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ORIGINAL ARTICLE

Potential invasion range of raccoon in Iran under climate change

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Abstract

Growing global evidence demonstrates that not only the invasion of alien species has imposed serious threats to native biodiversity, but it also threatens health and economics. The raccoon (*Procyon lotor*), medium-sized mammal, native to North America, as a result of escapes or deliberate introductions in the mid-twentieth century, is now distributed across much of mainland Europe and the Caucasus and known as an alien invasive species. The raccoon was observed and reported for the first time in 1991 in the Caspian Hyrcanian mixed forests ecoregion in Iran, near the border of Azerbaijan. Although it has been almost three decades since the first report in the northwest of the country, there are not many official reports nor scientific research on its dispersal and adaptive behaviour. In this study, we provide new evidence on the current distribution range and predict the potential distribution range and thus invasion risk of the raccoon under climate change in Iran. We trained an ensemble of species distribution models trained in native and European invaded range and transferred it over space and time to Iran in 6 future climate scenarios. We also calculated the potential dispersal range of the raccoon per year and explored potential invasion corridors. Our results show that the raccoon inclined to expand in the forests and rangelands near the Caspian Sea and toward west Iran. Our work provides evidence to conservationists and decision-makers to further focus on the areas where the species will most likely expand, under the future scenarios of the climate change in 2050.

Keywords Alien invasive species · Climate change scenarios · *Procyon lotor* · Species distribution model · Species dispersal

Introduction

Reliable information on the distribution of alien species is crucial for biodiversity monitoring and conservation management (Dornelas et al. 2014). Knowledge about the potential distribution of the alien species is also required by conservation managers for better planning in the decision-making of tasks such as bio-security (Catford et al. 2012), the identification of entry points (Seebens et al. 2013), the quantification of impacts posed by invasive alien species (Blackburn and Steele 1999), or the assessment of the ecological degradation of habitats (Vandekerkhove et al. 2013). Growing global evidence demonstrates that not only the invasion of alien species has imposed serious threats to native biodiversity (Usher 1988; Westman 1990; Groom et al. 2006; Sinkins and Otfinowski 2012), it also threats health and economics (Scalera et al. 2012).

The raccoon (*Procyon lotor*), medium-sized mammal, native to North America, as a result of escapes or deliberate introductions in the mid-twentieth century, is now distributed across much of mainland Europe and Caucasus (Sherman 1954; Aliev and Sanderson 1966; Michler and Hohmann 2005; DAISIE 2008). Although most unintentional introductions of the raccoon in eastern Europe did not reach a viable population in the past (Bartoszewicz et al. 2008), the recent investigations showed that the species had a trend of range expansion toward the south and east of the continent. Also, in the western and middle regions of Europe, this carnivore successfully increased in population size (Frantz et al. 2005; Canova and Rossi 2009). Today, the population growth and dispersal of the raccoon has become a real concern in the new regions (Ikeda et al. 2004; Biedrzycka et al. 2014). In 1991, for the first time, the raccoon was observed and reported, in the Caspian Hyrcanian mixed forests ecoregion in Iran, near

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the border of Azerbaijan (Farashi et al. 2013). Since then, scattered observation records of this species indicated that the distribution of raccoon is not only confined to the forests and woodlands but has been extended toward Elburz Range forest steppe and urban areas in the south and in the east of the ecoregion.

Considering the adaptability of the alien species to the physical and biological conditions of the invaded rage, the stage of invasion, known as invasion pathway (Hellmann et al. 2008), varies and might be altered by the changes in the environmental conditions. Invasive alien species are compounded by climate change. Climate change might facilitate dispersal and establishment of species and creates new opportunities for them to become invasive, or hinder the process and reduce the suitability, thus invasion range of the species. The response of invasive species to climate change will have ecological and economic implications, too (Hellmann et al. 2008). Due to potential impacts of alien species on environmental changes, early detection and rapid response initiatives are suggested a crucial ingredient of integrated programs for dealing with invasive species (Pyšek and Richardson 2010). Therefore, it is essential to understand and predict the impacts of climate change on invasive species. Although little is known about the potential environmental impacts of the raccoon introduction into Europe (Beltrán-Beck et al. 2012), anecdotal evidence suggests that the species may threaten reptiles and amphibians and may, therefore, impact conservation projects (Kauhala 1996; Frantz et al. 2005).

Although it has been a long time since the raccoon was observed and recorded in northwest of Iran, there are not many official reports or scientific research on its adaptive behaviour. In addition, it has been speculated that the raccoon had migrated from Azerbaijan (Farashi and Naderi 2017) and is expanding from west to east. Apart from frequent local media reports, there are few reports or confirmed evidence of the raccoon direct damages to the croplands to the agriculture insurance companies.

The capability of raccoon coping with a variety of environmental conditions due to its opportunistic habits may make another extensive invasion success in Iran too. The old deciduous forests close to watercourses, wetlands or lakes are the raccoon's preferred habitats (Kaufmann 1982). However, this species may also survive and settle in diverse habitats ranging from partly open and marshy ground to urbanized areas where food is available (Sanderson 1987; Zeveloff and Dewitte 2002). The raccoon's adaptability and the food availability (e.g. domestic wastes) in populated and dense rural and urban areas in northern regions of Iran may march up the invasion rate.

In this study, we aim to provide reliable information on the potential invasive range of raccoon in Iran. Therefore, we trained a global ensemble of species distribution models based on the available species data in native North America and invaded European ranges and then transferred it over time and space to predict potential invasion range of the raccoon in the mainland of Iran under different climate change scenarios.

Materials and methods

Study area

Iran is a heterogeneous country with a diverse climate ranging from arid and semi-arid to subtropical along the Caspian Hyrcanian mixed forests, which rarely experience freezing nights and remain humid for the rest of the year. To the west, the Zagros Mountains forest steppe ecoregion supporting oak-dominant deciduous and pistachio-almond forests experiences relatively lower temperature and severe winters with heavy snowfall. The coastal plains of the Persian Gulf and the Gulf of Oman are the Nubo-Sindian desert and semi-desert dominated by xeric shrublands with mild winters and very humid and hot summers.

We set 3 geographical extents for the modelling practices; Iran (hereinafter called IR) which we obtained the country border from GADM (https://gadm.org/ version 3.6), the native habitat of raccoon in North America (hereinafter called NA) and the invaded range in Europe (hereinafter called EU).

Environmental predictors

To allow for projections over time, the selection of the environmental predictors as input for the SDMs was limited to climatic variables. We obtained the 19 bioclimatic variables for current climate from the WorldClim (Hijmans et al. 2005) database averaged over the years 1950–2000 and the future climate averaged over the years 2041–2060. Altogether, 6 different climate scenarios were considered, including the three Generalized Circulation Models (GCM) CCSM4, HadGEM2-AO and MPI-ESM-LR and the three Representative Concentration Pathways (RCP) RCP2.6 (i.e. low concentration) and RCP8.5 (i.e. high concentration), representing an anthropogenic radiative forcing of 2.6 and 8.5 watts per square meter across the planet, respectively.

To avoid potential problems that the multicollinearity issue may cause model parameterisation and inference, all predictors were checked for multicollinearity by calculating the variance inflation factor (VIF). While there is an ongoing debate about the threshold above which correction for multicollinearity ought to be considered, we took 10 as the threshold value to be considered for multicollinearity (Hair Jr et al. 1995; Menard 2002).

Species occurrence data

Since the early 90s that the raccoon was first recorded in Iran, very few official (i.e. confirmed) recorders were reported by the authorities. However, there are several unofficial records being reported by locals either killed or photographed. With a systematic web search in social networks, news and media in Farsi and English, we collected over 100 fragmented records of the raccoon in Iran. We took records with solid evidence (e.g. photos and videos), or from locations with multiple records, or with a report by an expert. We also compared our observation list with the previous efforts (Farashi et al. 2013; Farashi and Naderi 2017). In the end, we used 48 records of raccoon in Iran in our modelling practices.

We obtained a dataset for occurrence records of raccoon within the native habitat range (i.e. NA) and invaded range in Europe (i.e. EU) from the Global Biodiversity Information Facility. The North America dataset is consist of more than 10,000 occurrence records (GBIF.org 2020a) and the Europe dataset (i.e. EU) contains 7500 occurrences (GBIF.org 2020b). Since the species occurrence records included species presences only and most of the modelling methods required a binary, absence-presence, data structure and pseudo-absence occurrences were generated randomly in the extent of the training data.

Species distribution models

The diversity of species distribution models has been constantly growing over the last few decades. While there has been considerable praise for each of them (Drake et al. 2006; Elith et al. 2006; Merow et al. 2014), the selection of an appropriate method for studies on distribution modelling requires extra attention which might result in a significantly different outcome, and often not possible to judge which of the algorithms will perform best. There are, however, recommendations to employ multiple modelling methods (i.e. a model ensemble) which combines different models and provides information about the overall output and the uncertainty around it (Seoane et al. 2005; Araújo and New 2007). To this end, we set up an ensemble approach consisting of 4 modelling methods: generalized linear models (GLM; McCullagh and Nelder 1989), generalized additive models (GAM; Hasties and Tibshirani 1990), boosted regression trees (BRT; Friedman 2001) and random forests (RF; Breiman 2001). To identify the current realized distribution range of raccoon in Iran, we employed MaxEnt (Phillips et al. 2006). We keep the parameters of the MaxEnt as default, except the regularization multiplier which were set to 3 to further increase the fit to the current presence occurrences.

Model evaluation

We evaluated the performance of the SDMs with their discrimination power. The discrimination power of an SDM is its ability to recognize a distinction between 'presence' versus 'absence' (Hosmer and Lemeshow 2000). The area under the curve (AUC) of the receiver operating characteristic (ROC) plot was computed in order to assess the discrimination power of the models for each data set. A ROC curve plots sensitivity values (i.e. a true positive fraction) on the y-axis against 1—specificity values (i.e. a false positive fraction) for all the thresholds on the x-axis. Sensitivity is the probability that the model correctly predicts an observation, while specificity is the probability that a known absence site is correctly predicted. The plot in ROC space of sensitivity versus specificity displays how well an algorithm classifies instances as the threshold changes. The AUC is a single measure of a model's discrimination power, which provides a threshold-independent measure across all the possible classification thresholds for each model (Fielding and Bell 1997). We randomly split the data, 70% of which were used to train the models and the remaining 30% of which were used to measure their discrimination power.

We assessed the calibration (Hosmer and Lemeshow 2000) of the models using Miller's calibration statistic (Miller et al. 1991; Pearce and Ferrier 2000) for the global ensemble of the trained models. Miller's calibration statistic evaluates the ability of a distribution model to correctly predict the proportion of species occurrences with a given environmental profile. It is based on the hypothesis that the calibration line—perfect calibration—has an intercept of 0 and a slope of 1. The calibration plot shows the model's estimated probability (x-axis) against the mean observed proportion of positive cases (y-axis) for equally sized probability intervals (number of intervals = 10). We then calculated the root mean square error (RMSE) of the calibration plot (Armstrong and Collopy 1992) for the ensemble using calibration function in Naimi and Araújo (2016).

Species dispersal

We estimated an annual dispersal range for the raccoon using the empirical model developed by Santini et al. (2013). They proposed a linear model for applicative purposes representing the relationship between dispersal distance and body size or home range area (Santini et al. 2013);

$$\text{Mean dispersal} = 5.78 \times B^{-}0.03 \times H^{0}.19$$

where B is the body size in kilogramme and H is home range.

There is a wide range of values reported for the body size and the home range of the raccoon in their native and invaded

Table 1 Environmental variables used in the SDMs

Predictors' code	Predictors' name	VIF value in NA	Range in NA	Range in EU	Range in EU not covered in NA	Range in EU + NA	Range in IR	Range in IR not covered in EU + NA
Bio 2	Mean diurnal range	2.55	60–213	43–107	43–60 *	43–213	64–175	All covered
Bio 7	Temperature annual range (BIO5-BIO6)	3.57	11.9–50.8	18.4–32.4	All covered	11.9–50.8	19.3–44.8	All covered
Bio 8	Mean temperature of wettest quarter	3.87	− 11.5–33.1	− 10.1–20.6	All covered	− 11.5–33.1	− 6.7–25.4	All covered
Bio 9	Mean temperature of driest quarter	5.63	− 16.1–32.2	− 10.2–22.8	All covered	− 16.1–32.2	− 9.7–36.5	32.2–36.5
Bio 10	Mean temperature of warmest quarter	4.12	5.0–35.7	0.9–23.4	0.9–50 *	0.9–35.7	7.1–36.5	35.7–36.5
Bio 13	Precipitation of wettest month	3.25	7–551	52–225	All covered	0.7–55.1	1.1–27.1	All covered
Bio 14	Precipitation of driest month	7.47	0–152	19–166	152–166 *	0–166	0–42	All covered
Bio 15	Precipitation seasonality	5.29	6–133	7–47	All covered	6–133	29–137	13.3–13.7
Bio 18	Precipitation of warmest quarter	4.65	1–728	135–575	All covered	1–728	0–261	0–1

areas. We assumed the home range area of 0.4 km^2 based on IUCN red list of threatened species (Timm et al. 2016) and the body size of 3 kg following the Atlas of Mammals of Iran (Karami et al. 2016). The annual dispersal range of 4.38 km is a conservative estimate as our inputs were. This means that we assumed expansion of about 43 km in every decade around the current geographical range through the potential habitat corridors.

Experimental settings

Our aim was to train a reliable ensemble model based on the native and the invaded range (i.e. NA + EU) for the current climatic condition that can predict the potentially suitable habitat of raccoon in IR; then to transfer the trained model over time to investigate the potential suitable habitat of raccoon in the near future under climate change; and finally by comparing the current realized suitable habitat and the future potential habitat, considering the land cover and accessibility and taking into account the dispersal (i.e. invasion) speed, we prepared an invasion path and discussed priorities of conservation actions for raccoons in Iran. The procedure to implement our work was as follows:

1. Accounting for multicollinearity. We first calculated the VIF, and 9 out of 19 bioclimatic variables had values less than 10 and were taken into the modelling procedure (Table 1).
2. Train and evaluate SDMs in NA. We set up an ensemble based on a set of trained models using occurrence records obtained from GBIF as presences and pseudo-absences sampled randomly from NA. We trained and evaluated them through 100 runs of subsampling, each draws 30% of training data as test dataset. We set our ensemble based on a weighted averaging, using AUC statistic with threshold criterion maximum sensitivity plus specificity.
3. Transfer the NA model to EU. We used the points obtained from GFIB for the invaded range in Europe to evaluate the performance of the ensemble trained in the native extent (i.e. NA) in the invaded extent (i.e. EU). We further investigated the extremes in the bioclimatic variables in EU that the NA model were unable to discriminate. We evaluated the performance of the ensemble with its discrimination capacity.
4. Train a global model. We used the observations from the native (i.e. NA) and the invaded (i.e. EU) extents to train a "global ensemble of trained models" for the raccoon and evaluated the performance of the ensemble with its discrimination capacity and calibration.
5. Transfer the ensemble to IR. The global ensemble of trained models of raccoon was transferred to IR to predict potentially suitable habitat of the raccoon in Iran. We used independently collected observation records to evaluate the prediction of the model.
6. Transfer over time. We also transferred the ensemble of trained models in IR over time to predict potentially suitable habitat of the raccoon in Iran under climate change scenarios. We calculated the maximum and minimum invasion potential map for Iran in 2050.
7. Realized distribution in Iran. We trained MaxEnt (i.e. presence-only) models using the collected observation records to predict the realized distribution (i.e. current geographical range) of the raccoon in Iran. We used the maximum sum of sensitivity and specificity as the threshold to

generate a binary map of realized distribution (Liu et al. 2013). Then we cropped the potential distribution with the binary map.

8. Estimated dispersal range in 2050. We calculate 4.38 km as the potential dispersal range per year and therefor draw a buffer of 175 km (i.e. 4.38 km/year in 40 years) around the current realized distribution of the raccoon to identify and discuss the potential invasion paths.

All models were executed in the R environment v.3.4.4 (R Core Team 2018) using the *sdm* (Naimi and Araújo 2016), *dismo* (Hijmans et al. 2013), *raster* (Hijmans et al. 2015), sp. (Pebesma and Bivand 2005), maptools (Bivand and Lewin-Koh 2013) and usdm (Naimi 2015) packages.

Results

The global ensemble of trained models

We built an ensemble of distribution models for raccoon in its native habitat with about 10,000 observation records and 9 bioclimatic variables: mean diurnal range, temperature annual range, mean temperature of wettest quarter, mean temperature of driest quarter, mean temperature of warmest quarter, precipitation of driest month, precipitation seasonality, precipitation of warmest quarter and precipitation of coldest quarter. See Table 1 for predictors' details and Fig. 1A for the distribution points.

Among all of the 4 models that we employed in our ensemble approach, the RF models overperformed others with the mean AUC of 0.97 (StDev = 0.08) followed by the GAM and

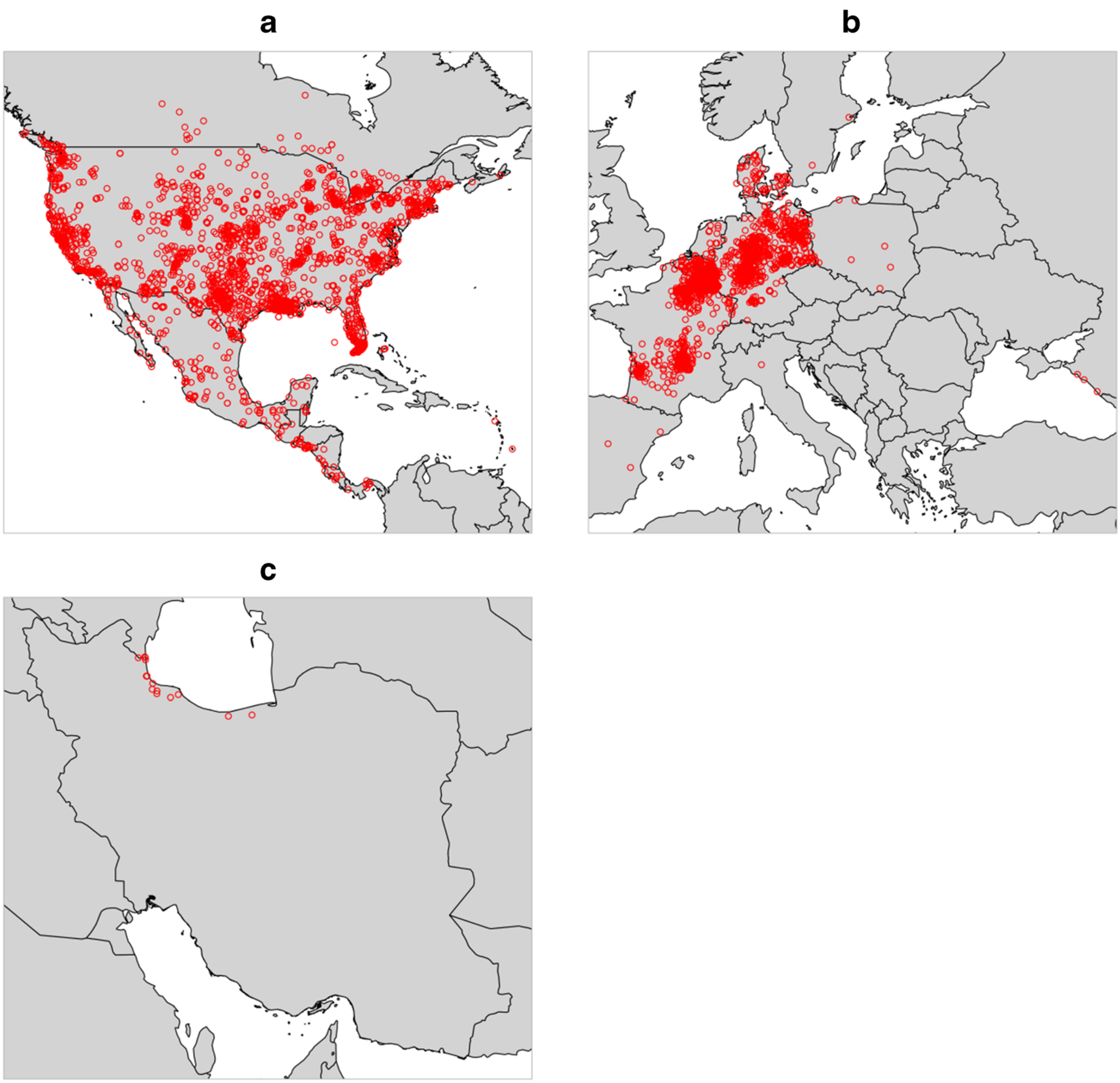


Fig. 1 Distribution of observation records (red circles) of the raccoon: (A) in its native habitat (i.e. North America), (B) in the invaded habitat in European, and (C) in Iran

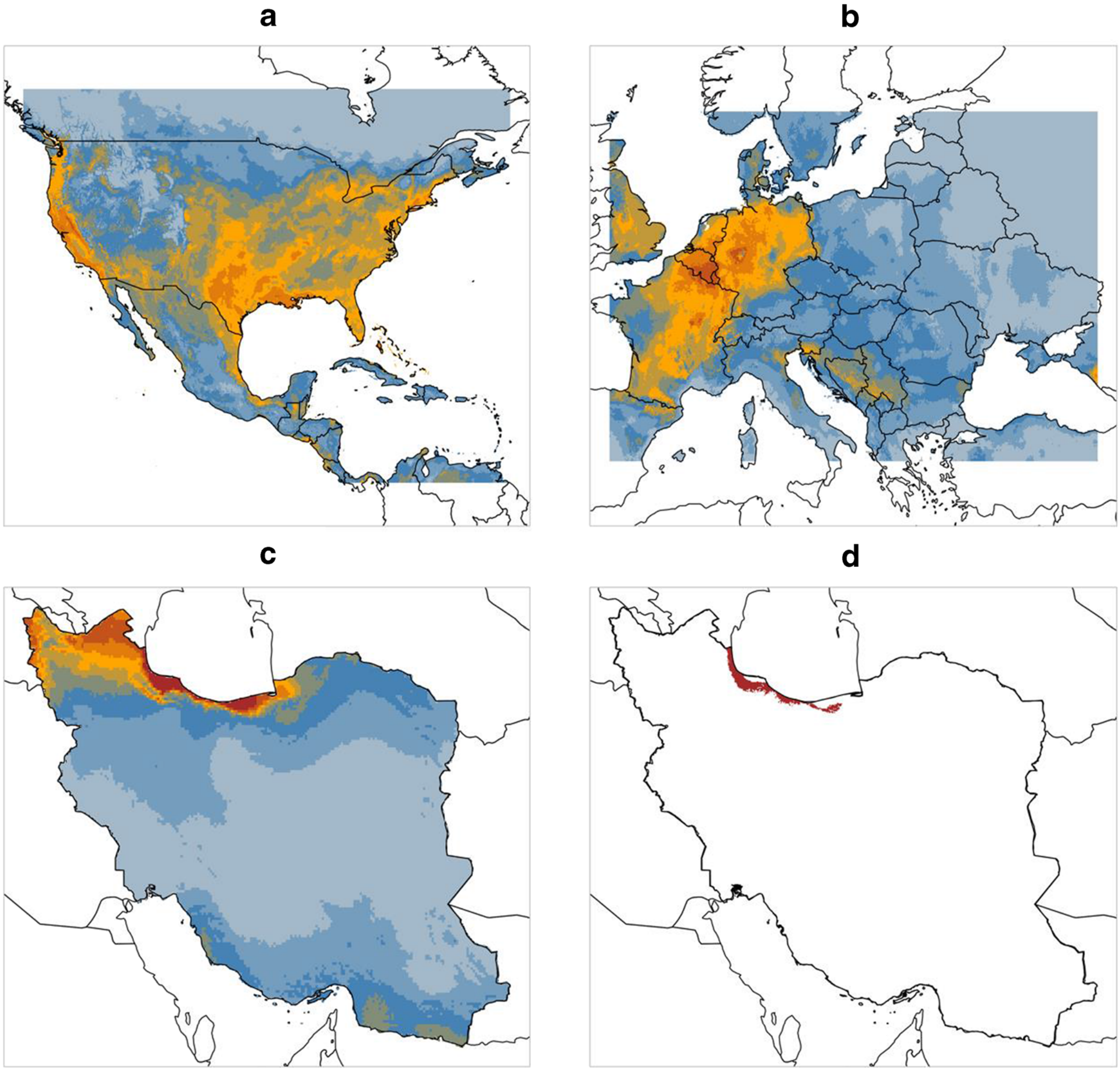


Fig. 2 Potential distribution of raccoon: (A) in NA (i.e. the native habitat in North America) based on the SDMs trained by species occurrence records in NA, (B) in EU (i.e. the invaded European habitat) based on the SDMs trained by species occurrence records in NA + EU, and (C) in IR (i.e. the invaded habitat in Iran) based on the SDMs trained by species occurrence records in NA + EU. The dark orange illustrates relatively most suitable and the dark blue illustrated relatively least suitable habitats. The panel D shows the current realized distribution range of raccoon in Iran in dark orange

the BRT with mean AUC of 0.87 (StDev = 0.11) and 0.78 (StDev = 0.07), and the GLM models were performed with the lowest mean AUC of 0.75 (StDev = 0.14). The ensemble model performed with the mean AUC of 0.94 (StDev = 0.01) discriminating the suitable from the unsuitable habitat of the raccoon in NA (i.e. the native habitat in North America) (see Fig. 2A). When we transferred the NA model over space to EU (i.e. the invaded extent in Europe), it performed slightly better than a random model with mean AUC 0.59 (StDev = 0.08) mainly due to low sensitivity. But when we set up another ensemble of distribution models for raccoon using the occurrences in NA plus occurrences in EU ($n = 8000$), the discrimination capacity improved to mean AUC value of 0.84 (StDev = 0.05). Thereafter, we will refer to this model as our 'global model' (see Fig. 2B). The calibration plot of the global model stretched the completed extent of the suitability range revealing the goodness of fit of the model to correctly predict the proportion of species occurrences over time and space. The root mean square error (RMSE) of the global model was 0.09, slightly underestimating the suitability of habitat in low suitability values and slightly overestimating the high suitability values.

Transfer the global model over space and time

We transferred the global model over space to predict the habitat suitability of raccoon in Iran using 9 climatic predictors. On average, the AUC of the global model in IR was 0.69 (StDev = 0.18). The global model was successful to predict higher probability value to locations with observation records (i.e. high specificity) but failed to discriminate areas with no records of the raccoon (i.e. low sensitivity). This might be due to the fact that the climate condition in the other areas is still suitable for the raccoon but due to lack of access or biotic conditions has not been invaded yet. The potential distribution of raccoon in Iran shows that the tiny line of Hyrcanian mixed forest in the south of the Caspian sea has the highest climate suitability, followed the Zagros mountain forest steppe (see Fig. 2C). We also transferred the global model over time to predict the habitat suitability of the raccoon in 2050 over a variety of climate scenarios and calculate the changes in the probability values (Fig. 3).

Realized geographical range and dispersal corridors

To model the realized distribution, the area that raccoon actually lives, we trained MaxEnt models using all of the 48 observation records as described in the 'experimental settings'. To convert the gradient of occurrence to a binary map of realized distribution range, we calculated the threshold of maximum sensitivity plus specificity and assumed area with values above the threshold, as the current realized geographical range of raccoon in Iran (Fig. 2D). Comparing the geographical range with the potential habitat suitability under climate change revealed that climatic suitability in the realized distribution of raccoon in Iran decreases over all of the Generalized Circulation Models (GCM) and Representative Concentration Pathways (RCP). In contrast, the suitability of habitat for the raccoon in the Zagros Mountain Forest Steppe increased in all GCMs and over all RCPs.

We cropped the future potential distribution habitat suitability maps in the buffer of 175 km, assuming the maximum range of dispersal by 2050. Then, we compare the suitability of habitat in the future with the present conditions and removed areas that either are not suitable or the habitat suitability will significantly decrease by 2050, thus remains areas that could act as potential dispersal corridors (Fig. 4).

Discussions

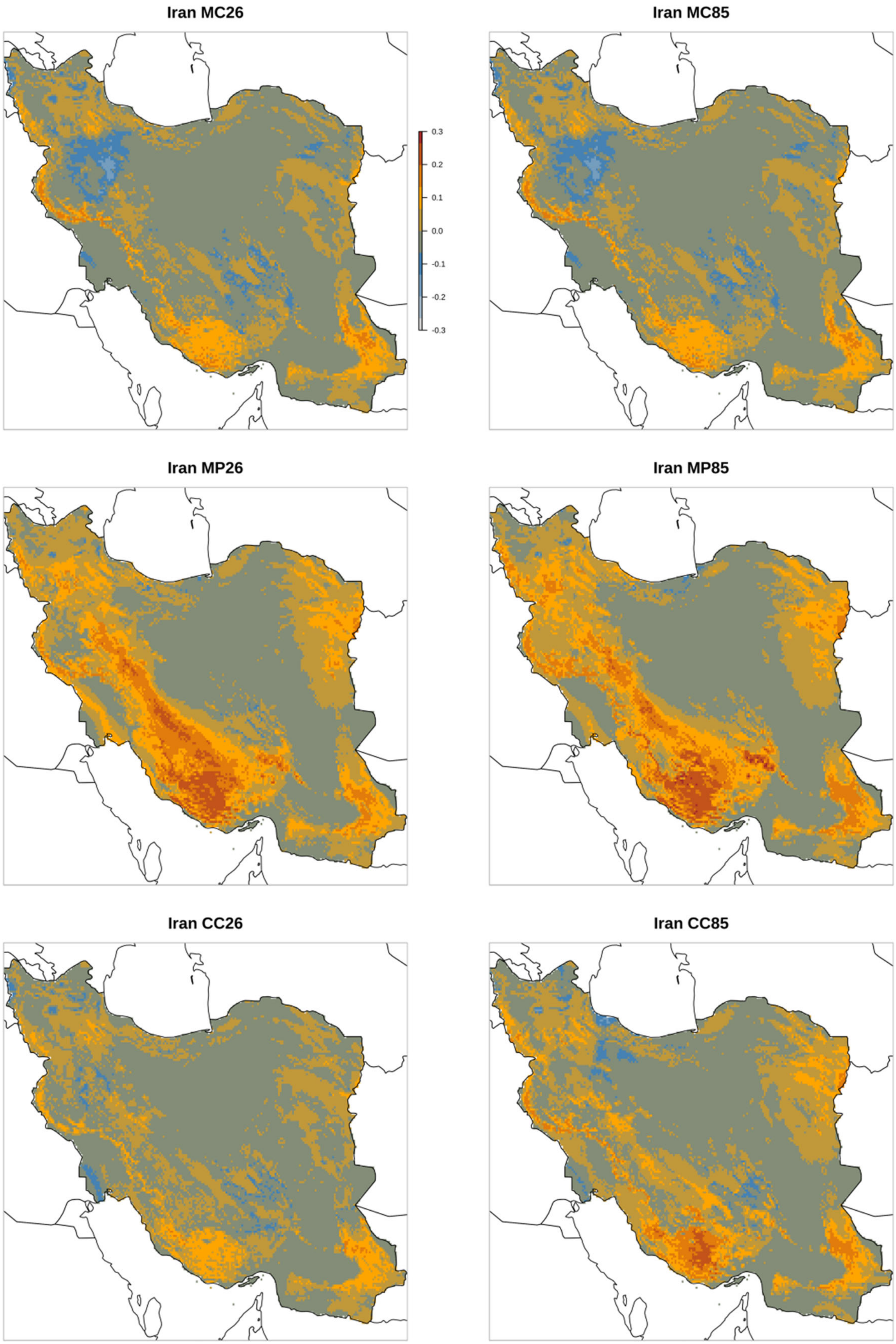
Our work provided new evidence on the current and future status of invasion risk of the raccoon in Iran. The predictions successfully identified worldwide occurrence records of the raccoon, including native (i.e. NA) and invaded regions (i.e. EU and IR), used in this study and demonstrated high areas predicted by previous studies such as Italy, Austria and Germany (Fischer et al. 2015; Mori et al. 2015; Farashi and Naderi 2017; Duscher et al. 2018). In addition, our realized distribution model illuminated the current distribution of this species, which is in line with the previous research carried out by Farashi and Naderi (2017), explaining the raccoon's population inclined to expand in the forests and rangelands near the Caspian Sea and some parts of western Iran. However, unlike the previous study, our realized model showed no signal of the raccoon's distribution in the central parts of the country; this might be due to complementary calibration of our models for the European extent.

Hellmann et al. (2008) argued that a species, to become invasive, needs to overcome new conditions. First, a species must pass major geographical obstacles to reach to a new location. Then, the species must survive in and adapt to the new environmental conditions at the arrival site. Third, a species must obtain critical resources, remain alive in interaction with natural enemies and likely form mutualistic relationships at the new location. Finally, the species must extend geographical distribution, establishing populations in new sites. This scenario will be less likely being applicable for the raccoon in Iran under the current climate conditions. Although the habitat conditions (i.e. old deciduous forests close to water) and food resources availability (i.e. wild plants, fruits berries, small rodents, frogs, eggs and domestic wastes in rural and urban areas) may provide advantages for the raccoon's dispersal toward the northern parts of Iran, the Elburz Mountain, at the southern edge of the current raccoon's range, is a great geographical obstacle for the species to pass and reach to new sites. However, the anthropogenic assistance (e.g. trade or unintentional transportation) may enable the raccoon to stretch out its distribution. The "Animal Rights activists" and press have been alerted with the increasing population size and the growth of trades and interests to keep the species as a pet (Khosravifard 2007; Animal Rights Watch 2015). This may alter the current distribution of this alien species in Iran.

The raccoon's habitat suitability calculated over the variety of climate scenarios in the year of 2050 illustrated that from north to south of the Zagros, mountains may become a destination and new location for the species. This new scenario along with the deliberate or undeliberate introduction of the raccoon should be considered in conservation and management plans.

Despite the anecdotal evidence suggesting that climate change is most likely to substantially increase the impact of current invasive species since many of them already spread a range of environmental conditions (Qian and Ricklefs 2006), our study illustrated that the future climate change scenarios are not in favour of the raccoon's distribution expansion. The abiotic variables (i.e. temperature and precipitation), which influence the raccoon's potential distribution, may slow down the future expansion of raccoon's range. This might provide conditions to have the population increased or maybe overpopulated in human settlements due to accessibility and abundance of food.

In Europe, the population growth of the raccoon is out of control because of increasing population trends, range


Iran MC26
Iran MC85
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
Iran MP26
Iran MP85
Iran CC26
Iran CC85

◀ **Fig. 3** Changes in the potential habitat suitability of raccoon in Iran under climate change scenarios. The gradient from light to dark orange illustrates increased relative habitat suitability and the gradient from light to dark blue illustrated decreased relative habitat suitability

expansion and no efficient management strategy. However, no ecological impacts have still been reported through an evidence-based approach (Salgado 2018). Although the negative impacts of the raccoon on native biodiversity are not yet reported and unknown in Iran, management and conservation plans are needed to prevent any possible or unforeseen threats. The prevention through legislation on pet trade, education and awareness-raising campaigns is suggested as the most efficient strategy for the raccoon's geographically expansion (Tollington et al. 2017). To eradicate the newly established population, early detection (using sign surveys and camera trapping) and rapid response (by trapping) may be carried out as measurable objectives (e.g. keeping the raccoon's population at low density) are considered. Control is a long-term management strategy and expensive and requires stable funding. Our study would assist conservationists and managers to focus on the areas where the species would most likely occur. This may ultimately lead to thrift for developing and executing management plans.

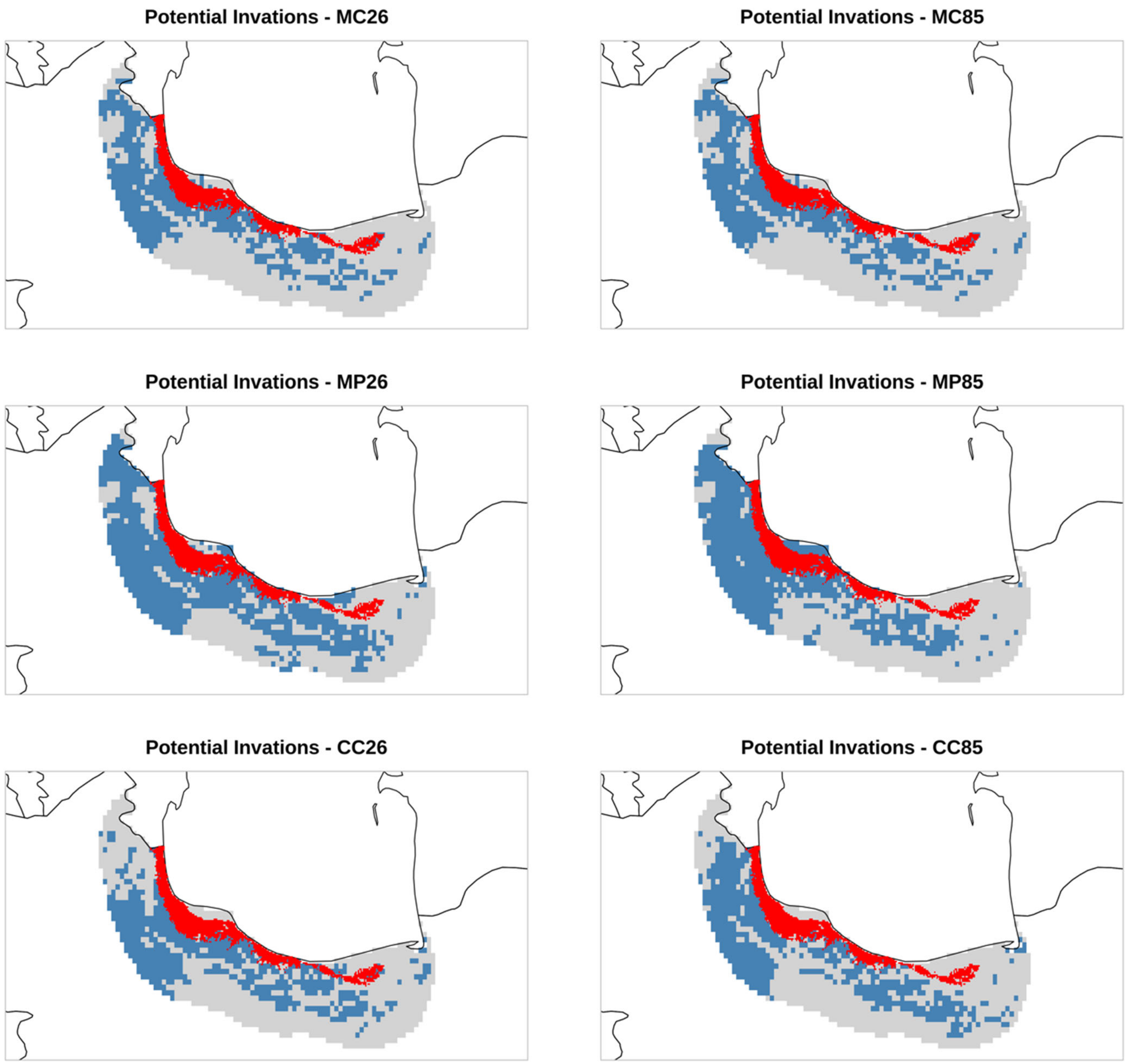


Fig. 4 Potential invasion corridors (in dark blue) of Raccoon in Iran under climate change. The current realized distribution range of raccoon in Iran in red. The panels show the extent of the potential dispersal range (~175 km) in year 2050. The grey areas are either not suitable or the habitat suitability will have a significant decrease over time

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