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How will climate change affect the temporal and spatial distributions of a reservoir host, the Indian gerbil (*Tatera indica*), and the spread of zoonotic diseases that it carries?

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ABSTRACT

Background: The Indian gerbil (*Tatera indica*) is a main reservoir host of cutaneous leishmaniasis, a great public health problem in many rural areas of Iran.

Questions: How do climatic variables affect the habitat suitability and distribution of *T. indica*? How will changes in climatic variables affect the spatial distribution of *T. indica* across Iran? Will those changes influence the outbreak regions of zoonotic cutaneous leishmaniasis?

Organism: The Indian gerbil, *T. indica*, a rodent.

Analytical methods: Maximum entropy modelling (MaxEnt) to predict suitable regions and the potential distribution of this gerbil in the present and future in Iran.

Results: Species distribution models revealed the four variables most effective in determining Indian gerbil occurrence: the mean precipitation of the year's driest month; the seasonality of precipitation; the mean temperature of the warmest quarter of the year; and the mean temperature of the wettest quarter. According to our model, the southern parts of Iran have the most suitable habitat for *T. indica*. With global climate change, suitable habitats for the gerbil will increase considerably in Iran spreading outwards toward the southwest, centrally, and the northeast.

Conclusions: Our results may be used to estimate outbreaks and prevalence of cutaneous leishmaniasis (as well as other infectious diseases which this gerbil carries).

Keywords: climate change, ectoparasites, Indian gerbil, leishmaniasis, species distribution projections.

INTRODUCTION

All wildlife can carry pathogens (bacteria, viruses, fungi, and parasites) that may cause infectious diseases in humans. These diseases are called zoonotic diseases. Because of this,

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small mammals (mainly rodents) play a major role in the outbreak of zoonoses (Krauss *et al.*, 2003). Mammalian reservoirs of zoonoses may be arthropods (fleas, lice, mites, ticks, flies) or they be transmitted directly from animals to humans (mainly viral diseases such as hantaviruses) (Smith *et al.*, 2008; Montoya *et al.*, 2010).

In Iran, both cutaneous and visceral leishmaniasis are significant arthropod-borne diseases. Zoonotic cutaneous leishmaniasis (ZCL) is a tropical disease caused by different species of the genus *Leishmania*. *Leishmania* is a kinetoplastid (Order: Trypanosomatida), a group of flagellated protozoans (which include free-living microorganisms and parasites of various invertebrate, vertebrate, and plant species). *Leishmania* is spread by sandflies of the genera *Phlebotomus* and *Lutzomyia* in the Old World and New World, respectively (de Vries *et al.*, 2015), whose primary hosts are vertebrates such as canids, rodents, and humans (Myler and Fasel, 2008). *Leishmania* occurs widely in rodent populations of savanna and arid regions. It is also a major public health problem in many rural areas of Iran (Khoobdel *et al.*, 2003; Akhavan *et al.*, 2010).

Several species of sandflies belonging to the genus *Phlebotomus* (Insecta; Diptera), including *P. alexandri*, *P. ansarii*, *P. caucasicus*, *P. mongolensis*, *P. papatasi*, and *P. salehi*, act as vectors in the transmission of ZCL between rodents. The most significant parasite carried by these sandflies is *Leishmania major* (Yaghoobi-Ershadi and Akhavan, 1999; Yaghoobi-Ershadi *et al.*, 2005). A few wild rodent species are known to be the principal reservoir hosts of ZCL in Iran (Bates *et al.*, 2015) – these are gerbilline rodents including jirds (*Meriones crassus*, *M. hurrianae*, and *M. libycus*) and gerbils (such as *Rhombomys opimus* and *Tatera indica*) (Rassi *et al.*, 2001, 2006; Hepburn, 2003; Gramiccia and Gradoni, 2005; Gholamrezaei *et al.*, 2016).

Tatera indica is found in Afghanistan, Pakistan, India, Iran, Iraq, Kuwait, Turkey, Syria, Nepal, and Sri Lanka (Harrison and Bates, 1991). Lay (1967) reported this rodent throughout the southern half of Iran. It is locally abundant and presumed to have a large population (Yiðit *et al.*, 2001). *Tatera indica* is the principal reservoir rodent in the western border foci of ZCL (e.g. Khuzestan province – mainly in Dezful and Shush – and Ilam province) (Mohammadi *et al.*, 2017), the southern foci (southern part of Fars province), and the southeastern foci (Sistan and Baluchestan province, especially Chabahar) in Iran (Mohebali *et al.*, 2004; Oshaghi *et al.*, 2009). The presence of numerous rodent burrows in an area portends a high risk of contracting the disease.

Distribution and ecological niche modelling is widely used to predict the potential ecological distribution of a species and to increase our knowledge about its distribution while identifying the habitats in which it may be undocumented. In the case of species that may carry diseases, ecological niche modelling may permit us to anticipate those areas at high risk for disease occurrence (Gonzalez *et al.*, 2010; Karimi *et al.*, 2014). Ecological niche modelling is based on the idea that the known occurrence of an organism can be related to raster geographic datasets summarizing the factors that likely influence the suitability of the environment for the species across the occurrence landscapes (Phillips and Dudík, 2008; Elith and Leathwick, 2009). So we conducted species distribution modelling to predict the distribution of *T. indica*, to reveal the most important abiotic factors influencing its distribution, and to assess the effects of future climate changes on that distribution. Thus we might estimate the outbreak and prevalence of cutaneous leishmaniasis in Iran.

METHODS

Occurrence records and environmental data

For mapping the distribution range and habitat suitability of *T. indica*, presence data (39 georeferenced distribution records) of the species were assembled during field expeditions using custom-made mesh live traps in North and South Khorasan provinces between the years 2017 and 2018, and also personal collections and available literature (e.g. Darvish and Rastegar-Pouyani, 2012; Hamidi *et al.*, 2015, 2016; Amirafzali *et al.*, 2017; author's unpublished data, and data available on the internet: GBIF at https://www.gbif.org and VerNet at http://www.vertnet.org). We assembled 19 bioclimatic variables as well as elevation with 30 arc-seconds (~1 km) resolution, obtained from the WorldClim database (http://www.worldclim.org/). Environmental layers and records were applied by open Modeler v.1.0.7 (de Souza Muñoz *et al.*, 2011) to determine the relevant grid values for each environmental layer. The extracted values were tested by SPSS v.16.0 to determine the Pearson correlation coefficient. We then approximated a set of independent layers by choosing layers with correlations less than 0.75 to run the final model.

Modelling of species distribution

We used MaxEnt (maximum entropy machine learning algorithm) v.3.4.1k (Phillips *et al.*, 2017) with 15 replications to produce the final model. MaxEnt uses 'presence only' records to achieve high-performance model predictions even with low occurrence data; several ecologists believe it to be the most efficient method of ecological niche modelling (Hernandez *et al.*, 2006; Phillips *et al.*, 2006; Elith *et al.*, 2011; Merow *et al.*, 2013). Finally, we considered the area under the receiver operating characteristic curve (AUC) as the criterion for the training data and act as a measure for the model's ability to discriminate 'present' from 'absent' at each point. The value of AUC ranges between 0 and 1. A model with no ability to discriminate should return an AUC of 0.5; an AUC greater than 0.5 indicates that the model is better than random; and a value close to 1 indicates near perfect accuracy of the model (Phillips and Dudik, 2008). These threshold values produced a potential species distribution map that we regrouped into two classes: high potential (>0.5) and low potential (<0.005) (Abolmaali *et al.*, 2018).

Climate data under the present and future change scenarios

To evaluate the potential future distribution of species for the year 2050 (average for 2046–2065), we projected the model using MaxEnt (Morueta-Holme *et al.*, 2010). Global coupled Atmospheric-Ocean General Circulation Models (GCMs) are essential tools in theoretical investigations of climatic change mechanisms (Covey *et al.*, 2003). By using GCMs from http://www.ccafs-climate.org/, we can simulate the present and project future climatic changes under different scenarios. We used the CCSM 4.0 (Community Climate System Model) simulations for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) in 44 CC (Climate Change) scenarios to predict habitat suitability of species in Iran (Pendergrass and Hartmann, 2012). All layers were downloaded in 30 arc-second resolutions and cropped for Iranian boundaries using ArcGIS v.10.3. Based on different inputs of greenhouse gas emission drivers (i.e. population and economic growth, and technological choices), land use changes, environmental policy options, and adaptation processes (Solomon *et al.*, 2007), the IPCC recommended four representative concentration pathways (RCPs) (Miao *et al.*, 2014). The RCPs are consistent with a wide range of possible changes in future anthropogenic, greenhouse gas (GHG) emissions, and aim to represent the atmospheric concentrations. We considered RCPs v.2.6 and 6, which described a possible future range of energy states for the earth on the basis of different trends in climate change drivers.

RESULTS

Based on the Pearson correlation coefficient results, we ran the MaxEnt model in seven layers. Table 1 records the layers we selected. The ecological niche modelling output based on the model calibration results for testing data was 0.7862 (standard deviation = 0.1032). The following had the most marked effect on the model's output:

- mean temperature of warmest quarter (percentage contribution value (PC): 54.12% and permutation importance value (PIMP): 7.92%);
- precipitation of driest month (PC: 13.90%, PIMP: 1.38%);
- precipitation seasonality (PC: 10.02%, PIMP: 27.88%);
- mean temperature of wettest quarter (PC: 9.53%, PIMP: 40.38%).

Environments with high temperatures and low rainfall were most likely to harbour the species (Fig. 1). The Khuzestan plain in southwest Iran, the coastal area of southeast Iran, southeast Dasht-e Kavir (the Great Salt Desert) in Kerman province, as well as central and northeastern areas in Sistan and Baluchestan province were the most suitable habitats for *T. indica* (Fig. 2). Figure 3 shows the potential distribution map of the MaxEnt model by CCSM4 and RCP45. The potential distribution map of *T. indica* in the future shows a remarkable expansion outwards from currently suitable areas, with shifts into the southwest, central, and northeast of the country. Meanwhile, the south of Iran will remain suitable.

Table 1. Bioclimatic variables used to develop the distribution model in MaxEnt. Contribution ratio (%) and permutation importance value for each layer are also shown

Variable	Percentage contribution	Permutation importance
Bio10 (mean temperature of warmest quarter)	54.12	7.92
Bio14 (precipitation of driest month)	13.90	1.38
Bio15 (precipitation seasonality; coefficient of variation)	10.02	27.88
Bio8 (mean temperature of wettest quarter)	9.53	40.38
Bio3 (isothermality)	5.36	3.14
Bio12 (annual precipitation)	4.27	8.64
Bio2 (mean diurnal range; mean of monthly [maximum – minimum] temperature)	2.79	10.67

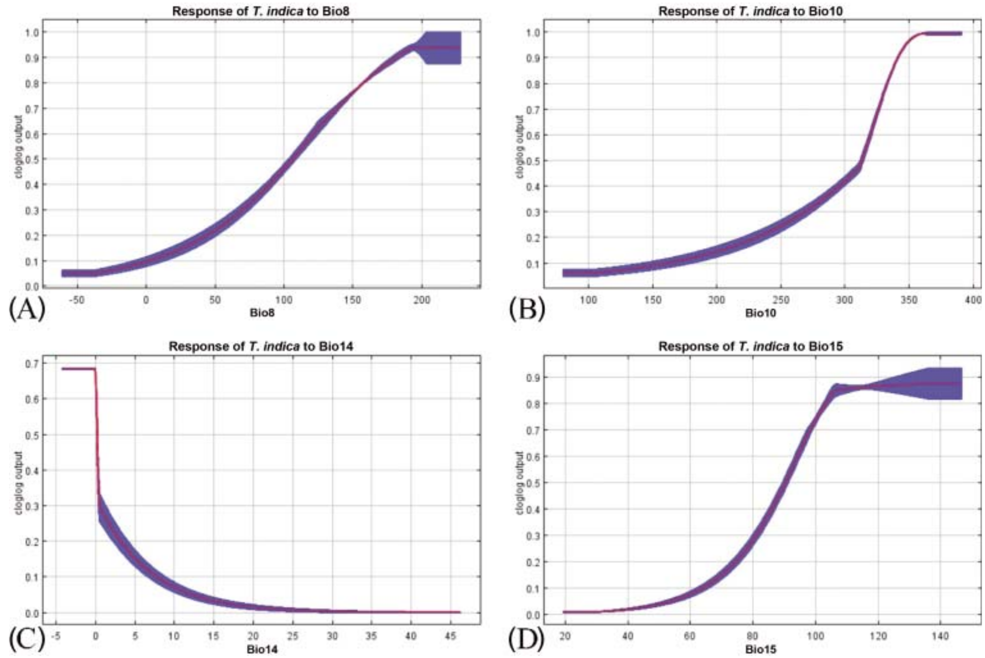

Fig. 1. The response curves of four variables with the greatest effect on the output of the model of current conditions. (A) Bio8: mean temperature of wettest quarter (in °C × 10); (B) Bio10: mean temperature of warmest quarter (in °C × 10); (C) Bio14: precipitation of driest month (in mm); (D) Bio15: precipitation seasonality (coefficient of variation) (%).

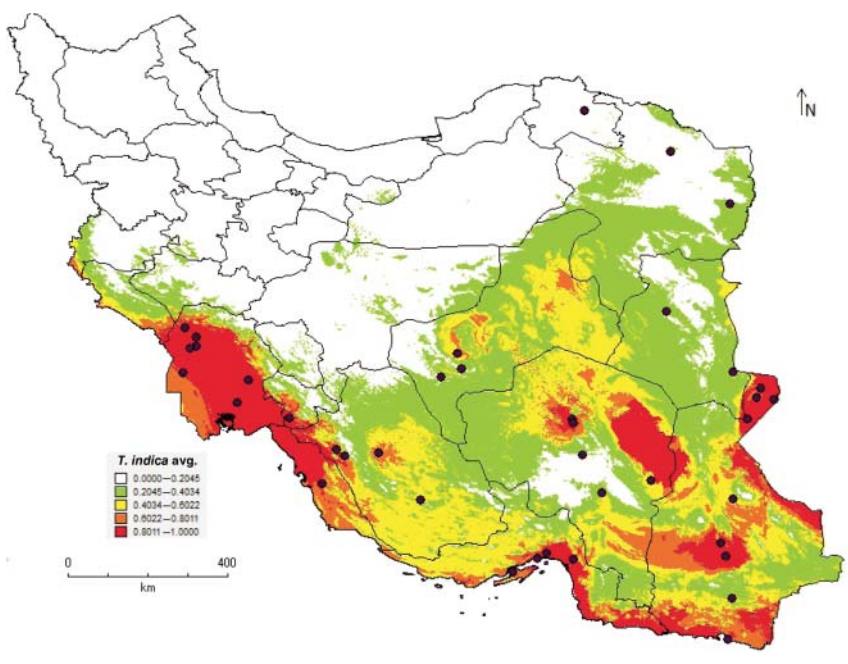

Fig. 2. Potential distribution map of the Indian gerbil, *Tatera indica*, and its classified map in the present. Black dots indicate the localities.

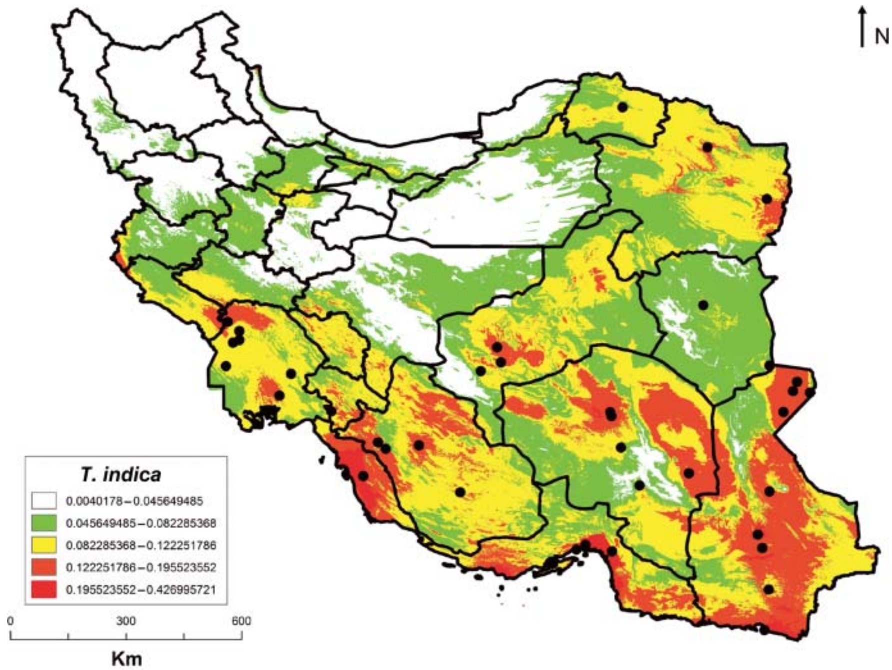

Fig. 3. Potential distribution map of the Indian gerbil, *Tatera indica*, and its classified map in the future. Black dots indicate the localities.

DISCUSSION

Species distribution patterns are among the most prominent issues in biodiversity management (Tittensor *et al.*, 2014). Distribution models have provided a new tool to explore diverse questions about species distributions (Nally and Fleishman, 2004). More specifically, investigating these patterns for host reservoir species helps us to use them for public health purposes. In spite of the growing number of GIS-based studies of leishmaniasis vectors, especially wild rodent hosts, only a few studies have been conducted in Iran (Ghatee *et al.*, 2013; Mollalo *et al.*, 2015; Fakhar *et al.*, 2017).

Zoonotic cutaneous leishmaniasis is an endemic zoonosis in many rural districts of Iran. The Indian gerbil, *Tatera indica*, together with sandflies of the genus *Phlebotomus* play a major role in the transmission of the pathogen (Mehrabani *et al.*, 2007; Ghatee *et al.*, 2017). Published literature shows that *T. indica*, in southern and southwestern Iran, is one of the main reservoir hosts (Gholamrezaei *et al.*, 2016). Our own output distribution map shows that the more southern parts of Iran have the largest amount of suitable habitat for *T. indica*. According to the response curves, increases in rainfall and decreases in temperature will result in the significant decline of its presence probability (Fig. 1).

Epidemiological research has shown that temperature and precipitation affect the distribution of tick-borne diseases (Gage *et al.*, 2008). Recent studies have illustrated that the geographical distribution of vectors and reservoirs of leishmaniasis can be affected by environmental variables (weather parameters, vegetation and topography changes) (Patz and Olson, 2006) and man-made disturbances (e.g. urbanization). Another important factor in the distribution of *T. indica* is seasonality of precipitation (coefficient of variation). This variation stems mainly from the fact that these areas are near the sea and show coastal climate conditions – mild climate with hot summers and cool winters, high seasonal precipitation, and temperatures averaging about 50°C (Islamic Republic of Iran Meteorological Organization Site, at http://www.irimo.ir/). In agreement with Molur *et al.* (2005), we confirm that this species lives in a range of dry or arid habitats with sparse or low density of vegetation, from low elevations in the south and centre to the northern part of Iran. When we overlaid our predicted distribution map on the map of Iran's biotopes, we could also see that *T. indica* prefers 'hot dry desert', 'hot semi-desert', and 'coastal dry' climatic zones (http://www.irimo.ir/). The average elevation of the observed localities in our study is 755 m a.s.l. (maximum elevation 2800 m a.s.l., only two points above 2000 m, and a minimum value of 4 m a.s.l.). The Indian gerbil is a warm area species that penetrated Torbat-e Jam in the northeast of Iran (Razavi Khorasan province) (Darvish and Rastegar-Pouyani, 2012).

A half century ago, the northeasternmost part of the range of *T. indica* was the Tabas region (South Khorasan province) (Misonne, 1959). But recent data indicate that *T. indica* is expanding further northeast, probably due to the effects of global warming and drought. The climate changes in Iran have increased attention towards the impact of climate change on the incidence and prevalence of cutaneous leishmaniasis in different provinces of Iran (Alvar *et al.*, 2012; Mollalo *et al.*, 2015; Ramezankhani *et al.*, 2017).

Climate change scenarios help us predict future conditions, prepare to face them, and plan better so that we may prevent disease. The future distribution showed that in Iran suitable habitats for the Indian gerbil will increase considerably outwards toward the southwest, centre, and northeast. The impact of climatic factors on the outbreak of leishmaniasis in the west of Iran showed that there was a significant negative correlation between the temperature and disease incidence, with leishmaniasis peaking in October and November. However, there is no significant correlation between disease outbreak and rainfall or relative humidity (Yazdanpanah *et al.*, 2013).

In a similar study, Akbari *et al.* (2014) showed that the highest incidence of the disease happened during the second half of the year (especially in the autumn; between October to December in Razavi Khorasan, northeast Iran). Moreover, they noted a weak positive correlation with relative humidity and rainfall, and a weak inverse correlation with sunshine and temperature. However, Entezari and Eskandari (2014) showed that zoonotic cutaneous leishmaniasis had the highest incidence and prevalence in January and February in Fars province. In analysing bioclimatic factors epidemiologically, Githeko *et al.* (2000) showed that temperature and hours of sunshine must play a fundamental role in the transmission of vector-borne diseases; these show a direct relationship with the prevalence of disease. Moreover, rainfall and relative humidity had an inverse correlation. On the other hand, the impact of vegetation cover on the incidence of leishmaniasis and the life cycle of sandflies was studied in Yazd-Ardakan Plain. Comparing spatial models of human disease with vegetation cover showed that the highest incidence of cutaneous leishmaniasis was concentrated in areas with sparse or low density of vegetation (Mozaffari *et al.*, 2012). Bavia *et al.* (2005) showed similar results in correlation analysis between sandflies and vegetation density of mosquitoes in Brazil.

Generally, the Indian gerbil lives in colonies. Its external morphology overlaps that of many species of *Meriones* (especially with Sundevall's jird, *M. crassus*, with which it co-occurs). These several species constitute alternative reservoirs for zoonotic diseases such as leishmaniasis (Fig. 4).

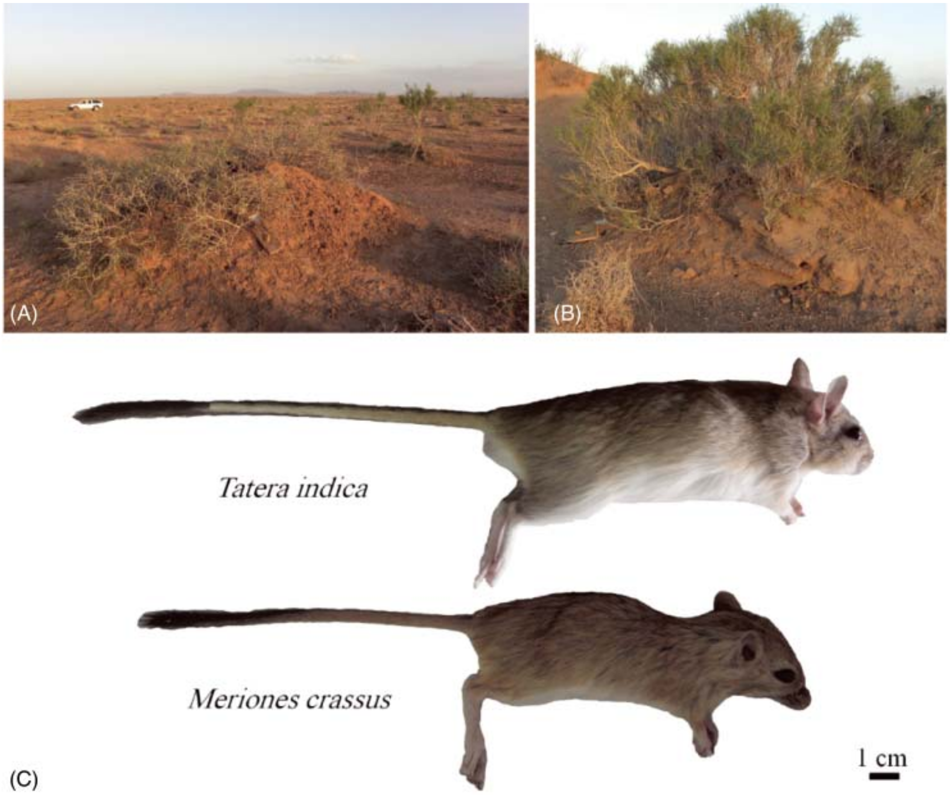

Fig. 4. (A) Habitat and vegetation cover of the Indian gerbil (*Tatera indica*) and Sundevall's jird (*Meriones crassus*), two gerbilline rodents that often co-occur. Both are reservoirs for leishmaniasis. Ferdows county, South Khorasan province, Iran. (B) Burrow entrances of a colony of *T. indica*. (C) Comparison of external morphology of *T. indica* and *M. crassus*. The main diagnostic character is the dual-coloured tail (dark colour above and below, pale at the sides) of *T. indica*.

The main diagnostic characters which distinguish *T. indica* from other gerbilline rodents are its tail colour (dark above and below, but pale at the sides); its tail sometimes being slightly shorter than its head and body length; and its hind feet having naked soles (Baramaki Yazdi *et al.*, 2011). So it can be difficult to discriminate from jirds in the field. And accurate identification is made no easier when we consider the great overlap of the habitats of different species of jirds and gerbils. Perhaps these similarities have even resulted in misidentification of the species. This, along with inadequate information about the ecological distribution of *T. indica* populations and its habitat structure (and also those of other gerbillines) are among the factors that may result in difficulties in the study of *Leishmania* outbreaks, and programmes to manage it by controlling its reservoir hosts. However, undertaking such studies is crucial to public health.

CONCLUSION

The Indian gerbil, *Tatera indica*, harbours several ectoparasites such as mites (e.g. *Dermanyssus americanus*, *Echinolaelaps echidninus*, *Haemolaelaps glasgowi*, *Laelaps nuttalli*, and *Ornithonyssus bacoti*), fleas (mainly *Xenopsylla buxtoni*), and lice species (such as *Polyplax gerbilli* and *Rhipicephalus* sp.) (Hanafi-Bojd *et al.*, 2007; Hamidi *et al.*, 2015, 2016). Reasonably accurate prediction of its distribution as well as the role of bioclimatic factors in its presence will be valuable for preventing zoonoses and is vital to programmes attempting to control zoonotic arthropod-borne diseases.

Some zoonotic infections have no vaccine and lack specific drugs for their treatment. Hence it is better to prevent the outbreak of a disease than to try to get rid of it once it has begun (Oglesbee, 2011). In a world with unusually rapid climatic change, our results can be used to improve prevention by anticipating which places will become havens for the rodent and so require enhanced public health defences.

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