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Comparing landscape suitability and permeability with and without migration data: the influence of species movement behavior

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Abstract: Maintaining landscape connectivity through identifying movement corridors is the most recommended conservation strategy to reduce the negative impacts of habitat loss and isolation. The basis of most connectivity modelling approaches for modelling corridors is that species choose movement pathways based on the same criteria they used to choose habitats. However, species behave differently in using landscape elements for moving than for selecting habitat. In other words, suitability of a given landscape feature may differ between moving and habitat use stages. In this study, we evaluated how the availability of migration occurrence points for wild sheep (*Ovis orientalis*) could affect the outputs of distribution models and consequently the strength and extent of landscape connectivity for migratory movements of this species in central Iran. We employed concepts of Maximum entropy and circuit theory and developed 2 groups of habitat suitability and connectivity models with and without migration data. Comparing the results of the developed models showed that the main differences in the outputs of MaxEnt models were associated with suitability values predicted for the unprotected migration habitats. Without migration occurrence points, MaxEnt did not identify the traditionally used migration habitats. In contrast, Circuitscape represented a similar performance in predicting the main migration corridor of the species when using or not using the migration occurrence data. These differences could be associated with wild sheep's different behavior in the selection of habitat during movement and home range stages. Owning to this difference, we suggest using migration data in modelling landscape connectivity as these data may include different environmental conditions to those collected from home range habitats. For wild sheep, we recommend protecting the migration corridor at least during migration time. Maintaining such connectivity would also largely depend on managing the unprotected matrix through preventing expansion of human land uses in the vicinity of the corridor and buffering it to some distance.

Key words: MaxEnt model, habitat security, landscape permeability, anthropogenic threats, current flow, functional connectivity

1. Introduction

Herbivorous mammals demand large tracts of continuous marginal and/or seasonal habitats (Forman and Gordon, 1986) to meet the full suite of their daily and year-round requirements. Most protected areas (hereafter, PAs), however, have been found insufficient to include the entire range of habitats needed throughout the year (Caro et al., 2009). Furthermore, the unprotected matrix between many PAs has been subject to increasing expansion of human activities (Gangadharan et al., 2017), with destruction and fragmentation of natural but unprotected habitat as one of the key current drivers threatening the survival of these species (Ramiadantsoa et al., 2015; Tapia-Armijos et al., 2015). Habitat fragmentation could severely impede or disrupt the movement of large mammals when their current habitat conditions become limiting temporarily and trigger local extinction (Berger, 2004; Bolger et al., 2008). Thus, to more effectively conserve large migratory herbivores, conservation efforts should be expanded beyond discrete seasonal habitats (Berger, 2004; Berger et al., 2014; Bolger et al., 2008; Sawyer et al., 2009) by incorporating landscape connectivity as a vital component. Increasing landscape connectivity could also significantly benefit these species in the context of changing climate as it facilitates the convenient movement of the species toward more suitable ranges (Heller and Zavaleta, 2009; Brost and Beier, 2012; Schloss et al., 2011).

Landscape connectivity is defined as the ability of a landscape in facilitating or impeding individuals' movements between suitable habitat patches (Taylor et al., 1993). This definition consists of 2 main components: structural connectivity which refers to the impact of

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the physical characteristics of a landscape that allows for movement of species (Rudnick et al., 2012) and is independent of species ecological characteristics (Taylor, 2006). The second component is functional connectivity describing movements of individuals or genes across a landscape (Taylor et al., 1993). This kind of connectivity results from interactions between individuals' ecological characteristics such as habitat preference and dispersal ability and structural characteristics of the landscape (Rudnick et al., 2012). Adding the functional feature to the concept of landscape connectivity has resulted in the definition of corridors to shift from simply linear habitats structurally connecting habitat patches (Tischendorf and Fahrig, 2000) to sections of the landscape providing high levels of connectivity. An important benefit of this definition is that from this perspective, every feature across a landscape could have the potential to provide functional connectivity regardless of being structurally connected or not.

Modelling landscape connectivity first requires obtaining estimates of landscape resistance or suitability to species movement. The most common approach to obtain such estimates is through modelling species distribution (habitat suitability), because of ease of studying habitat suitability compared with landscape use during dispersal or migration movements (Keeley et al., 2016; Keeley et al., 2017). Species distribution models (SDMs) use a set of environmental values at species occurrence points to fit a model describing the species-environmental relationship and then transfer it to space to predict the distribution of suitable habitats for a given species. Occurrence data used for connectivity modelling are usually collected within a set of habitat patches as the source and target habitats and the intervene matrix where the species are known to display movements (migration/dispersal) between the habitats (e.g., Poor et al., 2012; Ahmadi et al., 2017; Khosravi et al., 2018a). Assuming that species may choose habitats during migration/dispersal in the same way as they select habitats as home range, makes it reasonable to use these 2 groups of occurrence data together. However, species may act differently in selection of migration/dispersal and home range habitats (Elliot et al., 2014). Species have been shown to be more flexible in using landscape features for dispersal/ migration movements in a way that they may also use habitats that are otherwise of lower suitability as the home ranges (e.g., Gastón et al., 2016; Keeley et al., 2016; Trainor et al., 2013). This has been well documented using empirical movement data obtained by radio tracking techniques (e.g., Trainor et al., 2013; Gastón et al., 2016; Keeley et al., 2016). However, in many cases such empirical data on movement are not available (Khosravi et al., 2018b). Therefore, occurrence data associated with migration/dispersal may be an alternative to represent and compare such differences in habitat selection.

The most recent studies for modelling functional connectivity take advantage of the concept of circuit theory to estimate and map the movement probability of a given species (McRae and Beier, 2007; McRae et al., 2008; Zeller et al., 2017; Ahmadi et al., 2017). Applying concepts from circuit models into ecological studies is derived from similarities between electrical and ecological connectivity (Shah and McRae, 2008). Circuit theory converts a landscape into a circuit where every habitat pixel is represented as an electrical node connected to neighboring pixels by resistors (Shah and McRae, 2008). The density of current flowing across the circuit predicts a probability that a random walker moves between 2 habitat patches or pixels (Dickson et al., 2013). High current densities represent areas where an individual has the highest probability of movement between habitat patches. However, it may also be suggestive of many paths forced to concentrate through that area because of the high resistance values of the surrounding pixels, or limited extent of the study area.

Iran is considered as an important range country for vulnerable wild sheep (*Ovis orientalis*). The species mainly inhabit rolling steppes, foothills and low elevation mountains (Bashari and Hemami, 2013). Wild sheep were originally distributed over large areas in Iran; however, anthropogenic factors such as habitat destruction, poaching and overgrazing resulted in a considerable reduction of the species' range (Bashari and Hemami, 2013). Presently, substantial populations of the species are mostly confined to the Iranian PAs; however, in some regions they display regular movements between the PAs in response to seasonal changes in environmental conditions. In the past, the network of protected area across wild sheep's current distribution range has performed well in protecting the wild sheep. However, increasing loss of connectivity between the PAs has been largely ignored becoming a major issue in conserving the migratory populations. In harsh seasons, individuals are forced to move outside the protected habitats where they are likely to be exposed to anthropogenic threats such as poaching and disturbance. As a result, it is necessary to identify and protect permeable parts of the landscape maintaining or improving landscape.

In this study, we evaluated developing SDMs with and without migration occurrence points of wild sheep. We focused on wild sheep as the target species because contrary to the other ungulates in our study area, the wild goat (*Capra aegagrus*) and the Goitered gazelle (*Gazella subgutturosa*), this species still shows widespread regular seasonal movements between the PAs. By comparing results of the SDMs, and the circuit models, we aimed to find out how well circuit model can predict landscape connectivity based on occurrence data related to home range habitat (without incorporating migration data) and compare how different preferences of wild sheep in selecting home range and migration habitats would affect the output of the circuit model.

2. Material and methods

2.1. Study area

The study area encompasses 2 protected areas with significant populations of wild sheep in Iran including Mooteh wildlife refuge and Haftad-Gholleh protected area (Figure 1) and the unprotected landscape in between them. These 2 protected areas are among the sites with the best habitats for the wild sheep and harbor large numbers of the species within the country. In addition, because of their geographic position and their physical properties, they function as important winter and summer habitats for this ungulate. Mooteh is located at the lower latitude in the north of Isfahan province (50° 29' 27"-51° 7' 26" E, 33° 29'- 33° 50' N) with the majority of its area in dry climate while, Haftad-Gholleh on the other hand is located at higher latitude (49° 57'-50° 22' E, 33° 55'-34° 18' N) in the south of Markazi province dominated by semidry climate. The unprotected landscape in-between covers an area of about 670,000 ha and has long been used for seasonal migrations. Migration of the wild sheep populations starts in late September and continues into October from Haftad-Gholleh to the wintering ranges in Mooteh Wildlife Refuge (Hereafter, WR). Late winter and beginning of the spring (March-April) is the time when the migrants leave the wintering ranges and get back to the summer ranges in Haftad-Gholleh Protected Area (Hereafter, PA). Elevation in the study region ranges from 1420 to 2898 m above the sea level. Higher altitudes are mainly found in the vicinity of the southern edge of the Haftad-Gholleh PA in the north and near Mooteh WR in the south. Human-wildlife conflicts are mainly concentrated in the eastern part of the study area and include human settlements (i.e. towns and villages), agricultural lands, mines and industries.

2.2. Distributional data and geo-ecological variables

Wild sheep occurrence data were compiled during the fall and winter of 2015 which coincided with the peak time of migration movements. In addition to direct observation, we also recorded localities of individuals through indirect observations including footprints and droppings left as the migrants moved or rested in the region. In total, we complied a dataset of 102 occurrence points including 26 points recorded across the unprotected landscape and the remaining across home ranges within the 2 PAs. We then evaluated the complied occurrence points for spatial autocorrelation using Moran Index in ArcMap which

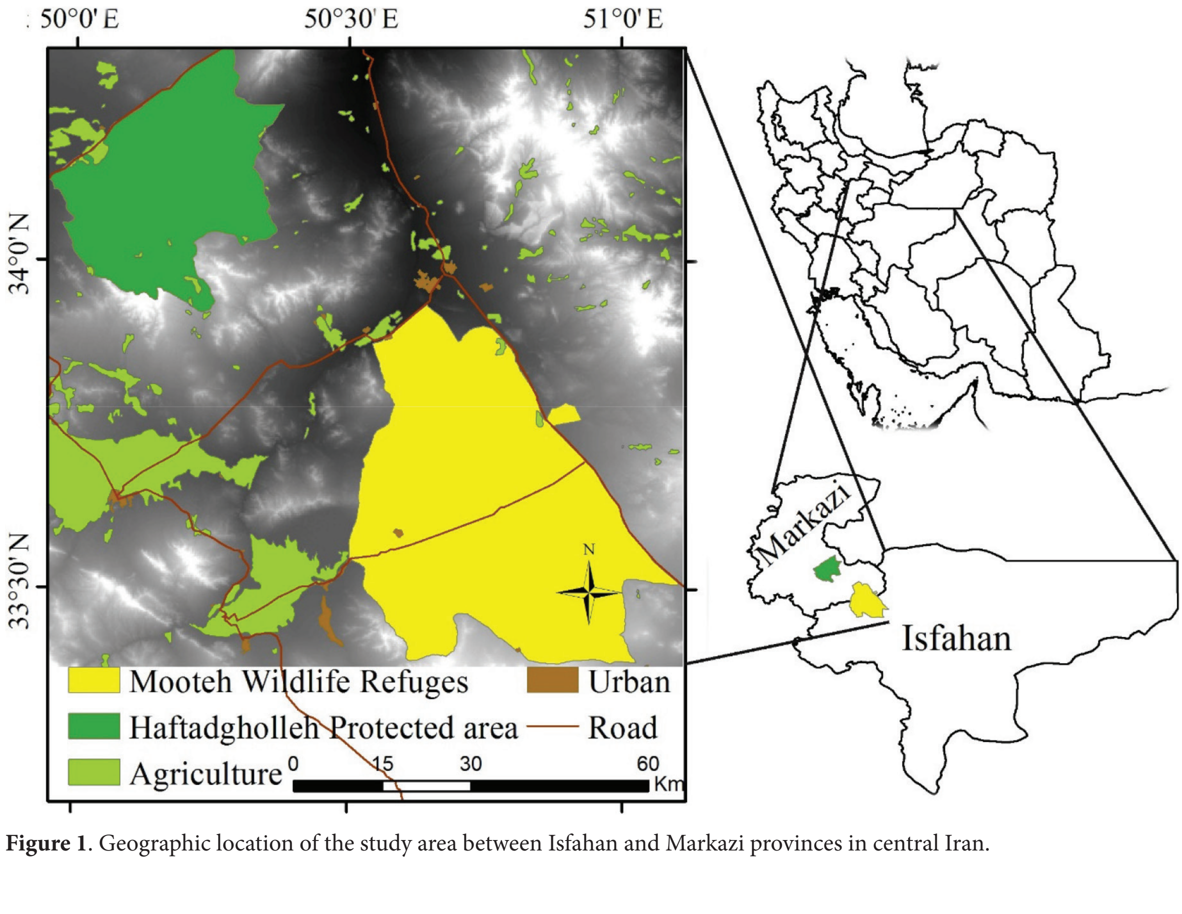

Figure 1. Geographic location of the study area between Isfahan and Markazi provinces in central Iran.

indicated no autocorrelation among the data. Therefore, we used all the 102 occurrence points to model wild sheep distribution.

We selected 34 eco-geographic parameters to develop the distribution models for wild sheep (Table S1). Data layers of these variables were either produced or obtained from various available databases all at a spatial resolution of 250 m. An elevation map for the study area was obtained from USGS.org with 90 m spatial resolution. Slope and aspect were produced using the DEM of the study area. For aspect, we developed a categorial map by assigning integer values from 1 to 5 to each class of aspect from 0–360 degrees (1: 0–45, 2: 45–135; 3: 135–225; 4: 225–315; 5: 316–360). Vegetation is an important habitat variable influencing habitats suitability for herbivores (Fryxell, 1991). For this reason, we used 2 related vegetation variables. The first variable was Soil Adjusted Vegetation Index (SAVI) developed by MODIS in 2015 at a spatial resolution of 250 m. To approximate the amount of green vegetation available during migration, we calculated SAVI values for the 2 months of September and October in 2015 (2 indices for each month). The 4 SAVI indices were then averaged and the resulting map was used as the final SAVI index. We also selected 4 important vegetation types preferred by the wild sheep from the landcover map of the study area (Table S1) which were converted into distance maps using ArcMap Spatial Analysis Tools. A similar conversion was performed for the 5 anthropogenic variables of roads, mines, human settlements (urban areas), village and agriculture fields extracted from the topographic map of the study area. We also considered the contribution of climate in wild sheep distribution by initially using 19 bioclimatic variables at the spatial resolution of 1 km downloaded from the WorldClim database (Hijmans et al., 2005) (Table S1) downscaled to match the defined spatial resolution of the analysis using SPLAIN tool (Khosravi et al., 2016). All the prepared variables were tested for collinearity using the variance inflation factor (VIF) and those with the VIFs > 6 (Sony et al., 2018) were considered as linearly dependent variables. For distribution modelling, we initially used all the nonlinearly and linearly correlated variables together and ran the MaxEnt model. Then, using jackknife results, we were able to select among the important linearly dependent variables based on their contribution in predicting wild sheep distribution which resulted in 11 eco-geographic variables (Table 1).

2.3. Wild sheep distribution modelling

Modelling distribution of wild sheep was based on a presence-only data approach using a machine learning algorithm implemented in MaxEnt software version3.3. MaxEnt predicts the distribution of a given species by finding the distribution of maximum entropy (i.e. that is closest to uniform). It performs under this constraint that the expected value of each environmental predictor should approximate its empirical average value (Phillips et al., 2006). Compared with other modelling techniques MaxEnt has several advantages including; 1) predicting species distribution without requiring absence data (Phillips et al., 2006); 2) efficiently handling complex interactions between predictor and response variables (Elith et al., 2006); 3) good performance in dealing with presence only data sets compared to other discriminative models and the ability

Table 1. Final geo-ecological variables used to develop distribution models for wild sheep.

Eco-geographic variable group	Variable	Description	Source
Topography	Slope	-	90 m DEM
	Aspect	-	90 m DEM
Vegetation related	SAVI	Enhanced vegetation index	MODIS 250 m images
	Vegetation cover	Euclidean distance to vegetation type	Center of agricultural and natural resource research
Climate	Bio 13	Precipitation of wettest month	Wordclim.org
	Bio14	Precipitation of driest month	Wordclim.org
Anthropogenic impact	Roads	Distance to primary and secondary roads	1/50,000 topography map
	Urban areas	Distance to urban areas	1/50,000 topography map
	Mines	Distance to mines	1/50,000 topography map

to handle categorical variables (Elith et al., 2011); and 4) ability to predict species distribution with small sample size (Philips and Dudik, 2008).

We predicted habitat suitability and distribution of wild sheep in 2 ways. First, a distribution model was developed using the full set of occurrence data collected inside both PAs and the unprotected landscape (hereafter, the first MaxEnt model). For the other distribution model, we excluded the migration data and predicted wild sheep distribution using only occurrence points associated with home range use within the 2 PAs (hereafter, the second MaxEnt model). To compare the differences in suitable habitats between the 2 approaches, predicted distribution maps of wild sheep were converted to binary maps of presence/absence using the 10-percentile training presence of suitability value at presence points. We then calculated the area and proportion of protected/unprotected suitable habitats across the study area under each modelling approach.

To predict habitat suitability for wild sheep, Maxent model was parameterized with these settings including: number of maximum model iterations to 500 which allows the model to have enough time for convergence preventing the model from over- or under-prediction (Young et al., 2011), 5000 background points randomly selected as the number of pseudoabsence points, and ten replicates run. To produce each SDM, 75% of the data were used to fit the model and the remaining proportion for evaluating MaxEnt predictive performance. We selected the model outputs to be represented in the logistic format (Phillips and Dudik, 2008). Predictions in this format range from 0–1 indicating the probability of species occurrence in each habitat grid cell (Phillips and Dudik, 2008). The performance of the MaxEnt model in accurately predicting the distribution of wild sheep was evaluated using AUC (Area under the receiver operating characteristic curve). The AUC is a threshold-independent index measuring how well a model can is able to discriminate between the presence and absence sites (Fielding and Bell, 1997). This index ranges from 0–1, where AUC score of 0.5 indicates a random model having no predictive ability, and value of 1 represents the perfect ability of the model in discriminating between the presence and absence sites.

2.4. Modelling migration corridors

Among the modelling approaches, circuitscape model is the only one with the capability to model landscape connectivity using suitability maps without the need to convert them to resistance surfaces. Circuitscape calculates 2 indexes of current density including the maximum and the cumulative current flow. The former index is used to measure the maximum of current flow between individual pairs of neighboring patches in order to identify pinch points between them regardless of their importance across the entire network of habitat patches (Dickson et al., 2013).The latter index however, is obtained by summing up the current density calculated between all possible pairs of habitat patches providing a measure of patch importance in maintaining the connectivity of the entire network of habitat patches (Dickson et al., 2013). In this study, migration corridors of wild sheep were predicted between 2 PAs as our focal areas so, maximum and the cumulative current flow were both of the same values. For the intervene matrix, we used the distribution maps produced by the MaxEnt model and introduced it as a conductive surface into the Circuitscape software (McRae and Shah, 2009). To calculate current density, we used the all-to-one model where in each iteration one of the PA was connected to the ground and the other to the 1- ampere current source and vice versa. The resulting current maps were then summed up where current values depicted the most probable areas for movement of the wild sheep between the target PAs.

3. Results

For both SDMs, we obtained AUC value above 0.90 (AUC $_{\text{first model}}$ = 0.927, AUC $_{\text{second model}}$ = 0.936) indicating good performance of MaxEnt in predicting distribution of wild sheep. Based on the results of jackknife analysis (Figure 2), distance to urban areas, precipitation of the wettest month, slope and vegetation type gained the highest ranking in the first MaxEnt model prediction. For the second MaxEnt model also the results were similar although with slope and vegetation both gained the same important ranking followed by SAVI index (Figure 2).

Predicted distribution of wild sheep using 2 different sets of occurrence data and the associated quantitative comparisons are shown in Figure 3 and Table 2, respectively. The majority of suitable habitat areas predicted under both models are located within the PAs mostly in mountainous and hilly terrains. In Mooteh WR however, habitats of high quality were of lesser extent and limited to a small patch in the northern part of the WR. The most obvious difference between outputs of the MaxEnt models was for the extent of unprotected suitable habitats in the study landscape. The first MaxEnt model well predicted the unprotected migration habitats linearly distributed in the north-south direction. While, these habitats were predicted to have very low suitability based on the prediction of the second model developed without the migration data. In the second MaxEnt model, unprotected highly suitable habitat patches were predicted in close proximity to the southern edge of the Haftad-Gholleh PA. Except for the Mooteh WR, potentially suitable habitats, both protected and unprotected, were predicted to have larger extents excluding the migration points from distribution modelling (Table 2). As the comparison of the estimates in Table 2 shows, in both distribution models, the largest change in

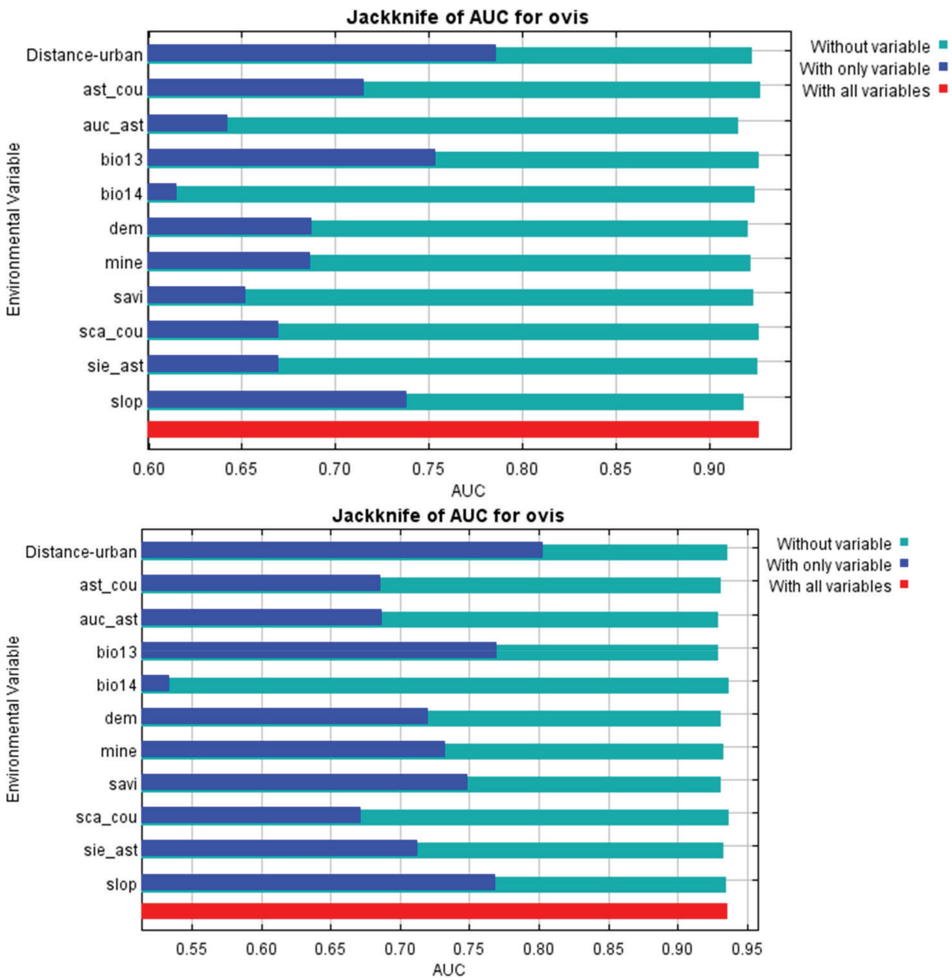

Figure 2. Importance of environmental variables evaluated based on jackknife analysis in the first (up) and second (down) MaxEnt model.

Table 2. Comparison between the extent of the protected and unprotected suitable habitats (km^2) predicted for wild sheep by the first and the second MaxEnt models.

Protected area	First MaxEnt model	Second MaxEnt model	Percentage change in area
Mooteh WR	54.18	43.75	–10.27
Haftad-Gholleh PA	217.06	237.15	+ 21.71
Unprotected landscape	40.56	43.75	+ 7.86
Total area	311.80	324.65	-

the area of suitable habitat was predicted for the protected habitats in Haftad-Gholleh PA (Figure 4, Table 2).

Based on the measured cumulative current flow, we identified areas of high permeability for movement of wild sheep between the PAs (Figure 5). In the first circuit model, the most likely movement corridor was predicted in the western part of the study landscape where a rather wide band of high current extending in the north–south direction connected the 2 PAs (connection number 1). As shown, the main migration corridor is intersected by the Delijan-Mahallat road stretching from west to east. Excluding the migration occurrence data, larger parts of the unprotected landscape were predicted as permeable for movement of wild sheep (Figure 5). Similar to the first

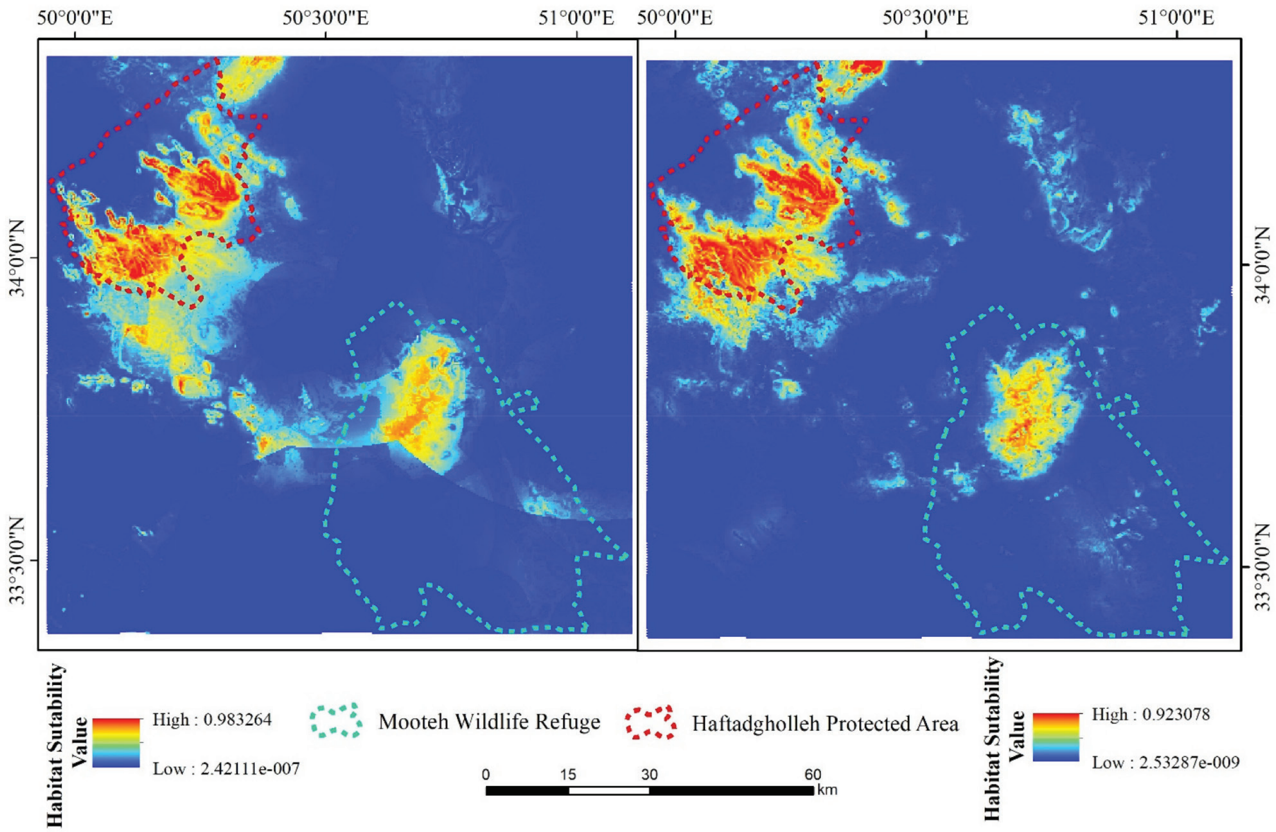

Figure 3. Distribution of wild sheep predicted using the full set of occurrence data (left panel) and only occurrence data associated with home range use within the PAs (right panel)

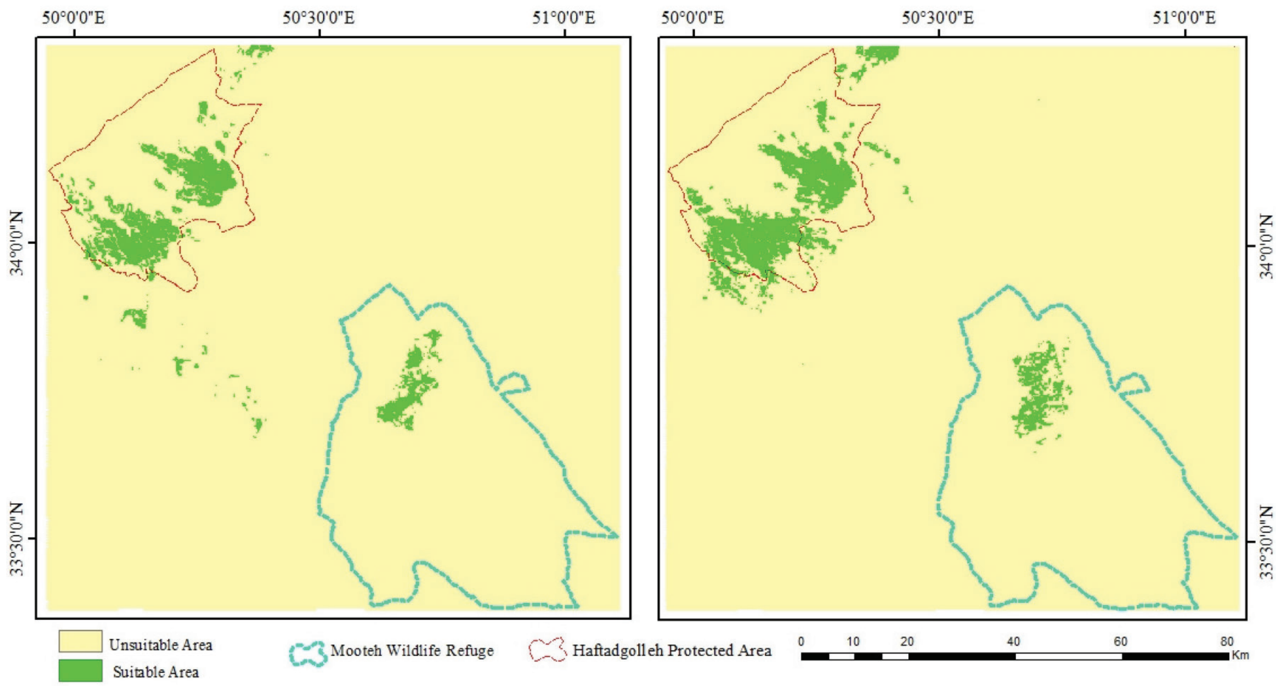

Figure 4. Suitable and unsuitable habitats of wild sheep using full set of occurrence data (left panel) and only data compiled within the PAs (right panel).

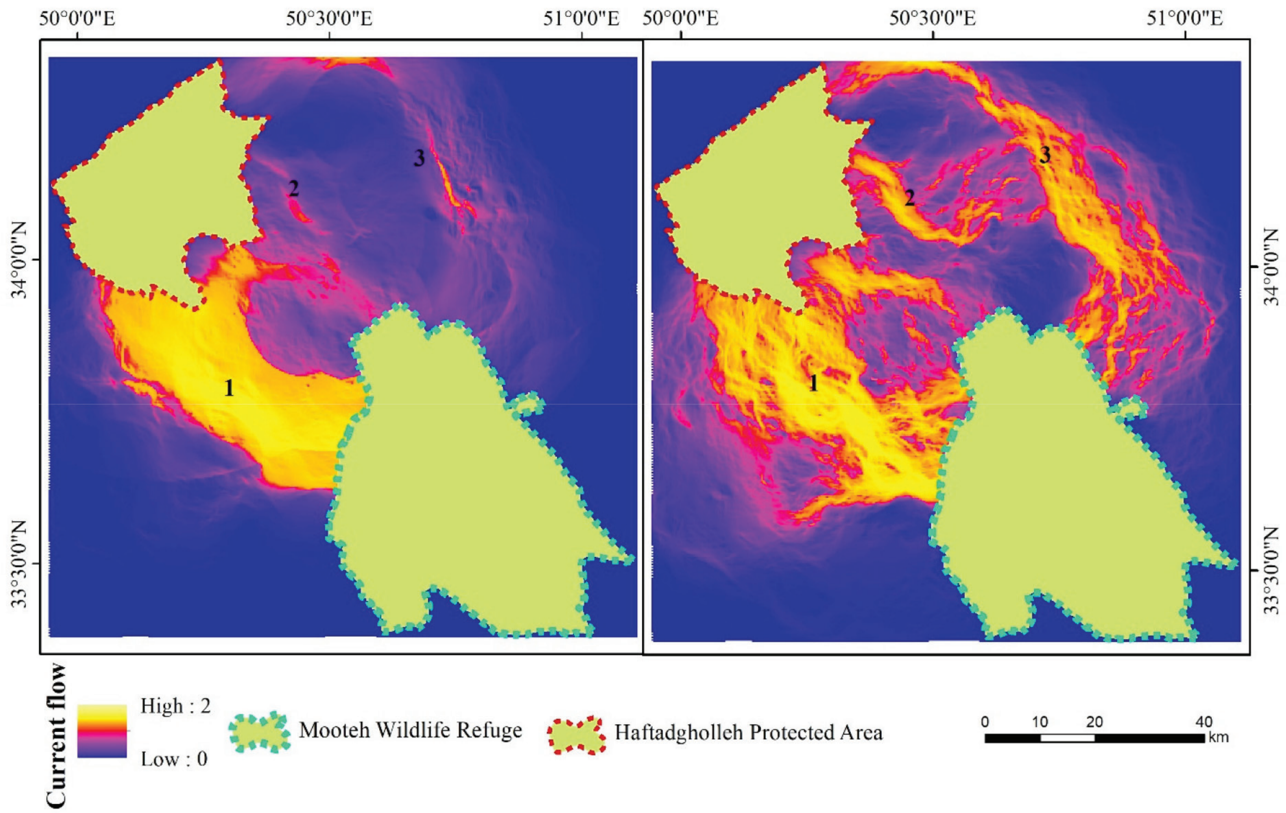

Figure 5. Predicted areas of high permeability for wild sheep's seasonal movements using full set of occurrence data (left panel) and only data compiled within the PAs (right panel) between Mooteh WR and Haftad-Gholle PA.

circuit model, the second circuit model also predicted the western connection, however, both connectivity models predicted additional potential connections connecting the PAs including a rather wide corridor in the furthermost east connecting the north-east of the Mooteh to Haftad-Gholleh through south-east (connection number 2) and north-east edges (connection number 3) as the longest corridor identified for migration of wild sheep in the region. Overlaying the second current map with the map of road network showed that the eastern connections were also interrupted at several locations by the Isfahan-Tehran highway.

4. Discussion

In this study, we evaluated how inclusion and exclusion of the migration data affect the outputs of distribution and connectivity models and thereby explain movement behavior of wild sheep. MaxEnt model uses environmental conditions at occurrence points as a surrogate to evaluate and estimate the environmental suitability of the whole landscape for a given species. When excluding the migration points, it was not possible to identify the whole migration habitats in the unprotected landscape, a result that could be associated with different range of environmental conditions captured by the 2 sets of occurrence points. When migration data were included, there was an increase in the contribution of the variables of distance to urban areas and slope in predicting wild sheep suitable habitats. This indicates the increasing role of habitat security in selection of migration habitats by wild sheep. From the Mooteh WR to the middle parts of the study area, the structure of the corridor consists of mountains and foothills as preferred habitat by the species. Along these parts of the corridor, slope would play an important part in reducing the risk of natural predation (Bashari and Hemami, 2013) and (illegal) hunting through providing escape terrain. From the middle part of the landscape to Haftad-Gholleh PA, however, migrating wild sheep moves along plains and low elevation areas, i.e. habitat that is normally avoided by this species. This fact could only be demonstrated by including migration data points. Otherwise the first MaxEnt model would have predicted this part of the corridor as unsuitable. These results show that the western movement corridor is still functional allowing these populations of wild sheep movements between the 2 protected areas.

Results obtained in this study were consistent with results of other studies that showed the tendency of species to select habitats of lower suitability during migration (e.g., Elliot et al., 2014; Mateo-Sánchez et al., 2015; Gaston et al., 2016; Keeley et al., 2016). For example, by comparing outputs of resistance maps, based on habitat suitability maps and empirical movement data, Keeley et al. (2016) found that bighorn sheep individuals traverse habitats of low and moderate suitability during long-distance movements. Here, our predictions of movement corridors for wild sheep were only based on environmental conditions captured at presence points collected during migration period. However, occurrence data provide part of the information required to identify species migration movements, and more detailed information could be obtained through radiotracking the species during migration time. Therefore, for similar studies in the future, it is recommended using radiotracking techniques along with the occurrence data to obtain more accurate and detailed information on species migration movements.

Another application of using empirical movement data is to evaluate the predictive performance of connectivity models (e.g., Poor et al., 2012; Lapoint et al., 2013; McClure et al., 2016). In this regard, some studies have used empirical movement data as a separate dataset to validate the modeled corridors while, others used them both for connectivity modelling and validating the predicted corridors. For example, Poor et al. (2012), used migration movement data of pronghorn (*Antilocapra americana*) and least-cost analysis to predict seasonal migration corridors for this species and evaluate the performance of the least-cost model based on the number of movement data fall within the defined corridors. Regarding Circuitscape, the predictive performance of this models has been evaluated comparing them with other connectivity models (e.g., Poor et al., 2012; La point et al., 2013; Malakoutikhah et al., 2013; McClure et al., 2016). In our study, however, we compared the performance of this connectivity model in mapping migration corridors assuming that no occurrence data on migration are available. As our results showed, the circuit model successfully predicted the main migration corridor traversed by the wild sheep populations when migration occurrence points were excluded. However, it failed to predict 2 other potential connections in the absence of the migration data. The reason for this may be associated with increased suitability of the habitats in the north-eastern of the study area, which has in increased flowing current, hence the probability of connectivity. Such increases were observed excluding the migration data from distribution modelling indicating the different behavior of wild sheep in using landscape features during migration compared to home-range stay. Regarding the 2 additional connections (number 2 and 3), there hase been no report about movements of wild sheep herds along these corridors, which could be associated with the long distance that the species has to traverse and more importantly, the Isfahan-Tehran highway as a barrier on the way of the species' movements. Predicting the eastern connection (connection number 2) as the longest movement pathway between the 2 PAs represented the unique characteristic of the circuit model compared with other common approaches such as least-cost analysis. In circuit theory current is not weighted by distance, therefore the model has the ability to identify all possible movement pathways regardless of their length and resistance. This ability of the model has important implication for conservation as it helps in identifying and assessing alternative pathways to consider when one connection is lost.

4.1. Conservation implications

According to the findings of this study, maintaining the functionality of the main migration corridors for wild sheep populations should be given a conservation priority in the study area. Mooteh and Haftad-Gholleh PAs harbor large populations of wild sheep with still active seasonal movements between the 2 sites. However, still expanding human land use and busy roads pose a serious threat to migration in terms of disrupting the main connection. In addition, lack of safety/control across the unprotected migration range is another concern as it could facilitate illegal hunting of the individuals by local people. Thus, it is necessary to protect the main corridor at least during the migration times in order to maintain the migration movements. By allowing individuals to move between the populations and thus gene flow, this corridor would play a vital role in mitigating the negative impacts of isolation on these populations (Cushman et al., 2013; Rabinowitz and Zeller, 2010; Theobald et al., 2012). In addition to the main corridor, it is necessary to manage the unprotected matrix specifically in areas located in the vicinity of the migration corridor. This could be possible by buffering the main corridor to prevent further expansion of anthropogenic activities into the vicinity of the corridors. Buffers could be established by expanding areas of high permeability for movement to a certain distance. As an example, such a buffer along connection number 2, which would increase safety for migrating wild sheep, could help to reconnect populations that are currently isolated.

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Table S1. List of the initial eco-geographical variables used to predict wild sheep' distribution.

Variable	Description	Source
Bio1	Annual mean temperature	Wordclim.org
Bio2	Mean diurnal range (Mean of monthly (max. temp– min. temp))	Wordclim.org
Bio3	Isothermality (BIO2/BIO7) (*100)	Wordclim.org
Bio4	Temperature seasonality (standard deviation *100)	Wordclim.org
Bio5	Max temperature of warmest month	Wordclim.org
Bio6	Min temperature of coldest month	Wordclim.org
Bio7	Temperature annual range (BIO5–BIO6)	Wordclim.org
Bio8	Mean temperature of wettest quarter	Wordclim.org
Bio9	Mean temperature of driest quarter	Wordclim.org
Bio10	Mean temperature of warmest quarter	Wordclim.org
Bio11	Mean temperature of coldest quarter	Wordclim.org
Bio12	Annual precipitation	Wordclim.org
Bio13	Precipitation of wettest month	Wordclim.org
Bio14	Precipitation of driest month	Wordclim.org
Bio15	Precipitation seasonality (coefficient of variation)	Wordclim.org
Bio16	Precipitation of wettest quarter	Wordclim.org
Bio17	Precipitation of driest quarter	Wordclim.org
Bio18	Precipitation of warmest quarter	Wordclim.org
Bio19	Precipitation of coldest quarter	Wordclim.org
Elevation	-	90m DEM
Slope	-	90m DEM
Aspect	-	90m DEM
Distance to road	-	1/50,000 topography map
Distance to urban	-	1/50,000 topography map
Distance to agricultural lands	-	1/50,000 topography map
Distance to village	-	1/50,000 topography map
Distance to river	-	1/50,000 topography map
Distance to spring	-	1/50,000 topography map
Distance to mine	-	1/50,000 topography map
Distance to Vegetation cover (*Artemisia aucheri – Astragalus*)	-	Center of agricultural and natural resource research
Distance to Vegetation cover (*Astragalus – Cousinia*)	-	Center of agricultural and natural resource research
Distance to Vegetation cover (*Scariola – Cousinia*)	-	Center of agricultural and natural resource research
Distance to Vegetation cover (*Artemisia sieberi- Astragalus*)	-	Center of agricultural and natural resource research
SAVI	Enhanced vegetation index	MODIS 250 m images