Received: 31 July 2019 | Revised: 22 May 2020 | Accepted: 28 May 2020

DOI: 10.1111/ddi.13117

BIODIVERSITY RESEARCH

Diversity and Distributions WILEY

Assessing future distribution, suitability of corridors and efficiency of protected areas to conserve vulnerable ungulates under climate change

Shima Malakoutikhah[1] | Sima Fakheran[1] | Mahmoud-Reza Hemami[1] | Mostafa Tarkesh[1] | Josef Senn[2]

[1]Department of Natural Resources, Isfahan University of Technology, Isfahan, Iran

[2]Swiss Federal Research Institute WSL, Birmensdorf, Switzerland

Correspondence
Shima Malakoutikhah, Department of Natural Resources, Isfahan University of Technology, Isfahan, Iran.
Email: s.malakouti@na.iut.ac.ir

Funding information
Iran National Science Foundation, Grant/Award Number: 95849735

Editor: José Brito

Abstract

Aim: Central part of Iran harbours populations of wild ungulates that are threatened or extinct over large parts of the region, and are likely to be impacted by climate change. In this study, we predicted the impact of climate change on the distribution of three vulnerable ungulates in central Iran. We then evaluated future suitability of corridors connecting the protected areas for movement of the ungulates in response to climate change.

Location: Central Iran.

Methods: Impact of climate change on distribution of goitered gazelle (*Gazella subgutturosa*), wild sheep (*Ovis* spp) and wild goat (*Capra aegagrus*) was predicted adapting an ensemble modelling approach and under the RCP 8.5 emission scenario. We then used CIRCUITSCAPE software with current and future distribution maps to identify corridors for movement of the three ungulates, and evaluate likely changes in their suitability under climate change.

Results: Our results revealed that climate change might result in loss of 55%, 69% and 76% of suitable habitats for goitered gazelle, wild sheep and wild goat by 2070, respectively. These losses also resulted in some protected areas to become unsuitable for the ungulates. However, we identified key protected areas with the potential for future protection of these ungulates. For the three species, we also identified corridors which would persist into the future, allowing the impacted populations to move in response to climate change.

Main conclusions: Conservation of ungulate populations in Iran mainly depends on the protected areas. To maintain the role of the protected areas in conserving these mammals under climate change, we recommend the incorporation of their potential future distribution into conservation plans, increasing protection status of the key protected areas, and maintain critical corridors. In this regard, combining results of distribution and connectivity models provides useful information for effective management of these ungulates in the future.

KEYWORDS
CIRCUITSCAPE, corridors, ensemble modelling, landscape connectivity, latitudinal shifts, protected areas, vulnerable ungulates

1 | INTRODUCTION

Climate change is now recognized as one of the main threats to biodiversity (IPCC, 2013). It has been estimated that as a result of climate change, nearly a quarter of all species may face increased extinction risk, among which are many large mammals (Thomas et al., 2004). Large mammals (adult body weight > 5 kg; Bourliere, 1975) are already at high risk of extinction as their intrinsic traits such as low population density, low reproduction rate, low life history and large body size (Fisher & Owens, 2004) make them highly vulnerable to anthropogenic factors including habitat loss, poaching and anthropogenic land uses. Synergistically acting with these factors, climate change could also put large mammals at greater risk of extinction in the future (Cardillo et al., 2005). These impacts may be more challenging when climate change forces large mammals to shift their ranges. Although their large body size enables large mammals to readily reach suitable habitats (Schloss, Nuñez, & Lawler, 2012), habitat fragmentation and reduced dispersal ability as a result of anthropogenic land uses could substantially hamper their range shifts in response to climate change (Robillard, Coristine, Soares, & Kerr, 2015). Therefore, to effectively conserve large mammals under climate change, high priority should be given to conservation plans aiming at incorporating their future distributions and enhancing landscape connectivity for their populations (Groves et al., 2012; Hannah et al., 2007).

Evaluating the impact of climate change on distribution of species is mainly accomplished by applying species distribution models (SDMs; Araújo & Peterson, 2008; Pearson & Dawson, 2003). Application of SDMs to predict the future distribution of species is subjected to several limitations as they do not include other factors limiting their distribution such as competition, dispersal and predation (Pearson & Dawson, 2004); however, they still remain the most widely used tools for this purpose. SDMs find the statistical relationship between a set of environmental variables (i.e. climate variables) and species geographic distribution which is then applied to different scenarios of greenhouse gas emission to predict climatically suitable habitats in the future (Pacifici et al., 2015). From future predictions, it is then possible to evaluate changes in the extent of species distribution by estimating proportion of habitats predicted to remain suitable and become unsuitable in the future. SDMs also enable us to evaluate the impact of climate change on protected areas and identify those resilient to climate change (Araújo, Alagador, Cabeza, Nogués-Bravo, & Thuiller, 2011; Carroll, Dunk, & Moilanen, 2010). Protected areas are the cornerstone component of biodiversity conservation (Chape, Harrison, Spalding, & Lysenko, 2005). However, their static nature and the dynamic distribution of species may reduce their efficiency in the future. Nevertheless, these conservation elements could still play a major role in conserving species under climate change by buffering them against anthropogenic impacts, and hence facilitating their future adaptation (Lehikoinen, Santangeli, Jaatinen, Rajasärkkä, & Lehikoinen, 2019; Watson, Dudley, Segan, & Hockings, 2014), functioning as climatic refugia (Berteaux et al., 2018; Michalak, Lawler, Roberts, & Carroll, 2018), target areas for future range expansion (Thomas et al., 2012) and stepping stones facilitating species dispersal in response to climate change (Beale, Baker, Brewer, & Lennon, 2013; Thomas & Gillingham, 2015).

The feasibility of species range shifts in response to climate change largely depends on the availability and accessibility of suitable habitats in the landscape (Warren et al., 2001). That is why increasing landscape connectivity—the degree to which it facilitates or hampers species movements—is one of the most important adaptive strategies to conserve species under climate change (Watson, Iwamura, & Butt, 2013). When highly suitable corridors are identified and maintained, species will have the chance to escape from unsuitable conditions resulting in increasing their resiliency to climate change (Hannah, 2011; Morecroft, Crick, Duffield, & Macgregor, 2012). Evaluating landscape connectivity and identifying corridors could be done by employing different approaches, one of the most common of which is using SDMs (Littlefield, Krosby, Michalak, & Lawler, 2019). When applied in the context of climate change, using SDMs offers three main advantages including: (a) identifying opportunities to maintain landscape connectivity based on current distribution of suitable habitats (i.e. stable habitats); (b) considering species-specific needs for connectivity under climate change with respect to the changes in distribution and availability of suitable habitats in the future (Littlefield et al., 2019); and (c) incorporating anthropogenic impacts into future predictions of species distribution, and identifying pathways assisting their future movements through the least disturbed parts of the landscape.

Across western Asia, Iran is regarded as one of the most important countries for future conservation of threatened wild ungulates. At global scale, Iran includes considerably large extent of suitable habitats for populations of goitered gazelle (*Gazella subgutturosa*). Until 2003, goitered gazelle was classified as a "near-threatened" species in IUCN red list; however, large reductions in population size caused this species to move into the "vulnerable" category (IUCN SSC Antelope Specialist Group, 2017). More topographically rich areas in the country harbour large populations of two vulnerable mountain ungulates (Valdez, 2008; Weinberg et al., 2008), the wild sheep (*Ovis* spp) and wild goat (*Capra aegagrus*) for which Iran encompasses major portions of their global populations. These three ungulates used to be largely distributed across the country; however, habitat degradation and poaching caused their populations to suffer from substantial reductions in distribution and population size (Bashari & Hemami, 2013; Esfandabad, Karami, Hemami, Riazi, & Sadough, 2010; Hemami & Groves, 2001). Currently, the majority of these ungulate populations live within protected areas, specifically those in central part of the country (Ansari, 2016; Esfandabad et al., 2010; Hemami & Groves, 2001). Central Iran has a large network of protected areas (PAs) and no-hunting areas (NHAs) with high potential to protect habitats and populations of the ungulates. However, the efficiency of this protected network and likely changes in suitability of protected habitats for these mammals has not been evaluated yet under climate change. The level of protection and restriction on anthropogenic activities differ within the central Iranian network of protected areas. Therefore, the efficiency of some of these sites under climate change may largely depend on the future management strategies implemented. This particularly holds true for protected areas with high future conservation capability, but low protection level, which will need more management considerations. Furthermore, considering the key role of the protected areas in survival of the ungulates in Iran, predicting future distribution of these mammals to inform future expansion of the current network of protected areas or selection of new sites could be an effective conservation strategy under climate change. More importantly, due to the expansion of human land uses, efficiency of the network of protected areas could be largely improved by maintaining key corridors that facilitate ungulate movements in response to climate change.

In this study, employing species distribution and connectivity modelling approaches, we predicted the impact of future climate change on geographic distribution and corridors for the three vulnerable ungulates of goitered gazelle, wild sheep and wild goat in dry and semi-dry regions of central Iran. Our aims were to the following: (a) predict how climate change would impact on future distribution of the target ungulates in central Iran; (b) identify highly suitable corridors for the ungulates likely to persist under climate change that could assist their future movements in response to climate change; and (c) evaluate future changes in the extent of suitable habitats within the protected areas and identify those sites with remained efficiency under climate change. Additionally, for the three ungulates, we hypothesized that as a result of climate change, their geographic distributions would display significant shifts towards higher elevations and latitudes in central Iran.

2 | METHODS

2.1 | Study area

The study area encompasses the central part of Iran within an extent of about 547,000 km^2 and elevational gradient of 518–4300 m (Figure 1). The region exhibits high diversity of topographic features which include a mixture of flat plains, rolling hills, mountain ranges and isolated mountains. Low relief areas are the dominant topographic features in

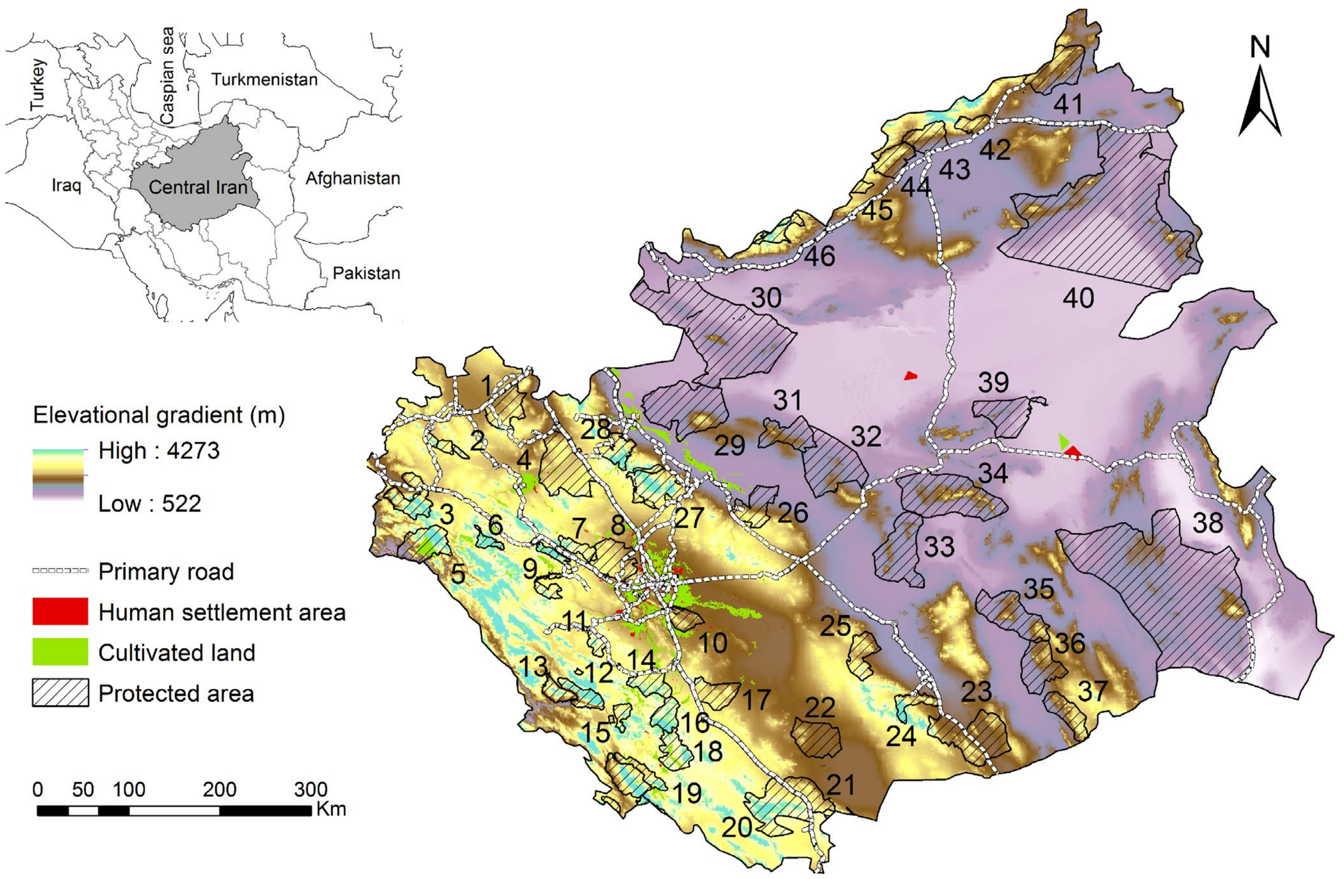

FIGURE 1 Geographic location of the study area in Iran and the network of protected areas in the region (map source: www. doe.ir). (See Table S1 for protection category and protected area code.)

central Iran occupying mainly the eastern and southern parts. In contrast, western and the south-western parts of the landscape are topographically more complex where high elevations of Qamsar, Karkas and Zagros mountain ranges are located. Most parts of the study area remain undisturbed; however, anthropogenic activities in some areas have caused large changes in the landscape. These regions are located across the western and central parts where there is high density of human settlements, roads and cultivated lands. The network of protected areas in central Iran includes more than 40 PAs (national park, NP, IUCN category II; protected area, PA, IUCN category V; wildlife refuge, WR, IUCN category IV) and NHAs (protection category which aims to stop poaching but, has no limitation on livestock grazing or human development plans (Pakniat et al., 2020)—not included as an IUCN category) protecting approximately 22% of the landscape of central Iran. The largest protected areas are located across low relief areas of the east and the north where there are very small-scale anthropogenic interventions. Towards central and the western parts protection is provided within comparatively smaller protected areas.

2.2 | Collection and preparation of occurrence data

Efforts to collect occurrence data for the three ungulate species were mainly based on extensive fieldwork conducted during 2016–2018. As parts of the occurrence data had been previously collected by environmental guards (field observations recorded during annual total counts of ungulates by Departments of Environment (DoE) across Iran), we first evaluated the existing datasets to identify data gaps and conducted further fieldwork to complement the datasets (Table S1). Due to the very low density of ungulates outside the protected areas (and general absence of goitered gazelle in eastern parts), we mainly focused the field observations within the protected areas for which we obtained most of the observations. However, fieldwork was also extended beyond the sites across the unprotected landscape where there have been reports of observing target ungulates (i.e. wild sheep and wild goat). During fieldwork, occurrence data were obtained from direct observations of individuals and indirect sources including scat identification. In total, we complied 167, 593 and 697 occurrence points for goitered gazelle, wild goat and wild sheep, respectively. We then checked the datasets for spatial autocorrelation and applied the global Moran's test to evaluate the structural pattern of the occurrence data. We then extracted three spatially independent subsets of the occurrence data by setting minimum interval distance of 5 km between all the occurrence points. This resulted in a total of 87, 235 and 224 spatially independent occurrence points for goitered gazelle, wild sheep and wild goat, respectively, which were used in the following analyses (Figure S1).

2.3 | Modelling species distributions

To predict distribution of the ungulates, we selected 26 environmental variables belonging to four categories of topography, bioclimate, vegetation and human impact (Table S2). For climate, we used 19 bioclimatic variables at 30-s spatial resolution from CHELSA database (Karger et al., 2017; CHELSA-climate.org). To describe the topography of the study landscape, we selected four variables of elevation, slope, aspect and ruggedness. The digital elevation model (DEM) of the study area was downloaded from the USGS database (USGS.org) at 30-m resolution which was resampled to 1-km resolution and used to produce rasters of slope and aspect using surface analysis tool in ArcGIS 10.3 (ESRI, 2014). For ruggedness, we calculated vector of ruggedness index (VRM) (Sappington, Longshore, & Thomson, 2007) using the DEM of the study area and 5 × 5 km moving window. We considered two vegetation-related variables of soil-adjusted vegetation index (SAVI) and vegetation cover in developing the distribution models. Important classes of vegetation cover for each ungulate were extracted from rangeland and forest map of the study area (www.frw.ir), and the associated map was converted to a raster of continuous values by calculating the proportion of each class within grids of 5 × 5 km using neighbourhood analysis in ArcMap. We also took the same approach to prepare maps of human impact using two land use categories of human settlements and cultivated lands extracted from rangeland and forest map of the study area. After preparing layers of the environmental variables, they were evaluated for collinearity using Spearman correlation coefficient and based on the threshold value of 0.8 (Elith et al., 2006). To include the most important variables into distribution modelling, we first inputted all the variables into the MaxEnt model (Phillips & Dudík, 2008) and ranked them based on the result of jacknife analysis. Then, among the most important linearly correlated variables, final variables were selected with respect to their ranking in predicting distribution of the target species (Table S2).

Potential current and future distributions of the target ungulates were predicted employing an ensemble modelling approach. For this reason, we selected five SDMs with high predictive performance including generalized linear model (GLM), generalized boosting model (GBM), random forest (RF), maximum entropy (MaxEnt) and multivariate adaptive regression splines (MARS) to develop the ensemble models (hereafter EMs) using BIOMOD2 package (Thuiller, Lafourcade, Engler, & Araújo, 2009) implemented in R 4.3.0 software (R Development Core Team, 2014). As a requirement for BIOMOD modelling framework, three sets of 5,000 background points were randomly selected for each species from the entire landscape of central Iran as pseudo-absence points. We used 75% of the occurrence data to fit the individual SDMs and used the remaining 25% to evaluate their predictive performance. The predictive performance of SDMs was evaluated using threshold-independent indices of area under the curve (AUC) of a receiver operating characteristic (ROC; DeLeo, 1993) and the true skill statistic (TSS; Allouche, Tsoar, & Kadmon, 2006). To obtain the consensus predictions, we used a weighted-averaging approach (Thuiller et al., 2009) in which individual SDMs are combined by assigning a weight based on predictive accuracy of each model. In this way, the value of each pixel in the final EM depicts the average weighted suitability of that pixel among all the SDMs. To determine contribution of each variable in predicting distribution of the ungulates, the associated scores were averaged across all the SDMs, and a total measure of importance for each variable was obtained.

future distribution of the ungulates was predicted under climatic conditions in the year 2070 and based on the representative concentration pathway (RCP) 8.5. The RCP 8.5 is the most pessimistic emission scenario (Riahi et al., 2011) in which 2.6–4.7 C increase in global temperature is expected (IPCC, 2013). Accordingly, using this extreme scenario, it was possible to predict future distribution of the ungulates under the maximum impact of climate change. To reduce uncertainties associated with the future predictions, we used bioclimatic variables produced by five global circulation models (GCMs) including CCSM4 (Gent et al., 2011), MIROC5 (Watanabe et al., 2010), GFDL-CM3 (Donner et al., 2011), MPI-ESM-LR (Block & Mauritsen, 2013) and HadGEM2-AO (Martin et al., 2011) which are among commonly used GCMs in similar studies (e.g. Tang et al., 2017; Yousefi et al., 2015) with high performance (McSweeney, Jones, Lee, & Rowell, 2015). In total, we developed five future EMs (1 future scenario × 5 GSMs) for each ungulate which were averaged, and a final EM representing the distribution of each species in 2070 was obtained. In the next stage, current and future EMs were converted into binary maps using the minimum suitability score at occurrence points and then overlaid. Accordingly, we quantified three indices of climate change impact on distribution of the ungulates including lost, gained and stable habitats. Overlaying these maps with the map of protected areas, we also evaluated future changes in the extent of suitable habitats within the individual sites and the whole protected network for each species. We also evaluated whether climate change would result in distribution of the ungulates to shift along elevational and latitudinal gradients. For elevational shift, we obtained mean elevation of current and future distributions for each species and calculated difference between them (Luo, Jiang, & Tang, 2015). For latitudinal shift, centroids of the current and future distributions were identified, and the geographic distance between pairs of centroids was taken as a measure of latitudinal shift (Luo et al., 2015).

2.4 | Modelling Landscape connectivity and identifying movement corridors

To predict the most permeable corridors for the three ungulates, we used concepts from circuit theory impalement in CIRCUITSCAPE software (ver. 3.5.8; McRae, Shah, & Mohapatra, 2013). By applying concepts from electric circuits (i.e. node, current flow and resistors) to those in landscape ecology (i.e. habitat patch and corridors), this method predicts the probability of individual movements or gene flow between habitat patches in a landscape (McRae, Dickson, Keitt, & Shah, 2008). As a result of this association, the landscape is represented as a conductive or resistant surface with habitat patches converted to focal nodes, and current density as a measure for probability of movement or strength of connectivity between the habitat patches (McRae et al., 2008). To Identify connectivity areas likely to persist into the future, we first modelled current and future potential

TABLE 1 Values of TSS and AUC indices calculated to evaluate the predictive performance of each SDM used to predict distribution of the target ungulates in central Iran

	Goitered gazelle		Wild sheep		Wild goat	
Model	AUC	TSS	AUC	TSS	AUC	TSS
GLM	0.88	0.66	0.88	0.65	0.91	0.73
MaxEnt	0.94	0.73	0.94	0.75	0.95	0.76
GBM	0.97	0.85	0.93	0.71	0.95	0.80
MARS	0.99	0.70	0.91	0.69	0.93	0.76
RF	0.99	0.99	0.99	0.99	0.99	0.99

corridors within the landscape of central Iran for each species. To do so, current and future distribution maps were used to convert the study region into a conductive surface with the individual protected areas set as focal habitats. By using the protected areas as focal areas, we evaluated the following: (a) to what degree future climate change is likely to negatively impact on the suitability of corridors connecting the protected areas for the target ungulates, and (b) if a protected area loses large amounts of suitable habitats, would it remain connected to other sites with large stable habitats in the future. We then applied the 20% percentile of the total current density calculated in the present scenario as the binary threshold and identified corridors with remained suitability under both current and future conditions.

3 | RESULTS

3.1 | Distribution of the ungulates under current and future conditions

Obtained values of TSS and AUC indices for the SDMs indicated good and excellent predictive performance of all five modelling algorithms in predicting distribution of the three species (TSS > 0.60 and AUC > 0.88, Table 1). Potential distributions of the target ungulates predicted under current conditions are shown in Figure S2. For goitered gazelle, 18.4% of the study area was estimated as suitable, of which 22.3% overlapped with the protected areas. The largest habitat areas for goitered gazelle were predicted across the northern and the western parts (Figure S2a). For wild sheep and wild goat, larger proportions of central Iran, mostly in the western parts, were predicted as potentially suitable habitats covering 25.2% and 20.9% of the study landscape, respectively (Figure S2b,c). From these suitable habitat areas, 29.2% and 30.6% were estimated to have protection coverage for wild sheep and wild goat, respectively.

Our future predictions revealed that as a result of climate change, goitered gazelle might lose up to 55.3% of its current distribution by 2070 (Figure 2a, Table 2) resulting in a 59.8% reduction in the extent of habitats within the protected areas. Significant losses were predicted for the habitats across the southern and

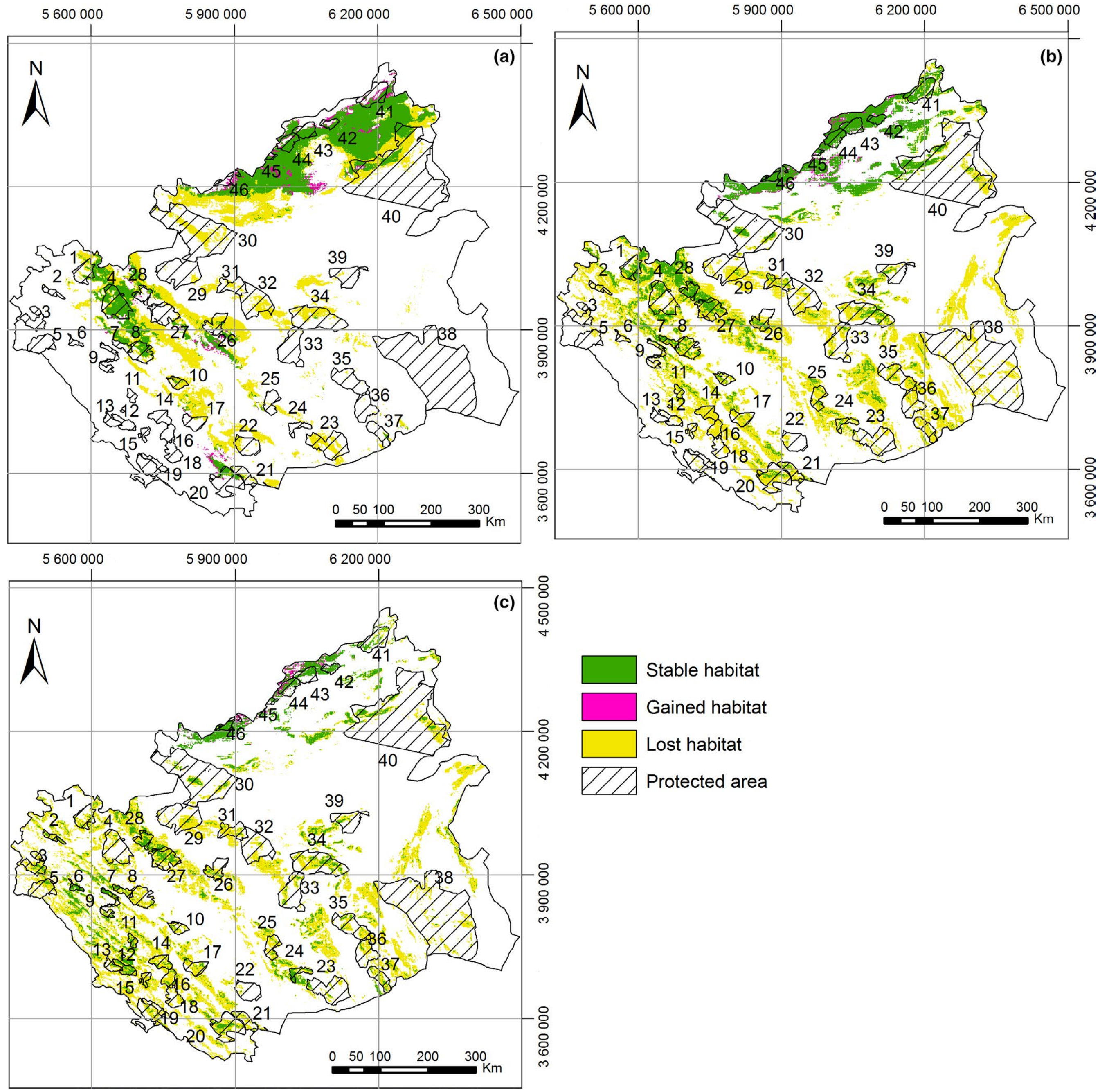

FIGURE 2 Future distribution of goitered gazelle (a), wild sheep (b) and wild goat (c) predicted based on the RCP 8.5 emission scenario for the year 2070 in central Iran. Predicted changes between current and future are depicted in yellow (suitable habitats predicted to become unsuitable) and pink (unsuitable habitats predicted to become suitable). Areas depicted in green represent suitable habitats predicted to remain suitable between current and future conditions. (See Table S1 for protection category and protected area code.)

central parts and the protected areas number 1, 23, 26 and 10 (Table S3). Within the current distribution, only proportions of the habitats in the north-east (largest patch of stable habitats) and the north-west were predicted to remain suitable by 2070 (Table 2). Across these regions, protected areas number 4, 8, 40, 43 and 44 were estimated to remain with more than 60% of their suitable habitats in the future (Table S3). Gained habitats only accounted for 3.7% of the future distribution of goitered gazelle mostly in the north of which 20.5% overlapped with the protected network mainly with protected areas number 41, 42 and 46 (Table S3). From the total area of protected suitable habitats, 66.22% were estimated to be protected by the NHAs and the rest by the categories of PAs.

Wild sheep and wild goat were predicted to even loss larger proportions of their current distribution by 2070 with 69.1% and 76% decrease by 2070, respectively (Figure 2b,c, Table 2). Such reductions also impacted the protected areas and resulted in loss of 65.6% and 21.4% of the protected habitats for wild sheep and wild goat,

TABLE 2 Area of current and future suitable habitats and percentages of lost, stable and gained habitats predicted for the target ungulates based on the RCP 8.5 emission scenario in 2070 in central Iran

		Stable habitats	Lost habitats		Gained habitats		Suitable habitats	
Species	Time	Km^2	Km^2	%	Km^2	%	Km^2	%
Goitered gazelle	Present	100,531.53	–	–	–	–	–	–
	RCP 8.5	–	55,585.95	55.30	3,719.50	3.7	44,888.45	44.65
Wild sheep	Present	137,945.5	–	–	–	–	–	–
	RCP 8.5	–	95,280	69.07	1,420.86	1.03	42,399.4	30.73
Wild goat	Present	114,252.42	–	–	–	–	–	–
	RCP 8.5	–	86,818.40	76.00	940.17	0.82	27,009.54	23.64

respectively, particularly for protected areas number 15, 18, 31, 32, 33, 36 and 38 (Tables S4 and S5). The largest stable habitats for these ungulates were found across the northern and north-western regions along with several small patches in high elevations of the southern and central parts. Within the network of protected areas, large areas of stable habitats for both species were predicted within protected areas number 40–46, 34, 27 and 28 (Tables S4 and S5). Similar to goitered gazelle, gained habitats accounted for a very small part of future distribution of these mountain ungulates (1% and 0.8%, respectively) (Table 2). For wild sheep, only 7.5% of the gained habitats were protected, mostly by the protected areas number 43–46. For wild goat, however, we estimated a higher protection level, mostly provided by the same protected areas as wild sheep. Within the protected network, NHAs included the largest areas of protected gained habitats with coverage of nearly 80.7% and 96.3% for wild sheep and wild goat, respectively. The provided protection by the NHAs was estimated to be lower for the protected stable habitats with 29.1% and 32.3% coverage for wild sheep and wild goat, respectively, and the majority by the categories of PAs. As a result of climate change, distribution of wild goat, goitered gazelle and wild sheep was estimated to change about 115.0 m, 103.0 m and 87.0 m along elevational gradient, respectively, by 2070 (on average, 102.0 ± 14 m). Such spatial response was also predicted to occur along the latitudinal gradient with larger magnitude and accounted for about 167.0 km, 123.7 km and 116.1 km for wild sheep, wild goat and goitered gazelle, respectively (on average, 136.0 ± 27 km).

3.2 | Impact of climate change on suitability of corridors for the ungulates

Based on the measured density of current flow, areas of highest suitability for movement of goitered gazelle were predicted between the protected areas located in the north-western part (Figure 3a) (protected areas number 1, 4, 8 and 26). The pattern of current density also predicted a rather strong corridor among the protected areas in the north-east; however, these areas were poorly connected to those located in the west. Towards the south, the amount of cumulative current tended to decrease, resulting in weaker connections between the western and southern protected areas, such as a corridor connecting protected areas number 10 and 20. Comparing current and future connectivity maps revealed that 34.5% of areas of high suitability for movement of goitered gazelle might become unsuitable by 2070 (Figure 4a). In this regard, the most affected corridors were predicted between protected areas number 10 and 26, and number 4 and 8. This reduction in connectivity was also predicted for a small section of the corridor connecting protected areas number 10 and 20 in south. For wild sheep and wild goat, the density of current flow predicted the strongest connections between the protected areas across high elevations of the western and central parts (Figure 3b,c). Towards low relief areas of the east and the south-east, however, corridors were weaker and smaller in extent resulting in protected areas to be largely isolated (protected areas number 35, 37, 38, 40 and 41). As a result of climate change, 41% and 43% of the most suitable areas for movement of wild sheep and wild goat were estimated to become unsuitable, respectively (Figure 4b,c). Major connectivity reductions/disruptions for wild goat were predicted for the corridors connecting protected areas number 4 and 8; 32 and 33; and 1, 2 and 4. For wild sheep, significant losses were predicted for the protected areas number 32, 33 and 34. For both mountain ungulates, the most stable parts of the connectivity areas were identified in the western and the northern parts of the study area. In addition to climate change, we also identified sections along the stable corridors impacted by primary roads (intersected areas) which were of higher frequency for goitered gazelle (Figure 4). For wild sheep and wild goat, however, most of the stable corridors were found in parallel or far away from the main roads.

4 | DISCUSSION

4.1 | Climate change and future distribution of the vulnerable ungulates in central Iran

For our mostly arid region, we estimated, on average, 66.5 ± 10.11% reduction in current distribution of the target ungulates by 2070, which is similar to the estimate calculated for Marco polo sheep (*O. ammon polii*) in Tajikistan (65.6% loss; Salas, Valdez, Michel, &

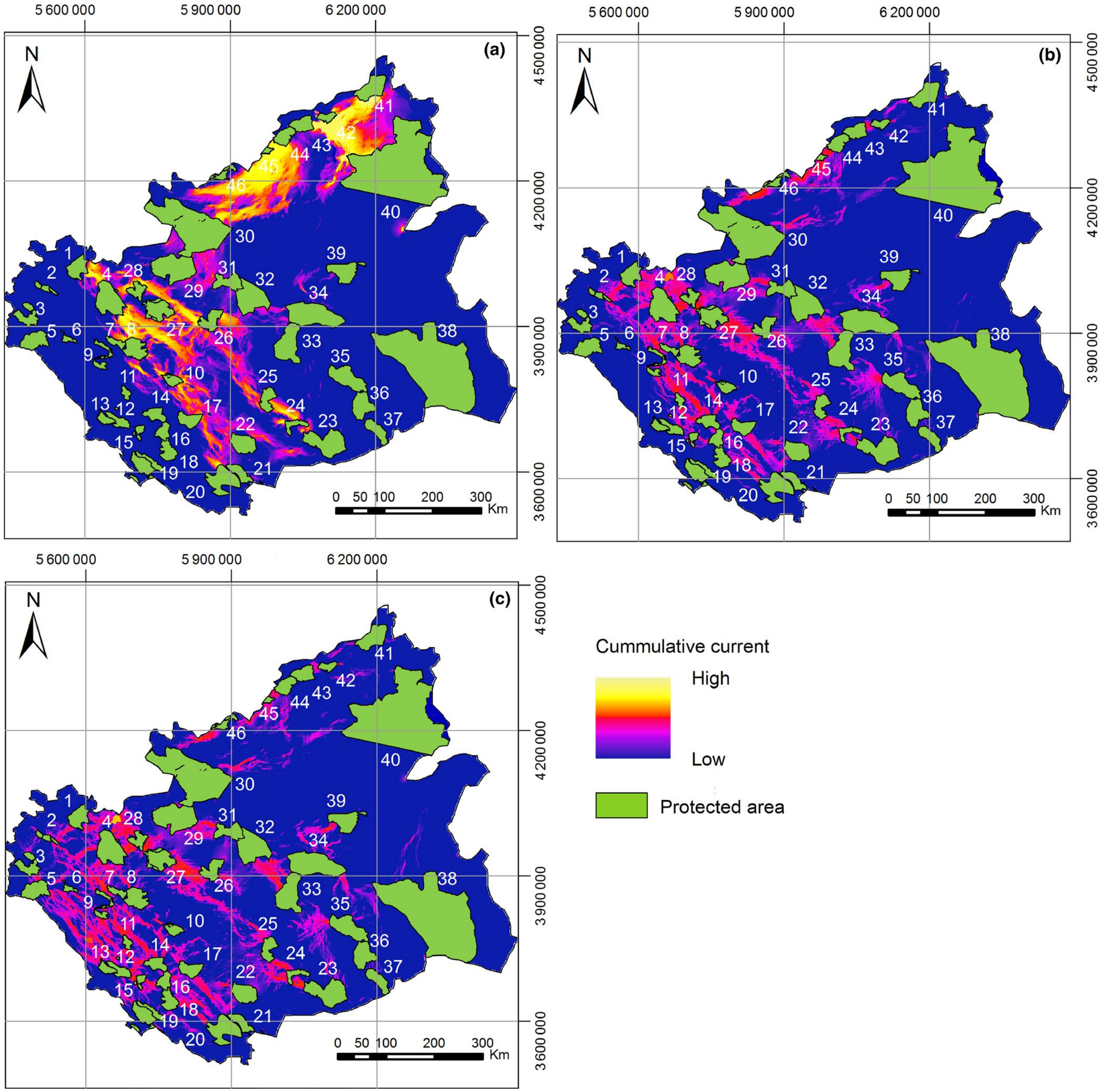

FIGURE 3 High suitability corridors predicted based on the density of cumulative current for movement of goitered gazelle (a), wild sheep (b) and wild goat (c) between the protected areas in central Iran. Areas depicted in yellow and red have the highest density of flowing cumulative current, and represent areas with the highest probability of movement. (See Table S1 for protection category and protected area code.)

Boykin, 2018), but higher than those obtained for large mammals in generally less arid regions like the Tibetan Plateau (30%–55% loss; Luo et al., 2015), the African continent (18% loss; Thuiller et al., 2006), in tropical forests of Asia (37% loss; Deb, Phinn, Butt, & McAlpine, 2019) and temperate Europe (30% loss; Levinsky, Skov, Svenning, & Rahbek, 2007) indicating that climate change could have generally larger impacts on species in arid regions (Heffelfinger et al., 2018), such as central Iran. Within central Iran, however, we obtained different estimates of climate change impact on the future distribution of the ungulates, which may be related to varying rates of climate change across their habitats. Wild sheep and wild goat were predicted to lose larger proportions of their distribution compared with goitered gazelle. This is because mountainous regions have been predicted to become warmer at a higher rate than low-lying areas (Rangwala, Sinsky, & Miller, 2013), a trend that could result in more widespread negative changes in the distribution of mountain species in relation to their lower elevational counterparts.

Comparing current and future predictions showed that as a result of climate change, current distribution of the three ungulates is likely to change along both elevational and latitudinal gradients. Along

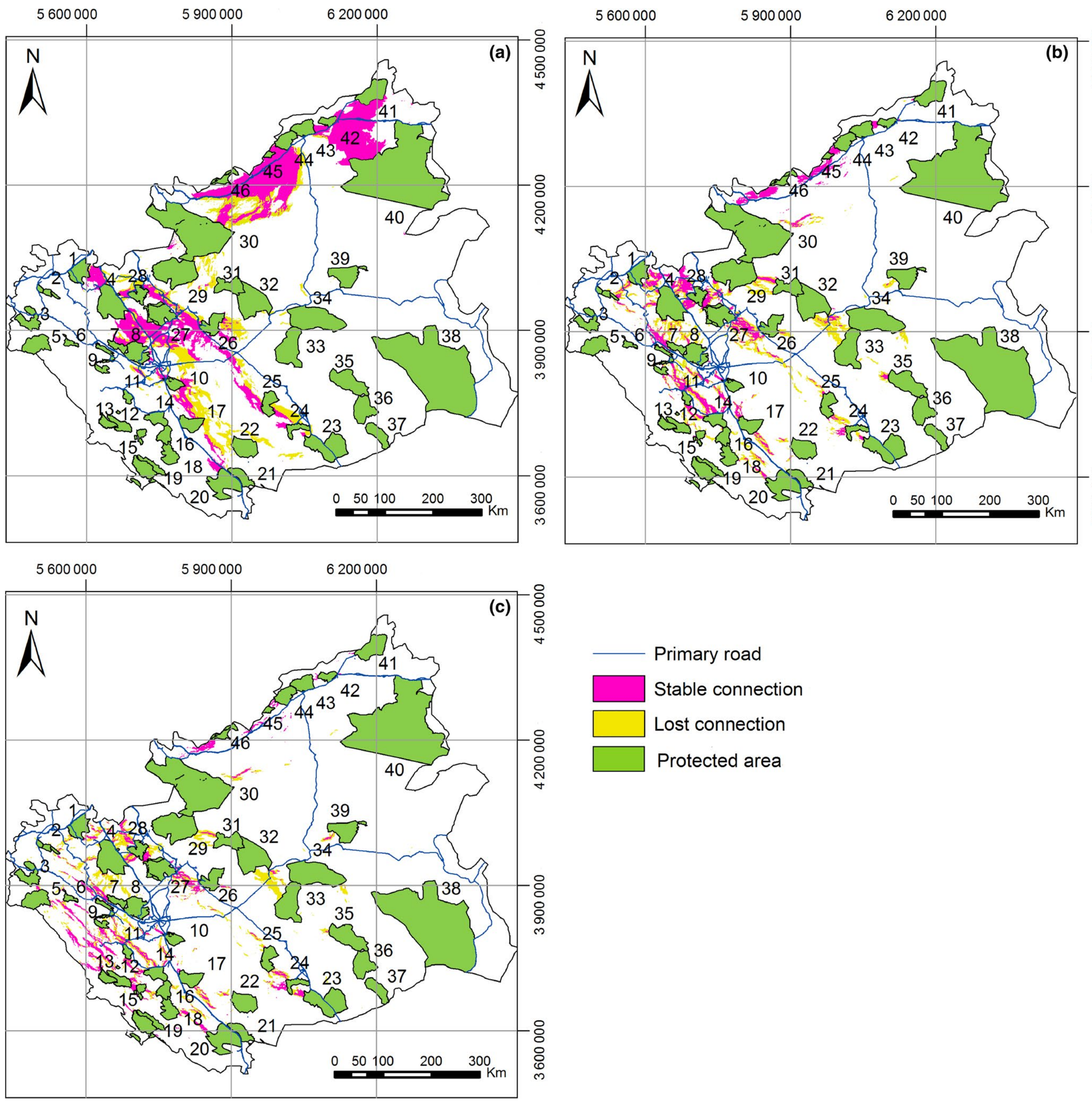

FIGURE 4 Future changes in suitability of modelled corridors for goitered gazelle (a), wild sheep (b) and wild goat (c) predicted based on the RCP 8.5 emission in 2070. Areas depicted in yellow and pink represent connectivity areas predicted to become unsuitable and remain suitable under future conditions, respectively. (See Table S1 for protection category and protected area code.)

elevational gradient, the estimated changes were mainly associated with large reduction in their geographic distribution and not range expansion towards higher elevations. This result contradicted our hypothesis in this study and was inconsistent with the result of Luo et al. (2015). The main reason for this result could be associated with the topography of central Iran as it spans a rather limited elevational gradient of up to 4,300 m. Accordingly, wild sheep and wild goat may have already occupied the upper limit of their preferred elevational gradients with no more opportunities for future range expansions towards higher elevations. Regarding goitered gazelle, which lives in low elevation areas, there may be more potential opportunities for upward movements compared with the two other species. However, a reduced area of potential habitats with increasing elevation will hamper future upward shifts as these habitats may not be large enough to sustain viable populations. Our models also did not predict any climate-related northern range expansion for the three ungulates. However, because of the stability of northern habitats and the large habitat loss in southern parts, the estimated change could be regarded as northward shifts which are expected to occur to compensate limited opportunities for elevational movements.

In this study, our inference on the impact of climate change on the distribution of the target ungulates was obtained based on the consensus predictions of several SDMs. As the results of model evaluation demonstrated, all employed SDMs represented high performance in predicting the distribution of the three ungulates in our study. However, owning to different assumptions of these models, we could not say for sure which model provides the most accurate prediction of species distributions in the future (Thuiller, 2004). Thus, we integrated the projections produced by the individual SDMs through the ensemble modelling approach as it considers a range of possible predictions, which tends to reduce the associated uncertainties. In another conservative approach, we used minimum suitability value at occurrence points to produce binary distribution maps associated with current and future conditions. Using this threshold allows us to reduce the risk of misidentifying additional suitable habitats when planning for the future conservation of these ungulates (Sony, Sen, Kumar, Sen, & Jayahari, 2018). However, it may come with the cost of including habitats of lower suitability which entails explicitly assessing the reliability of these predictions through field investigations before being used in future conservation plans.

Capturing the full realized niche of species is a key assumption when projecting SDMs in space and time (Guisan, Thuiller, & Zimmermann, 2017). In this study, the SDMs developed for the target ungulates were calibrated based on environmental conditions captured at occurrence data from part of their geographic distribution in Iran. Such incomplete coverage of species range may increase uncertainties associated with future predictions as the truncated range of environmental variables may not represent the full realized niche of species but their partial realized niche (Thuiller, Brotons, Araújo, & Lavorel, 2004). The partial SDMs developed for our target species demonstrated that climate change could have a widespread impact on their distribution. However, for implementing reliable conservation strategies, we need complete knowledge of their future distribution which is obtained by making future projections based on their full realized niche.

4.2 | Combined role of protected areas and corridors in increasing adaptation of the ungulates to climate change

Using SDMs as the basis for connectivity modelling enabled us to evaluate the potential of the study landscape in facilitating future movements of the ungulates with respect to the future changes in distribution of their suitable habitats. The combination of distribution and connectivity models allowed identifying three groups of the target ungulates with varying degrees of vulnerability to climate change, including populations predicted to (a) stay in large enough suitable habitats in the future, but that may become isolated or (b) lose their habitats, but that can potentially move via stable corridors to access suitable habitats; or (c) lose both of their suitable habitats and connection to other suitable habitats. For goitered gazelle, impacted populations belonged to the second group and were found in three sites of Kalmand PA (23), Kahyaz PA (26) and Kolah Ghazi NP (10) in the southern part of central Iran. Based on the output of connectivity model, Kalmand and Kahyaz PAs are most likely to be connected to Mouteh (4) and Qamishlou WRs (8), a result that has been recently confirmed by analysing gene flow among the central Iranian populations of goitered gazelle (Khosravi et al., 2018). For populations in Kalmand PA (23), the only connection to the west was predicted via Kahyaz PA (26). In this regard, this PA could play a significant function as a stepping stone and maintain connectivity to the western protected areas. For populations in Kolah Ghazi NP (10), we predicted two potential corridors, one towards Mouteh WR (4) and Kahyaz PA (26) in the north, and the other towards Basiran NHA (20) in the south. Populations of goitered gazelle in Kolah Ghazi NP are already isolated due to extensive expansion of urban areas, cultivated lands and roads in the vicinity of this NP. This isolation has also been shown by genetic differentiation of populations in Kolah Ghazi from others in Mouteh WR (4) and Kahyaz PA (26) (Khosravi et al., 2018). Currently, there is no information regarding gene flow and movement of goitered gazelle between Kolah Ghazi NP and Basiran NHA. However, considering the absence of human land uses in the intervening landscape and the species' dispersal ability, the predicted corridor could potentially play a critical role in reducing further isolation of the populations in this NP in the future. In the north-east, only populations in Touran PA (40) were predicted to lose parts of their habitats in the future. North of Touran PA, in Semnan province, encompasses the northernmost arid habitats of goitered gazelle in central Iran. This region was identified as the largest stable habitat area for goitered gazelle in central Iran which represents a potential key region for implementing future conservation actions (e.g. establishing new protected areas/expanding the current network of protected areas).

For wild sheep and wild goat, we identified impacted populations from all three vulnerability groups. Across the study region, there is more concern about the future impact of climate change on populations inhabiting low relief areas of the east and the south-east for two reasons: (a) existence of mountains with small elevational gradient within the protected areas that could limit future upward movements of the ungulates, and (b) low topographic heterogeneity and therefore low permeability of the surrounding landscape that may largely hamper species movements towards key protected areas in the future (Malakoutikhah, Fakheran, Hemami, Tarkesh, & Senn, 2018). As a result of these landscape characteristics, populations inhabiting these parts are expected to be particularly vulnerable to climate change. Across eastern deserts, Abbasabad WR (34) was predicted to retain the largest stable habitats (nearly 600 km^2) in the future, as it includes the highest mountainous areas among the protected areas in this part. Accordingly, this WR could be considered as an important refugia buffering populations of wild sheep and wild goat under climate change. In this part of the landscape, the only corridor predicted to remain suitable is the one connecting Kharoo (31) and Yakhab (29) NHAs. This corridor is highly crucial for the populations in these NHAs, as it provides the only pathway towards key protected areas in the north (both species) and the west (only for wild sheep). In this region, Yakhab NHA (29) could largely contribute in facilitating and maintaining this connection, and thus function as a stepping stone for both species.

Across the west and the north-west, we also identified vulnerable populations of wild goat and wild sheep to climate change; however, high level of topographic heterogeneity across these parts could largely help buffering the negative effects of climate change on these populations (Gavin et al., 2014; Loarie et al., 2009). Protected populations of wild sheep and wild goat in the west and the north-west were identified as belonging to the second group of vulnerability; that is, populations predicted to lose habitats, but remain connected to other suitable habitats. We predicted, on average, stability of 28.5% of currently suitable habitats for both species in the future. However, with respect to high topographic heterogeneity of the landscape in these parts, the area of available habitats in the future may be larger than what was estimated by our predictions. This is because high topographic heterogeneity of these areas could contribute to climatic heterogeneity and creation of microclimatic refugia (Ford, Ettinger, Lundquist, Raleigh, & Lambers, 2013). Furthermore, high topographic heterogeneity is expected to reduce the velocity of climate change (Loarie et al., 2009), meaning that as climate changes, species could find suitable habitats within relatively short distances. Inside the protected areas, this means more opportunities for the ungulates to survive under climate change (Cantú-Salazar & Gaston, 2010). Outside the protected areas, the major role of these heterogeneous habitats is associated with increasing landscape connectivity for these mountain species (Malakoutikhah et al., 2018) as was well illustrated by the connectivity models. The structural connectivity promoted in this way is specifically important for wild goat considering the species comparatively limited dispersal ability. If climate change forces populations of this species to leave the protected areas, probable northward movements will be only facilitated by these heterogeneous habitats. However, it should be considered that structural connectivity alone is not enough for species to fulfil their range shifts as species' dispersal ability is also a key factor. For example, for the southern populations we are unsure if they are able to traverse over hundreds of kilometres to reach the closest key protected areas in the north. Due to lack of information, we did not include dispersal limitations of the target ungulates into SDMs. However, if available, the incorporation of such information could provide more accurate future predictions (e.g. see Bush et al., 2016; Razgour, 2015) which in turn help designing unbiased conservation plans for proper management of their populations.

4.3 | Conservation implications

Iran has a relatively well-established network of protected areas (approximate coverage of 15%) compared to other nearby countries with effective protection provided for most species, particularly ungulate species (Kolahi, Sakai, Moriya, & Makhdoum, 2012). For these mammals, if these conservation elements are to maintain their role under climate change, impact of climate change on their distribution should be incorporated into the future conservation plans. Maintaining such role will also depend on the proper management of the protected areas particularly category of NHA. NHAs receive the lowest protection level in Iran; however, as our results demonstrated, they could play a major role in protecting the target ungulates under climate change. For this reason, enhancing protection level of NHAs (i.e. first to PA/ WR and then to NP if meeting required qualifications) is an effective management option as they could substantially contribute to strengthen the network of protected areas under climate change. Our predictions showed that as a result of climate change, some of the central Iranian protected areas may become completely unsuitable for the inhabiting ungulates increasing their risk of extirpation if unable to track suitable habitats elsewhere. However, as the predictions of connectivity models demonstrated, some of these populations would still have the chance to access climatically suitable habitats using stable corridors. Therefore, maintaining functionality of the key corridors will significantly help increasing adaptation of these vulnerable mammals to climate change. Such maintenance largely depends on reducing/ preventing expansion of anthropogenic activities as they have already resulted in isolation of some of the central Iranian protected areas. This is particularly the case for roads, a major issue for conservation of large mammals in Iran (Moqanaki & Cushman, 2017). As our results showed, in some areas the predicted stable corridors are already impacted by roads. Many populations of these ungulates occur inside protected areas away from roads and their impacts. However, these structures could be a serious threat in the future by interrupting ungulate movements when tracking suitable habitats or increase their risk of mortality through collision. Therefore, road networks and their current status/ future development with respect to the future need of these mammals should be seriously considered in future conservation programs.

Our study was a case example demonstrating that climate change could have significant impact on our target ungulate species across a proportion of their global range. Accordingly, further studies could provide better insights into the impact of climate change on these mammals, which could be used to inform conservation programs and assist in evaluating their conservation status. Based on our results, we suggest three main conservation strategies for the conservation of the three ungulates, which may also be applicable for their populations in other regions. These include the following: (a) enhancing protection status of the NHAs, PAs and WRs predicted to maintain efficient in future and those likely to function as stepping stones; (b) expanding the network of protected areas through enlargement/ establishment of new sites in areas predicted to remain potentially suitable (protecting more heterogeneous habitats for wild sheep and wild goat, and larger suitable areas for goitered gazelle); and (c) preventing future expansion of anthropogenic land uses across areas with high potential to facilitate future movements of the ungulates, particularly for goitered gazelle as its movement corridors have a higher chance of being disrupted by human land uses.

ACKNOWLEDGEMENTS

We would like to greatly thank the authorities in Departments of Environment within provinces for coordination and cooperation in conducting fieldwork. We are also grateful to the Swiss Federal Research Institute (WSL) for their support and the Iran National Science Foundation, Presidency of Islamic Republic of Iran, for providing financial support to this research (project number: 95849735).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Shima Malakoutikhah https://orcid.org/0000-0001-6925-068X
Mahmoud-Reza Hemami https://orcid.org/0000-0002-8321-6776

REFERENCES

Allouche, O., Tsoar, A., & Kadmon, R. (2006). Assessing the accuracy of species distribution models: Prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology*, *43*(6), 1223–1232. https://doi.org/10.1111/j.1365-2664.2006.01214.x

Ansari, A. (2016). Comparison of Habitat Suitability Model for the Wild sheep (*Ovis orientalis*) using ENFA and MAXENT methods in Markazi province, Iran. *Iranian Journal of Animal Environment*, *8*(2), 9–16. (In Persian).

Araújo, M. B., Alagador, D., Cabeza, M., Nogués-Bravo, D., & Thuiller, W. (2011). Climate change threatens European conservation areas. *Ecology Letters*, *14*(5), 484–492. https://doi.org/10.1111/j.1461-0248.2011.01610.x

Bashari, H., & Hemami, M. R. (2013). A predictive diagnostic model for wild sheep (*Ovis orientalis*) habitat suitability in Iran. *Journal for Nature Conservation*, *21*(5), 319–325. https://doi.org/10.1016/j.jnc.2013.03.005

Beale, C. M., Baker, N. E., Brewer, M. J., & Lennon, J. J. (2013). Protected area networks and savannah bird biodiversity in the face of climate change and land degradation. *Ecology Letters*, *16*(8), 1061–1068. https://doi.org/10.1111/ele.12139

Bellouin, N., Collins, W. J., Culverwell, I. D., Halloran, P. R., Hardiman, S. C., Hinton, T. J., … Wiltshire, A. (2011). The HadGEM2 family of met office unified model climate configurations. *Geoscientific Model Development*, *4*(3), 723–757. https://doi.org/10.5194/gmd-4-723-2011

Berteaux, D., Ricard, M., St-Laurent, M. H., Casajus, N., Périé, C., Beauregard, F., … de Blois, S. (2018). Northern protected areas will become important refuges for biodiversity tracking suitable climates. *Scientific Reports*, *8*(1), 4623. https://doi.org/10.1038/s41598-018-23050-w

Block, K., & Mauritsen, T. (2013). Forcing and feedback in the MPI-ESM-LR coupled model under abruptly quadrupled CO2. *Journal of Advances in Modelling Earth Systems*, *5*(4), 676–691.

Bourliere, F. (1975). Mammals, small and large: The ecological implications of size. In *Small mammals: Their productivity and population dynamics* (pp. 1–9). London, UK: Cambridge University Press.

Bush, A., Mokany, K., Catullo, R., Hoffmann, A., Kellermann, V., Sgrò, C., … Ferrier, S. (2016). Incorporating evolutionary adaptation in species distribution modelling reduces projected vulnerability to climate change. *Ecology Letters*, *19*(12), 1468–1478. https://doi.org/10.1111/ele.12696

Cantú-Salazar, L., & Gaston, K. J. (2010). Very large protected areas and their contribution to terrestrial biological conservation. *BioScience*, *60*(10), 808–818. https://doi.org/10.1525/bio.2010.60.10.7

Cardillo, M., Mace, G. M., Jones, K. E., Bielby, J., Bininda-Emonds, O. R., Sechrest, W., … Purvis, A. (2005). Multiple causes of high extinction risk in large mammal species. *Science*, *309*(5738), 1239–1241. https://doi.org/10.1126/science.1116030

Carroll, C., Dunk, J. R., & Moilanen, A. (2010). Optimizing resiliency of reserve networks to climate change: Multispecies conservation planning in the Pacific Northwest, USA. *Global Change Biology*, *16*(3), 891–904. https://doi.org/10.1111/j.1365-2486.2009.01965.x

Chape, S., Harrison, J., Spalding, M., & Lysenko, I. (2005). Measuring the extent and effectiveness of protected areas as an indicator for meeting global biodiversity targets. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1454), 443–455. https://doi.org/10.1098/rstb.2004.1592

Deb, J. C., Phinn, S., Butt, N., & McAlpine, C. A. (2019). Adaptive management and planning for the conservation of four threatened large Asian mammals in a changing climate. *Mitigation and Adaptation Strategies for Global Change*, *24*(2), 259–280.

Deleo, J. M. (1993). Receiver operating characteristic laboratory (ROCLAB): Software for developing decision strategies that account for uncertainty. In B. M. Ayyub (Ed.), *Proceedings of the second international symposium on uncertainty modeling and analysis* (pp. 318–325). Los Alamitos, CA: IEEE Computer Society Press.

Donner, L. J., Wyman, B. L., Hemler, R. S., Horowitz, L. W., Ming, Y. I., Zhao, M., … Zeng, F. (2011). The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL global coupled model CM3. *Journal of Climate*, *24*(13), 3484–3519. https://doi.org/10.1175/2011JCLI3955.1

Elith, J., Graham, C. H., Anderson, R. P., Dudík, M., Ferrier, S., Guisan, A., … Zimmermann, N. E. (2006). Novel methods improve prediction of species distributions from occurrence data. *Ecography*, *29*(2), 129–151. https://doi.org/10.1111/j.2006.0906-7590.04596.x

Esfandabad, B. S., Karami, M., Hemami, M. R., Riazi, B., & Sadough, M. B. (2010). Habitat associations of wild goat in central Iran: Implications for conservation. *European Journal of Wildlife Research*, *56*(6), 883–894. https://doi.org/10.1007/s10344-010-0386-9

ESRI (2014). *ArcGIS 10.3*. Redlands CA: Environmental Systems Research Institute.

Fisher, D. O., & Owens, I. P. (2004). The comparative method in conservation biology. *Trends in Ecology & Evolution*, *19*(7), 391–398. https://doi.org/10.1016/j.tree.2004.05.004

Ford, K. R., Ettinger, A. K., Lundquist, J. D., Raleigh, M. S., & Lambers, J. H. R. (2013). Spatial heterogeneity in ecologically important climate variables at coarse and fine scales in a high-snow mountain landscape. *PLoS One*, *8*(6), e65008. https://doi.org/10.1371/journal.pone.0065008

Gavin, D. G., Fitzpatrick, M. C., Gugger, P. F., Heath, K. D., Rodríguez-Sánchez, F., Dobrowski, S. Z., … Williams, J. W. (2014). Climate refugia: Joint inference from fossil records, species distribution models and phylogeography. *New Phytologhazeriist*, *204*(1), 37–54. https://doi.org/10.1111/nph.12929

Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Hunke, E. C., Jayne, S. R., … Zhang, M. (2011). The community climate system model version 4. *Journal of Climate*, *24*(19), 4973–4991. https://doi.org/10.1175/2011JCLI4083.1

Groves, C. R., Game, E. T., Anderson, M. G., Cross, M., Enquist, C., Ferdaña, Z., … Shafer, S. L. (2012). Incorporating climate change into systematic conservation planning. *Biodiversity and Conservation*, *21*(7), 1651–1671. https://doi.org/10.1007/s10531-012-0269-3

Guisan, A., Thuiller, W., & Zimmermann, N. E. (2017). *Habitat suitability and distribution models: With applications in R*. Cambridge, UK: Cambridge University Press.

Hannah, L. (2011). Climate change, connectivity, and conservation success. *Conservation Biology*, *25*(6), 1139–1142. https://doi.org/10.1111/j.1523-1739.2011.01788.x

Hannah, L., Midgley, G., Andelman, S., Araújo, M., Hughes, G., Martinez-Meyer, E., … Williams, P. (2007). Protected area needs in a changing climate. *Frontiers in Ecology and the Environment*, *5*(3), 131–138. https://doi.org/10.1890/1540-9295(2007)5[131:PANIAC]2.0.CO;2

Heffelfinger, L. J., Stewart, K. M., Bush, A. P., Sedinger, J. S., Darby, N. W., & Bleich, V. C. (2018). Timing of precipitation in an arid environment: Effects on population performance of a large herbivore. *Ecology and Evolution*, *8*(6), 3354–3366. https://doi.org/10.1002/ece3.3718

Hemami, M. R., & Groves, C. P. (2001) Global antelope survey and regional action plans: Iran. In D. P. Mallon, & S. C. Kingswood (Eds.), *Antelopes: Part 4. North Africa, the Middle East and Asia* (pp. 114–118). Gland, Switzerland: IUCN/SSC Antelope Specialist Group.

IPCC (2013). *Working Group I Contribution to the IPCC Fifth Assessment Report, Climate Change 2013: The Physical Science Basis*. IPCC, AR5, 2014.

IUCN SSC Antelope Specialist Group (2017). *Gazella subgutturosa. The IUCN Red List of Threatened Species 2017.*

Karger, D. N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R. W., … Kessler, M. (2017). Climatologies at high resolution for the earth's land surface areas. *Scientific Data*, *4*, 170122. https://doi.org/10.1038/sdata.2017.122

Khosravi, R., Hemami, M. R., Malekian, M., Silva, T. L., Rezaei, H. R., & Brito, J. C. (2018). Effect of landscape features on genetic structure of the goitered gazelle (*Gazella subgutturosa*) in Central Iran. *Conservation Genetics*, *19*(2), 323–336. https://doi.org/10.1007/s10592-017-1002-2

Kolahi, M., Sakai, T., Moriya, K., & Makhdoum, M. F. (2012). Challenges to the future development of Iran's protected areas system. *Environmental Management*, *50*(4), 750–765. https://doi.org/10.1007/s00267-012-9895-5

Lehikoinen, P., Santangeli, A., Jaatinen, K., Rajasärkkä, A., & Lehikoinen, A. (2019). Protected areas act as a buffer against detrimental effects of climate change—Evidence from large-scale, long-term abundance data. *Global Change Biology*, *25*(1), 304–313. https://doi.org/10.1111/gcb.14461

Levinsky, I., Skov, F., Svenning, J. C., & Rahbek, C. (2007). Potential impacts of climate change on the distributions and diversity patterns of European mammals. *Biodiversity and Conservation*, *16*(13), 3803–3816. https://doi.org/10.1007/s10531-007-9181-7

Littlefield, C. E., Krosby, M., Michalak, J. L., & Lawler, J. J. (2019). Connectivity for species on the move: Supporting climate-driven range shifts. *Frontiers in Ecology and the Environment*, *17*(5), 270–278. https://doi.org/10.1002/fee.2043

Loarie, S. R., Duffy, P. B., Hamilton, H., Asner, G. P., Field, C. B., & Ackerly, D. D. (2009). The velocity of climate change. *Nature*, *462*(7276), 1052. https://doi.org/10.1038/nature08649

Luo, Z., Jiang, Z., & Tang, S. (2015). Impacts of climate change on distributions and diversity of ungulates on the Tibetan Plateau. *Ecological Applications*, *25*(1), 24–38. https://doi.org/10.1890/13-1499.1

Malakoutikhah, S., Fakheran, S., Hemami, M. R., Tarkesh, M., & Senn, J. (2018). Altitudinal heterogeneity and vulnerability assessment of protected area network for climate change adaptation planning in central Iran. *Applied Geography*, *92*, 94–103. https://doi.org/10.1016/j.apgeog.2018.02.006

McRae, B. H., Dickson, B. G., Keitt, T. H., & Shah, V. B. (2008). Using circuit theory to model connectivity in ecology, evolution, and conservation. *Ecology*, *89*(10), 2712–2724. https://doi.org/10.1890/07-1861.1

McRae, B. H., Shah, V. B., & Mohapatra, T. K. (2013). *CIRCUITSCAPE 4 user guide*. Arlington, TX: The Nature Conservancy.

McSweeney, C. F., Jones, R. G., Lee, R. W., & Rowell, D. P. (2015). Selecting CMIP5 GCMs for downscaling over multiple regions. *Climate Dynamics*, *44*(11–12), 3237–3260. https://doi.org/10.1007/s00382-014-2418-8

Michalak, J. L., Lawler, J. J., Roberts, D. R., & Carroll, C. (2018). Distribution and protection of climatic refugia in North America. *Conservation Biology*, *32*(6), 1414–1425. https://doi.org/10.1111/cobi.13130

Moqanaki, E. M., & Cushman, S. A. (2017). All roads lead to Iran: Predicting landscape connectivity of the last stronghold for the critically endangered Asiatic cheetah. *Animal Conservation*, *20*(1), 29–41. https://doi.org/10.1111/acv.12281

Morecroft, M. D., Crick, H. Q., Duffield, S. J., & Macgregor, N. A. (2012). Resilience to climate change: Translating principles into practice. *Journal of Applied Ecology*, *49*(3), 547–551. https://doi.org/10.1111/j.1365-2664.2012.02136.x

Pacifici, M., Foden, W. B., Visconti, P., Watson, J. E. M., Butchart, S. H. M., Kovacs, K. M., … Rondinini, C. (2015). Assessing species vulnerability to climate change. *Nature Climate Change*, *5*(3), 215–224. https://doi.org/10.1038/nclimate2448

Pakniat, D., Hemami, M. R., Shahnaseri, G., Maleki, S., Adibi, M. A., Besmeli, M. R., … Tohidi, M. (2020). The potential distribution of wintering and breeding populations of Asian Houbara *Chlamydotis macqueenii* in Iran. *Bird Conservation International*, 1–15. https://doi.org/10.1017/S0959270920000167

Pearson, R. G., & Dawson, T. P. (2003). Predicting the impacts of climate change on the distribution of species: Are bioclimate envelope models useful? *Global Ecology and Biogeography*, *12*(5), 361–371. https://doi.org/10.1046/j.1466-822X.2003.00042.x

Pearson, R. G., & Dawson, T. P. (2004). Bioclimate Envelope Models: What they detect and what they hide: Response to hampe (2004). *Global Ecology and Biogeography*, *13*(5), 471–473. https://doi.org/10.1111/j.1466-822X.2004.00112.x

Phillips, S. J., & Dudík, M. (2008). Modelling of species distributions with MaxEnt: New extensions and a comprehensive evaluation. *Ecography*, *31*(2), 161–175.

R Development Core Team. (2014). *R: A language & environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Rangwala, I., Sinsky, E., & Miller, J. R. (2013). Amplified warming projections for high altitude regions of the northern hemisphere mid-latitudes from CMIP5 models. *Environmental Research Letters*, *8*(2), 024040. https://doi.org/10.1088/1748-9326/8/2/024040

Razgour, O. (2015). Beyond species distribution modeling: A landscape genetics approach to investigating range shifts under future climate change. *Ecological Informatics*, *30*, 250–256. https://doi.org/10.1016/j.ecoinf.2015.05.007

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., … Rafaj, P. (2011). RCP 8.5—A scenario of comparatively high greenhouse gas emissions. *Climatic Change*, *109*(1–2), 33.

Robillard, C. M., Coristine, L. E., Soares, R. N., & Kerr, J. T. (2015). Facilitating climate-change-induced range shifts across continental land-use barriers. *Conservation Biology*, *29*(6), 1586–1595. https://doi.org/10.1111/cobi.12556

Salas, E. A. L., Valdez, R., Michel, S., & Boykin, K. G. (2018). Habitat assessment of Marco Polo sheep (*Ovis ammon polii*) in Eastern Tajikistan: Modelling the effects of climate change. *Ecology and Evolution*, *8*(10), 5124–5138.

Sappington, J. M., Longshore, K. M., & Thomson, D. B. (2007). Quantifying landscape ruggedness for animal habitat analysis: A case study using bighorn sheep in the Mojave Desert. *Journal of Wildlife Management*, *71*, 1419–1426. https://doi.org/10.2193/2005-723

Schloss, C. A., Nuñez, T. A., & Lawler, J. J. (2012). Dispersal will limit ability of mammals to track climate change in the Western Hemisphere. *Proceedings of the National Academy of Sciences*, *109*(22), 8606–8611. https://doi.org/10.1073/pnas.1116791109

Sony, R. K., Sen, S., Kumar, S., Sen, M., & Jayahari, K. M. (2018). Niche models inform the effects of climate change on the endangered

Nilgiri Tahr (*Nilgiritragus hylocrius*) populations in the southern Western Ghats, India. *Ecological Engineering*, *120*, 355–363. https://doi.org/10.1016/j.ecoleng.2018.06.017

Tang, C. Q., Dong, Y.-F., Herrando-Moraira, S., Matsui, T., Ohashi, H., He, L.-Y., … López-Pujol, J. (2017). Potential effects of climate change on geographic distribution of the Tertiary relict tree species *Davidia involucrata* in China. *Scientific Reports*, *7*, 43822. https://doi.org/10.1038/srep43822

Thomas, C. D., Cameron, A., Green, R. E., Bakkenes, M., Beaumont, L. J., Collingham, Y. C., … Williams, S. E. (2004). Extinction risk from climate change. *Nature*, *427*(6970), 145. https://doi.org/10.1038/nature02121

Thomas, C. D., & Gillingham, P. K. (2015). The performance of protected areas for biodiversity under climate change. *Biological Journal of the Linnean Society*, *115*(3), 718–730. https://doi.org/10.1111/bij.12510

Thomas, C. D., Gillingham, P. K., Bradbury, R. B., Roy, D. B., Anderson, B. J., Baxter, J. M., … Hill, J. K. (2012). Protected areas facilitate species range expansions. *Proceedings of the National Academy of Sciences*, *109*(35), 14063–14068. https://doi.org/10.1073/pnas.1210251109

Thuiller, W. (2004). Patterns and uncertainties of species range shifts under climate change. *Global Change Biology*, *10*(12), 2020–2027. https://doi.org/10.1111/j.1365-2486.2004.00859.x

Thuiller, W., Broennimann, O., Hughes, G., Alkemade, J. R. M., Midgley, G. F., & Corsi, F. (2006). Vulnerability of African mammals to anthropogenic climate change under conservative land transformation assumptions. *Global Change Biology*, *12*(3), 424–440. https://doi.org/10.1111/j.1365-2486.2006.01115.x

Thuiller, W., Brotons, L., Araújo, M. B., & Lavorel, S. (2004). Effects of restricting environmental range of data to project current and future species distributions. *Ecography*, *27*(2), 165–172. https://doi.org/10.1111/j.0906-7590.2004.03673.x

Thuiller, W., Lafourcade, B., Engler, R., & Araújo, M. B. (2009). BIOMOD–a platform for ensemble forecasting of species distributions. *Ecography*, *32*(3), 369–373. https://doi.org/10.1111/j.1600-0587.2008.05742.x

Valdez, R. (2008). *Ovis orientalis. The IUCN Red List of Threatened Species 2008*. Retrieved from http://www.iucnredlis.org

Warren, M. S., Hill, J. K., Thomas, J. A., Asher, J., Fox, R., Huntley, B., … Thomas, C. D. (2001). Rapid responses of British butterflies to opposing forces of climate and habitat change. *Nature*, *414*, 65–69. https://doi.org/10.1038/35102054

Watanabe, M., Suzuki, T., O'ishi, R., Komuro, Y., Watanabe, S., Emori, S., … Kimoto, M. (2010). Improved climate simulation by MIROC5: Mean states, variability, and climate sensitivity. *Journal of Climate*, *23*(23), 6312–6335. https://doi.org/10.1175/2010JCLI3679.1

Watson, J. E., Dudley, N., Segan, D. B., & Hockings, M. (2014). The performance and potential of protected areas. *Nature*, *515*(7525), 67–73. https://doi.org/10.1038/nature13947

Watson, J. E., Iwamura, T., & Butt, N. (2013). Mapping vulnerability and conservation adaptation strategies under climate change. *Nature Climate Change*, *3*(11), 989–994. https://doi.org/10.1038/nclimate2007

Weinberg, P., Jdeidi, T., Masseti, M., Nader, I., de Smet, K., & Cuzin, F. (2008). *Capra aegagrus. The IUCN Red List of Threatened Species 2008*. Retrieved from http://www.iucnredlis.org

Yousefi, M., Ahmadi, M., Nourani, E., Behrooz, R., Rajabizadeh, M., Geniez, P., & Kaboli, M. (2015). Upward altitudinal shifts in habitat suitability of mountain vipers since the last glacial maximum. *PLoS One*, *10*(9), e0138087. https://doi.org/10.1371/journal.pone.0138087

BIOSKETCH

Shima Malakoutikhah is a PhD researcher at Isfahan University of Technology (IUT). Her research is mainly focused on species distribution and landscape connectivity modelling with a specific interest in their application to predict and understand the impact of climate change on species.

Author contributions: S.M. and S.F. jointly convinced the ideas; S.M. and M.R.H. jointly collected the data; S.M. performed the analyses; and all the authors led the writing.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Malakoutikhah S, Fakheran S, Hemami M-R, Tarkesh M, Senn J. Assessing future distribution, suitability of corridors and efficiency of protected areas to conserve vulnerable ungulates under climate change. *Divers Distrib*. 2020;00:1–14. https://doi.org/10.1111/ddi.13117