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Research Article

Potential geographic distribution and habitat suitability of the Greater horseshoe bat, *Rhinolophus ferrumequinum* (Chiroptera: Rhinolophidae) in Iran

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Abstract

We present a review of earlier records of the greater horseshoe bat distribution in Iran together with new distribution records of this bat obtained during recent years (2012–2016). The present study describes 41 new localities that increase the species known range mainly over Zagros and Elburz ranges at elevations between 27 - 2560 m above sea level. Moreover, based on these data potential geographic distribution of the greater horseshoe bat has been estimated using the Maximum Entropy modeling (MaxEnt). The MaxEnt model showed that the environmental variables including bio-12 (average annual precipitation), bio-6 (minimum temperature of the coldest month), and bio-19 (precipitation of the coldest quarter of the year) were the most important predictors of *Rhinolophus ferrumequinum* distribution. AUC values indicated an excellent power of MaxEent to create potential habitat map (AUC=0.845). The MaxEnt model predicted climate suitability to be high in Zagros and Elburz Mountains especially in northwest of Iran, low in some parts of south, east and southeast of Iran. Suitable habitat was absent in the two vast deserts (Dasht-e lut and Dasht-e Kavir) in the Iranian Plateau basin where there had not been any report of *R. ferrumequinum*.

Keywords: Chiroptera, habitat suitability, MaxEent, new records, *Rhinolophus ferrumequinum*.

Introduction

The greater horseshoe bat (*Rhinolophus ferrumequinum)* is a relatively large insectivorous bat and has a vast distribution range from western Palearctic to eastern Asia. *R. ferrumequinum* is distributed in southern Europe and northern Africa through the Mediterranean Sea including all central European large islands (Pavlinić *et al.* 2010). Toward the east, it is distributed in the Middle East to the Caucasus up to China, Korea, and Japan (Dietz *et al.* 2009). This bat was first described by Schreber (1774) on the basis of specimens collected from France as *Vespertilio ferrumequinum* (Schreber 1774). After Schreber (1774), many changes occurred on the taxonomic status of this species both at the sub-specific and specific levels. In 1803 the species was placed in the genus *Rhinolophus* as *Rhinolophus major* (Geoffroy 1803) and Koch (1863) described the specimens from Germany and Italy as *R. f. germanicus* and *R. f. italicus* respectively. Following Koch (1863), 13 subspecies were described for this species (Csorba *et al.* 2003). However, recently 6 subspecies are known in the range of *R. ferrumequinum* including *R. f. ferrumequinum* (Europe and northwestern Africa), *R. f. irani* (Iran, Iraq and Turkmeniya), *R. f. proximus* (Afghanistan and Uzbekistan east to Kashmir), *R. f. tragtus* (northern India to eastern China), *R. f. Korai* (Korea), and *R. f. nippon* (Japan and eastern China) (Csorba *et al.* 2003).

Although *R. ferrumequinum* was first reported by Gmelin (1774) from Elburz Mountain in north Iran but Cheesman (1921) was the first to describe *R. ferrumequinum* as *R. f. irani* from Shiraz in south west Iran. This author also attributed the Torbat-e Heydariyeh specimen from eastern Iran to this form (DeBlase 1980). This subspecies was also described based on specimens from Shiraz and Bushehr (Missone 1959), Mozduran Cave, Shandiz village, Shahpur cave, Azad-Khan cave, and Baba-jabar cave (Etemad 1967). Bobrinskii *et al.* (1965) listed *f. ferrumequinum* from the European portion of the USSR and the western Caucasus, and listed *R. f. proximus* Andersen 1905 from eastern Transcaucasia and central Asia. Gaisler (1970) pointed out that the real relationship between *R. f. irani* and *R. f. proximus* (type locality, Gilgit, Kashmir) is yet to be determined.

R. ferrumequinum occurs throughout Iran, with the exceptions of the central deserts, Sistan and Baluchistan in the east and Mesopotamia in the west (DeBlase 1980, Etemad 1984, Benda *et al.* 2012, Shahabi *et al.* 2017a,b, Shahabi *et al.* 2019). Following introduction of this bat in Iran by Gmelin (1774) from Elburz Mountain near Rasht, more authors reported the species in different part of the country. Cheesman (1921), Etemad (1967), Lay (1967), Farhang-Azad (1969), DeBlase (1980), and Karami *et al.* (2008) reported this bat from various locality of Iran. Sharifi *et al.* (2000) provided a review of distribution of bats from Iran. Recently, Benda *et al.* (2012) presented another review of bat fauna of Iran representing 58 records of this rhinolophid bat from Iran.

Species distribution modeling in ecology is becoming increasingly popular. Generally, these models define distribution of various species based on their environmental requirements. Among many species distribution, HSM has provided a strong assessment tool for prediction of geographic distributions of species (Ortega-Huerta and Peterson 2008, Scott *et al.* 2002). As a result, delimiting species boundaries using HSM approach has also generated interest in various group of biological scientists to use genetic, ecological and spatial data to define other population distinctiveness and classify populations as evolutionary significant units (Crandall *et al.* 2000, Moritz 2002), management units (Eastman 2007), distinct population segments (Rosen 2007), conservation unit (May *et al.* 2011) or provide solely taxonomic evaluation of different populations. HSM by using empirical data has also been able to rapidly characterize several evolutionary and ecological processes such as identifying species ecological requirements (Austin and Meyers 1996, Luoto *et al.* 2006, Diekotter *et al.* 2006), delimiting biogeography and dispersal barriers (Bauer and Peterson 2005), forecast species invasions (Thuiller *et al.* 2005), realize the effects of habitat alterations (Rissler and Apodaca 2007), identify effects of climate change (Thuiller *et al.* 2005), delimit species boundaries (Raxworthy *et al.* 2007, Graham *et al.* 2004) and predict unknown populations and species (Kumar *et al.* 2009, Franklin 2009).

Here, we present a review of earlier records of the species distribution in Iran and report new distribution records for the greater horseshoe bat. Based on these data we used MaxEent distribution modeling to provide a general distribution map to predict the potential geographic distribution and the main environmental variables associated with its distribution.

Material and methods

The study area is the territory of Iran. This country represents the easternmost part of the Middle East, lying eastwards of the proper Mediterranean Basin and belonging to the Mediterranean region only in its broader sense (Blondel *et al.* 2010). Iran occupies the western two-thirds of the Iranian Plateau, a geographic unit that arises in the Armenian Knot at the east end of the Anatolian Plateau of Turkey, expands southward to include most of Iran, Afghanistan, and Pakistan, and constricts again at the Pamir Knot at the west edge of the

Tibetan Plateau (DeBlase 1980).

Field studies targeted caves and crevices in the two mountainous areas in western and northern parts of Iran; Zagros and Elburz ranges. Fifty caves representing different habitats in Iran were visited (Fig. 2). From these, nine caves have been previously visited by bat biologists. The study was conducted in various regions of Iran excluding central, eastern, and southeastern Iran, where rhinolophid bats had not been reported. Bats were netted with mist nets (6 × 3 m) placed on caves entrances or were collected using hand nets. Identification of *R. ferrumequinum* was based on forearm size over 55 mm and presence of the complex noseleaf (DeBlase 1980). Geographical coordinates and altitude for each cave was recorded using a Garmin GPS unit (GPSMAP 60CSx; Garmin International, Inc., New York, USA). The published distribution data for *R. ferrumequinum* were basically obtained from two sources: DeBlase (1980) and Benda *et al.* (2012).

In total, 99 point localities including 41 new records in the present study and 58 in earlier published records (Fig. 2) were used for generating habitat suitable models of *R. ferrumequinum*. Nineteen BioClimatic data, biologically more meaningful to define eco-physiological tolerances of a species (Murienne *et al.* 2009) were obtained from the WorldClim dataset (http://www.worldclim.org/) in the raster format at 30 arc-second resolution (0.93 × 0.93 = 0.86 km ^{2} at the equator). Furthermore, the elevation was also used in the analysis (https://www.iscgm.org/gmd). To avoid over-parameterizing the habitat suitable models with redundant climatic information, correlation tests conducted among all BioClimatic data to remove redundant variables with correlation coefficient over 0.75 (Rissler and Apodaca 2007, Wang *et al.* 2007, Mehdizadeh *et al.* 2018, Najafi *et al.* 2018).

The environmental information were extracted from a preliminary generated model of 500 random points obtained from across the Iran by DIVA-GIS Software (http://www.diva-gis.org). Extracted data were tested for normality (Shapiro-wilk test, p= 0.05). Spearman correlation coefficient of 0.75 was used to identify highly correlated variables (Rissler and Apodaca 2007, Wang *et al.* 2007). For pairs that were highly correlated, the more biologically meaningful variables were considered. Ten bioclimatic variables as well as elevation were chosen and used in all subsequent analyses. The following climatic variables were included in the final subset for calibration: BIO3 (Isothermal parameter (BIO2/BIO7) * (100)), BIO4 (Temperature seasonality (standard deviation * 100)), BIO5 (Maximum temperature of the warmest month), BIO6 (Minimum temperature of the coldest month), BIO7 (Annual temperature scale), BIO8 (Average temperature of the wettest quarter of the year), BIO12 (Average annual precipitation), BIO15 (Seasonality of precipitation (coefficient of variation), BIO18 (Precipitation of warmest quarter of the year), BIO19 (Precipitation of the coldest quarter of the year) and Alt (Elevation). We masked all environmental layers and setting up the extent and cell size and exported them as ASCII grids for use in model development. We used maximum number of 10,000 points to determine the background distribution, a regularization multiplier of 1 for both the northern and southern models, maximum interactions of 1000, and a convergence threshold of 0.001.

For evaluating models accuracy, we used the area under the ROC curve (AUC) and omission rate. The plots represent a model's ability to discriminate species locations from pseudo-absences by plotting sensitivity against 1 – specificity. AUC is a measure of classifier performance and compares model fit to that of a random prediction. AUC values can be changed between 0–1, where 1 is a perfect fit. Area under the curve values range from 0 to 1, and models with an AUC of P 0.7 are generally considered acceptable, models with an AUC of P 0.8 are considered excellent and models with an AUC of P 0.9 are considered outstanding (Hosmer and Lemeshow 2000). The jackknifing shows the training gain of each variable if the model was run in isolation, and compares it to the training gain with all the variables. This is useful to identify which variables contribute the most individually (Phillips *et al.* 2006).

For the MaxEnt Combined Model, 5,000 random points were drawn from the minimum convex polygon of each range and combined to a 10,000 point background (Sobek-Swant *et al.* 2012). The MaxEnt results presented are the mean values of 15 randomized runs per model. For each run, presence records were split into 75% training and 25% test data. ASCII file of MaxEnt's logistic output (ranging from 0 to 1, with 0 indicating low and 1 indicating high suitability) were converted into raster format using software ArcGIS 9.3 (ESRI 2006) and finally climate suitability map of *R. ferrumequinum* in Iran was created.

Results

Review records

In the present study, we recorded *R. ferrumequinum* from 50 localities in Iran of which, 41 records are reported for the first time and nine localities had been previously published (Fig. 1). We also reviewed literature cites and found 49 other previously published records of the species in different regions of Iran. Therefore, *R. ferrumequinum* is known from 99 localities of Iran. The occurrence points of *R. ferrumequinum* reported since 2012 is shown in figure 1. The occurrence data for *R. ferrumequinum* shows that this species is mainly distributed in various localities along Elburz and Zagros mountains (Fig. 1).

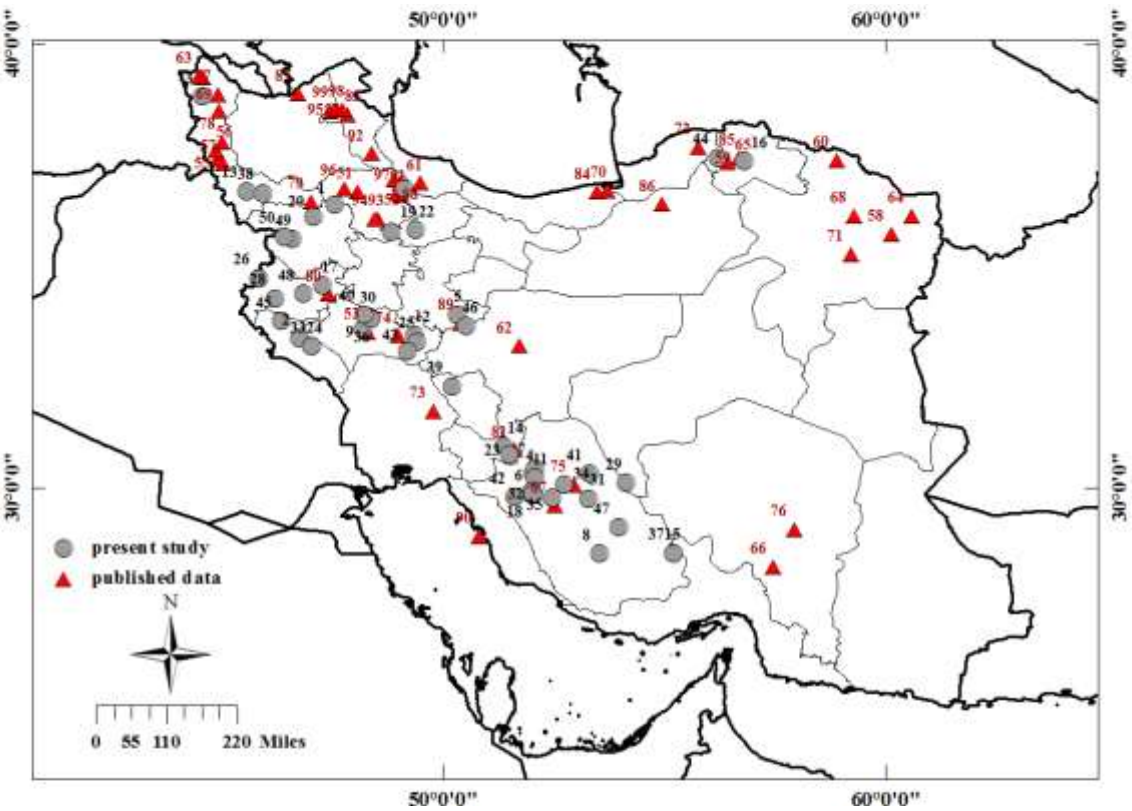


Figure 1. Geographical distribution of the greater horseshoe bat in Iran including the records presented in this study (circles) and earlier locality records provided from published data (triangles).

Ecological niche modeling

Habitat suitability of *R. ferrumequinum*

Based on maximum entropy modeling algorithm and using 11 environmental variables, we obtained a distribution map for *R. ferrumequinum.* Figure 2 shows the distribution maps with cooler colors indicating more suitable habitat and warmer colors indicating unsuitable habitats.

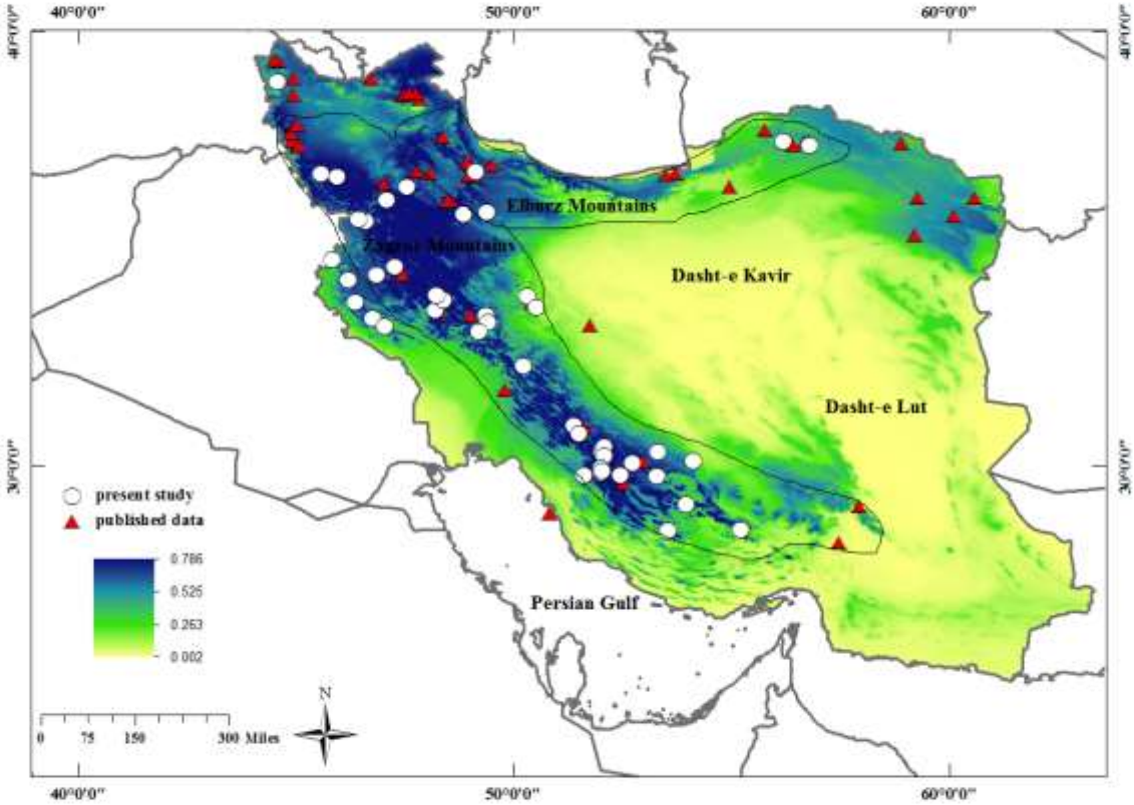


Figure 2. Continuous predicted map of environmental niche for *R. ferrumequinum* in Iran depicting areas in which the environmental conditions are suitable for the species.

Predictions of the distribution of *R. ferrumequinum* were good and coincided well with the known distribution of the species (Fig. 2). The ability to differentiate presence from random background points for all generated models (training AUC values) was larger than 0.83 and thus considered as excellent. Analysis of variable contributions show the environmental variables used in the model and their percent predictive contribution of each variable. In this study bio-12, bio-6, and bio-19 had the highest predictive contribution of 62.6%, 11.9 %, and 10.6 % respectively. By considering the regularized training gains, the most important variables were determined. Both Jackknife of regularized training gain and jackknife of test gain (Fig. 3) showed bio-12 and bio-19 were most important predictors of *R. ferrumequinum* distribution (Table 1).

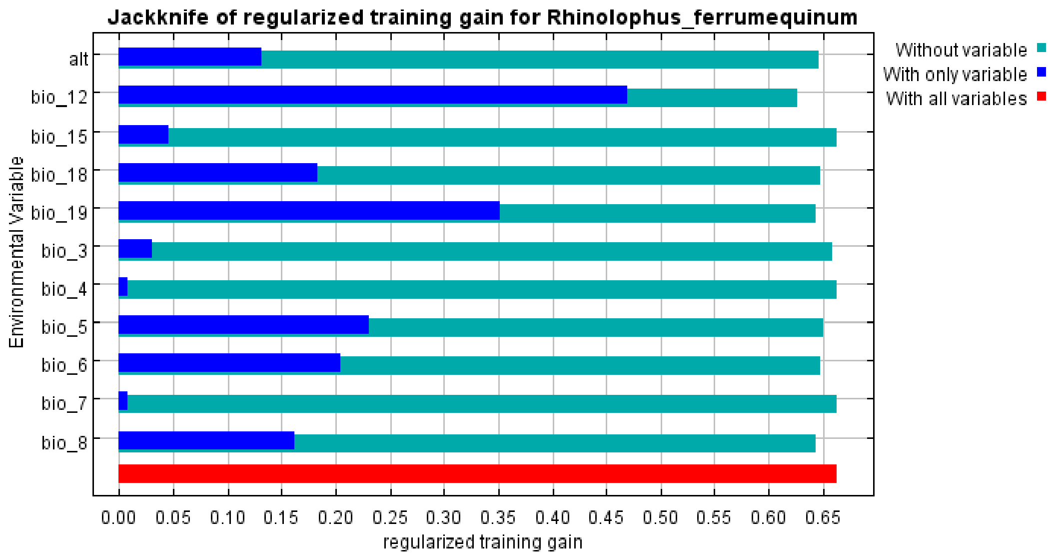
Discussion

Records of *R. ferrumequinum* (past and present)

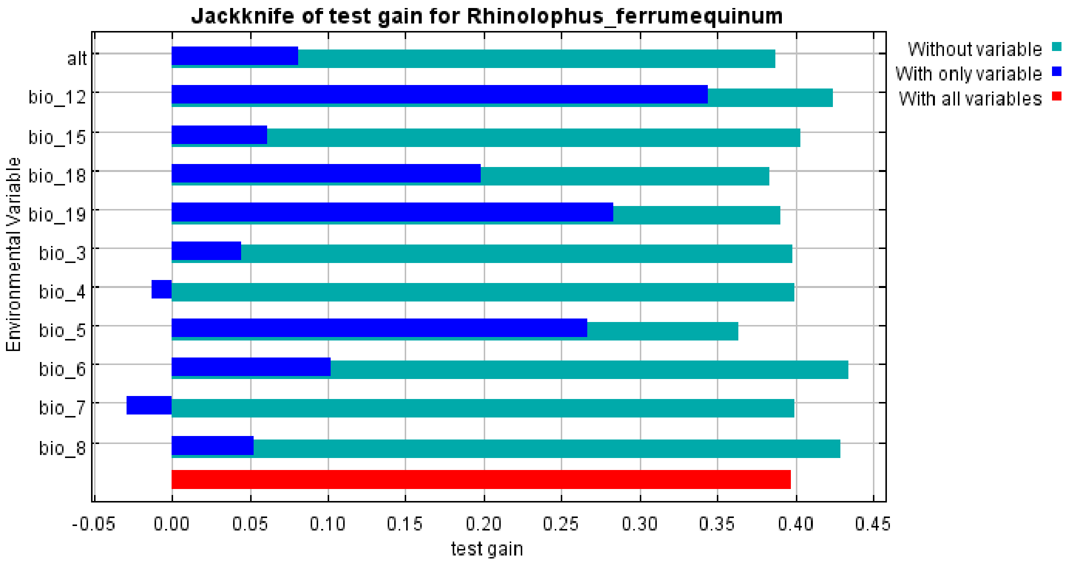
Previously assumed distribution of *R. ferrumequinum* as indicated by Benda *et al.* (2012) is much smaller than what the results of present study revealed (Fig.1). In the present study, we report 41 new records of *R. ferrumequinum* from Iran for the first time (Fig. 1). Today, *R. ferrumequinum* is known from 99 localities of Iran. The occurrence points of *R. ferrumequinum* reported since 2012 is shown in figure 1.

Table 1. Analysis of percent contribution and permutation importance of bioclimatic variables to the MaxEent model.

Variable	% contribution	Permutation importance
Average annual precipitation (bio_12)	62.6	37.9
Minimum temperature of the coldest month (bio_6)	11.9	18.4
Precipitation of the coldest quarter of the year (bio_19)	10.6	18.7
Precipitation of warmest quarter of the year (bio_18)	5.2	11.4
Average temperature of the wettest quarter of the year (bio_8)	3.2	4.6
Elevation (alt)	2.9	3.6
Maximum temperature of the warmest month (bio_5)	2	4.1
Isothermal parameter (bio_3)	0.7	0.8
Temperature seasonality (bio_4)	0.4	0.2
Seasonality of precipitation (bio_15)	0.4	0.2
Annual temperature scale (bio_7)	0	0.2



(a)



(b)

Figure 3. Jackknife of regularized training (a) and test gain (b) for *R. ferrumequinum* from Iran. The Jackknifing shows the training gain of each variable, and compares it to the training gain with all the variables.

The occurrence data for *R. ferrumequinum* shows that this species is mainly distributed in various localities along Elburz and Zagros Mountains (Fig. 1). Inappropriate climate as well as natural boundaries of the two big mountainous ranges (Zagros and Elburz), the lowlands of the central deserts and also lowlands of the Persian Gulf littoral appear to make a limit its range. From the results of this study, it is clear that distribution of *R. ferrumequinum* is dependent on mountainous areas in north and western part of the country. Long-term survival of this species both in terms of the suitable climate conditions and in terms of vegetation cover is dependent to the presence of protected areas within the very vast distribution range of *R. ferrumequinum*.

Habitat suitability of *R. ferrumequinum*

Predictions of suitable area and occurrence records

We have demonstrated that maximum entropy modeling (MaxEent) can be a useful tool for directing exploratory surveys for detecting *R. ferrumequinum* in various habitats in Iran. Our results of potential habitat distribution maps for *R. ferrumequinum* may help to discover new populations, identify top-priority study sites, or set priorities to restore its natural habitat for more effective conservation. Using the results of MaxEnt model can direct our survey efforts in previously unrecognized location within Zagros and Elburz range particularly in northwestern parts of the country where these two mountain ranges meet. This detection is significant because it represents the species' southernmost point of occurrence.

The MaxEnt model predicted environmental suitability to be high in Zagros and Elburz Mountains especially in west and northwest of Iran (West Azerbaijan, East Azerbaijan Qazvin, Kurdistan, Kermanshah, Zanjan, Hamedan and Lorestan provinces). Another part of Iran such as north of Iran (Gilan and Mazandaran), northeastern Iran (Khorasan-e Shomali and Khorasan-e razavi) and south of Iran (north of Fars and Kohgiluyeh and Boyer-Ahmad) are also suitable for this species (Figure 2). Environmental suitability is low in some parts of south, east and southeast of Iran whereas suitable habitat was absent in Dasht-e lut and Dasht-e Kavir and some parts of central and southeast of Iran (Fig. 2). Predictive modeling showed that currently there is a low potential for eastern populations to be connected to west and southwestern ones. This is due to the two vast plateaus Dasht-e lut and Dasht-e Kavir situated in central and eastern Iran. However, the caves located in the best suitable area are proposed to be considered for protection by department of environmental conservation in Iran.

Relevant environmental factors

Few studies have taken a habitat suitability modeling (HSM) approach to greater horseshoe bat, and this is the first HSM study of this horseshoe bat in Iran and in the World. Our analysis revealed that variables derived to correspond with *R. ferrumequinum* ecology can contribute substantially to HSM performance. In particular, average annual precipitation (bio-12) was the most influential variable in all HSMs, followed by minimum temperature of the coldest month (bio-6) and precipitation of the coldest quarter of the year (bio-19). These variables match with habitat characteristics thought to be important to support insect population and sustain *R. ferrumequinum* populations. Precipitation and temperature of the coldest month were the most important ecological factors delimiting distribution, while the bats also avoided areas with high temperatures. The bioclimatic model showed that there is a large area of unsuitable climatic conditions in the central and southeast Iran where higher temperatures are recorded. These regions also are driest parts of the country. The western boundary of Iran far from Zagros Mountain in Ilam and Khuzestan province, and also shoreline of Persian Gulf are unsuitable area for the species (warm and dry area). Therefore, the species are almost restricted to the mountains and wettest region with moderate climate and cold winter (Zagros and Elburz mountains). This might give a possible explanation why its occurrence is lesser in the shoreline of Caspian Sea in spite of the highest rainfall.

Model evaluation

Models were evaluated using area under the curve (AUC) statistics of the receiver operating characteristic (ROC) plot. The area under curve (AUC) of the ROC analysis provides a single measure of the model performance (Liu *et al.* 2005). Models with an AUC of P 0.7 are generally considered acceptable and AUC of P 0.8 considered excellent (Hosmer and Lemeshow 2000, Anderson *et al.* 2003, Sobek-Swant *et al.* 2012). In the present study, Bioclimatic models showed good predictive power for training data (average AUC = 0.763 ± 0.034) (Fig 4.).

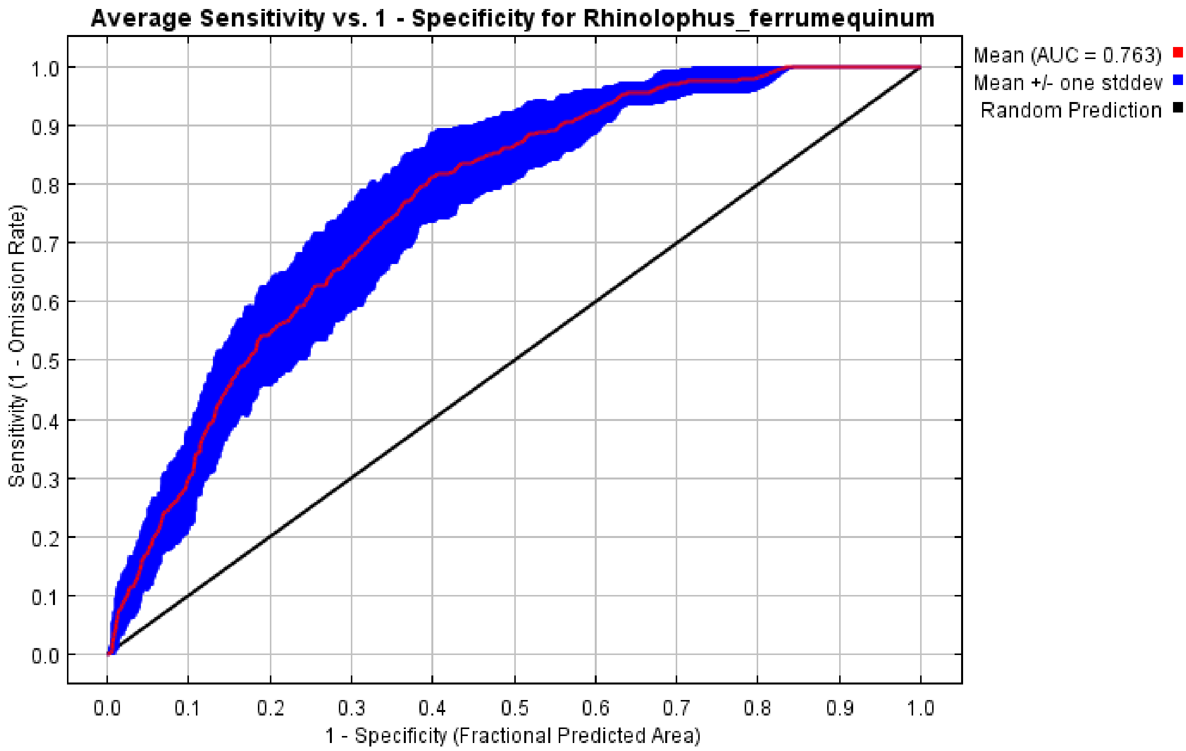


Figure 4. The receiver operating characteristic (ROC) curve for the environmental data, averaged over the replicate runs. The specificity is defined using predicted area, rather than true commission.

Conservation status of *R. ferrumequinum*

Global conservation status of *R. ferrumequinum*as indicated by IUCN is Lower Risk, Near Threatened (Hutson *et al.* 2001). However, local and regional status of the species could be different. For example in the UK, the population decline of *R. ferrumequinum* is believed by more than 90% over the past 100 years (Rossiter *et al.* 2000). Similar decline in population of *R. ferrumequinum* has been reported from Luxembourg, Ukraine, and Malta are now rarely recorded as a result of the loss of roosts and decline In the quality of feeding habitat (Hutson *et al.* 2001). Attempt has also been made by Sharifi *et al.* (2000) to estimate the conservation status of the Iran bats by devising an index of relative abundance, which combines the effect of the number of the physiographic units a species being reported, number of sites in which each species being observed and the number of specimens described in various observation sites. This assessment designate *R. ferrumequinum* as a common in a conservation evaluation system consisting of common, rare, very rare and extremely rare (Sharifi *et al.* 2000). However, although the records of this species in Iran are approximately high relative to other bat species, but some records should be removed from all records as we couldn't find this species from some caves of which this bat reported earlier, such as Azadkhan, Baba-jaber, Shahpur and, Ganjah-kuh (Etemad 1967, Lay 1967, DeBlase 1980).

For this species and other chiropteran species, further field studies are urgently needed to gather data about the remaining population size, genetic diversity, and population structure, distribution boundaries of all populations, and current threats.

Conclusion

This study highlights the fact that although *R. ferrumequinum* is reported in vast area in Iran its population seem to be vulnerable to the threats of habitat loss and habitat fragmentation. Although the MaxEnt models of the distribution based on suitable climate for *R. ferrumequinum* has reliable predictive power due to the intermediate sample size (99), nevertheless, niche models are effective as guidelines for further field surveys to accelerate the discovery of unknown populations. Finally, we recorded *R. ferrumequinum* from 50 localities in Iran of which, 41 records are reported for the first time and nine localities had been previously published.

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