temperate to tropical, forest to arid, low to high elevation, and natural to cultivated crops (Akram et al. 2017; Safeer et al. 2018; Amori et al. 2021). Our analysis indicated that soil type and slope were the most important predictors influencing habitat suitability (Fig. 3b) echoing similar findings of Monetti et al. (2005) and Mori et al. (2013) on porcupine habitat preferences. We also found that habitat suitability of porcupine increased with increasing NDVI across Iraq: these findings are not surprising as soil and vegetation type can be directly linked to the diet and home-range requirements of the porcupine: each of these are known to vary seasonally and geographically, and hence, its spatial and temporal distribution is largely connected to foraging opportunities and food availability (Saltz and Alkon 1989). Kadhim (1997) found that variation in the porcupine diet is greatly dependant on plant diversity in Iraq, and similar observations have been found across other parts of its range (Alkon and Saltz 1985; Hafeez et al. 2011; Khan et al. 2014; Akram et al. 2017). Additionally, the Indian crested porcupine belongs to the Rodentia order, of which many species including the porcupine excavate and inhabit underground caves or burrows (Mushtaq et al. 2010; Mukherjee et al. 2017). Thus, soil type and slope are likely to play major roles in burrow site selection and habitat preferences (Mukherjee et al. 2017). One interesting finding, which contrasts other studies (Mori et al. 2021) and is in opposition to our original hypotheses about the most suitable predictors, is that the porcupine's distribution was influenced more strongly by geographical and topographical factors than environmental variables e.g., temperature and precipitation. This suggests that adaptation of the porcupine to different habitats is most influenced by the availability of food or burrowing potential (Akram et al. 2017).

The landscape of Iraq shows the most variation towards the middle of the country (from the Tigris and Euphrates rivers and their banks) leading upwards towards the north plateau and the Kurdistan areas (Figure S1). Kadhim (1997) reported in his paper that all porcupine records were situated around stream banks and close to rivers (see Fig. 1), and our results also suggest that these are areas of high habitat suitability. The southern area of Iraq is less diverse, and is generally categorised as a non-vegetative area. However, these arid regions are not necessarily devoid of suitable habitat or environmental conditions for the porcupine: records of the porcupine have been noted in desert biomes such as the Negev desert in Israel (Saltz and Alkon 1989), as well as areas in the United Arab Emirates (Al Dhaheri et al. 2018; Chreiki et al. 2018). In our distribution maps, habitat suitability is generally lower in these arid areas, although there are a few hot spots, especially approaching the Red Sea and the Arabian Sea. We found that elevation had little influence on porcupine distribution, but interestingly, Awan et al. (2004) recorded the species at relatively high elevations reaching up to 3200 m in Pakistan. It has also been seen in the Himalayas at elevations of around 2400 m (Gurung and Singh 1996), and recorded using camera traps in the Mountains of Qara Dagh in Kurdistan (Raza et al. 2012). The porcupine is an elusive species that shows high sensitivity in its foraging activity, such as an aversion to the full moonlight, likely as a predator-avoidance behaviour (Alkon and Saltz 1988). Therefore, we strongly argue that by increasing sampling effort and taking into account the species ecology and behaviour, we can delignate more information about its distribution and habitat preference in other less-studied areas, including in the South, along the border with Saudi Arabia, and in areas of moderate-to-high elevation.

The porcupine is an interesting and complex species to study, as it is considered a pest that has to be subjected to numerical control in some parts of its range, while being threatened due to intensive hunting and trapping in other parts. For example, Safeer et al. (2018) reported that some farmers are using different measures to eliminate the porcupine in Pakistan, whereas in Jordan, Eid and Handal (2018) reported that Indian crested porcupine were being illegally hunted, and they counted 32 instances of carcasses posted to social media platforms. Such attitudes have resulted in significant threats to its conservation status in Jordan (Eid et al. 2020). Similar conflict and practices are also present in Iraq, where captured individuals are sold in local markets or exported to Arabia Gulf countries (Raza et al. 2011). Additionally, traditional medicinal practices associated with this species are still used including for the treatment of infertility and general weakness (Eid et al. 2020), and reducing blood pressure (Raza et al. 2011). Kadhim (1997) first raised the concern that the population number is declining in Iraq and the species is not as abundant as it used to be. In the absence of official information and effective restrictions on wildlife trade, we should be concerned that the conservation status of the porcupine might be worse than previously thought. Furthermore, porcupine do have some positive contributions to the ecosystem (Mukherjee et al. 2017): other species can use their burrows as shelters, and the burrows hold water, seeds, and organic matter (Akram et al. 2017; Mukherjee et al. 2017).

The demand for machine-learning methods in SDM and ecology is increasing (Cutler et al. 2007; Benito et al. 2013) and developments in technology and methods have produced highly accurate and reliable SDM tools that often outperform regression-based methods (Cutler et al. 2007; Marmion et al. 2009; Bucklin et al. 2015). Our results similarly support machine-learning methods, particularly MaxEnt and random forest (rf), over alternative algorithms echoing other similar studies (Bucklin et al. 2015; Kaky et al. 2020). Methods like MaxEnt have also been shown to be effective at modelling rare species, or species with very limited number of occurrence records (Breiner et al. 2016; Mi et al. 2017), and as such, is an excellent choice of method to use here in a unique situation where species recording is limited due to the political climate and risk to safety of ecological researchers. We acknowledge that there is likely to be some uncertainty in our modelling process, for example the georeferencing process of the collated occurrence records from the literature or field work may introduce a small amount of human error, as may the original recording process itself, and obviously, there are huge areas of Iraq where no surveys have been carried out, so sampling bias will be present in our dataset. Here, we have to minimize these errors by computing MESS surfaces, using multiple SDM algorithms and comparing the results to that of null models. Nevertheless, given the political and security circumstances of Iraq which greatly restrict fieldwork opportunities and ability to collect and share data, the current data we have represent the best comprehensive description of the distribution of Indian crested porcupine in Iraq. This study highlights the challenges posed in many areas like Iraq of a shortage of species data, yet also how SDM can address ecological questions in such areas, and that robust and accurate distribution predictions can still be produced to inform conservation and management practices.

Conclusion

Iraq has a variety of ecosystems that support a wide range of mammal species endemic to this region including the Indian crested porcupine. This study presents the first baseline distribution map of this species, with the most suitable habitat extending from the Tigris and Euphrates river banks to the north of the Kurdistan areas in Iraq. The lack of species data in this area, coupled with the high levels of often illegal hunting and trapping of the porcupine, mean that it is imperative to comprehensively study this species immediately to assess its conservation status and to prevent disastrous population declines. Much work and effort is still needed in Iraq to achieve a solid ecological understanding of the Indian crested porcupine, as well as many other species, that can inform effect conservation strategies, especially in the southern areas. Nevertheless, studies like this using SDM provide a robust starting point for the baseline estimation of a species distribution when data are sparse. Following on from this however, systematic surveys of Iraq's biodiversity through joint efforts of the authorities, communities, conservationists, etc., are desperately needed in a country that is still scientifically suffering.

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Author contributions All authors share common research interests in ecology, species distribution modelling, and conservation across a wide variety of study species and geographical areas, including Europe, the Middle East, and the USA.

Data availability All Indian crested porcupine species data and code used for analysis will be made freely available online following acceptance and publication of this manuscript.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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