Exploring structural and functional corridors for wild sheep (*Ovis orientalis*) in a semi-arid area

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Abstract:
Although corridors have been the subject of extensive research in the recent years, the probable correlation between structural and functional corridors have not been addressed to date. To fill this scientific gap, we compared structural and functional corridors of wild sheep (*Ovis orientalis*) as a threatened species in a semi-arid area of central Iran. We first used Maximum-Entropy to develop wild sheep habitat suitability map. We then used Morphological-Spatial-Pattern-Analysis (MSPA) and circuit theory to map structural and functional corridors of wild sheep respectively. Bootstrapping techniques then were used to compare structural and functional corridors. We found that structural corridor is a concept which is dependent on the scale of observation. By changing edge-width from 600 to 1200 m, the total area of structural corridors increased by 63%. We also only found very small differences in the functional connectivity role of different MSPA categories (including structural corridors). All MSPA categories together accounted for only 20% of the functional connectivity. Although, in some cases functional corridors had a better performance in showing migration path of wild sheep between reserves, other cases showed that for effective conservation, both structural and functional corridors should be identified and considered in the planning step.

Keywords:
Animal movement, Circuitscape, Connectivity, Functional corridor, Habitat suitability modeling, MaxEnt, MSPA, Structural corridor, Wild sheep

Introduction:

Human activities have led to habitat loss and fragmentation (de la Torre et al. 2017; Woodruff 2001). Habitat fragmentation can influence genetic structure, individual behavior, population dynamics, and interspecies relationships (Swihart et al. 2001). Species with low population density are more vulnerable against habitat fragmentation (Thornton et al. 2011), especially in arid and semi-arid areas where only limited resources of forage and water are available (Hobbs et al. 2008).

Corridors refer to parts of the landscape that animals use to move between habitat patches and cause improvement of connectivity (Farina 2000; Hilty et al. 2006; Vos et al. 2002). Corridors can assist in maintaining the natural integrity of suitable habitats and protected areas (Cushman et al. 2013; Harker 2000; Worboys and Mackey 2013).

Structural corridors (Baudry and Merriam 1988) are narrow landscape components which connect two or more habitat cores (Clerici and Vogt 2013) and enhance the "connectedness" of the landscape (Baudry and Merriam 1988). The structural corridor concept is based on the spatial configuration of suitable habitats (physical continuity of habitat) without considering species' behavioral responses to the landscape (Saura et al. 2011; Tischendorf and Fahrig 2000). Functional corridors, on the other hand, describe the paths that animals would take between habitat patches whether these habitats are structurally connected to each other or not (Burel and Baudry 2003; Farina 2006; Taylor et al. 2006). Therefore, structural connectedness is not necessarily synonymous to functional connectivity (Tischendorf and Fahrig 2000), and relying solely upon the concept of structural corridors (connectedness) ignores the species' reaction to the landscape structure and heterogeneous environments (connectivity) that affect the distribution of the species (Taylor et al. 2006).

Mapping structural corridors is easier than functional corridors. To map structural corridors, landscape metrics can easily be used (Taylor et al. 2006). Recently, image processing techniques such as mathematical morphology have been employed in the delineation of structural corridors (Saura et al. 2011; Soille and Vogt 2009; Vogt et al. 2009).

For mapping functional corridors, the Least Cost Path (LCP) method (Adriaensen et al. 2003; Clevenger et al. 2002) and circuit theory (McRae 2006; McRae and Beier 2007; McRae et al. 2008) have become more accepted by researchers; both are based on graph theory (Poor et al. 2012). LCP usually selects one link between the two cores, while in the circuit theory; there is a possibility to select several links between two cores (Laita et al. 2011; Poor et al. 2012). Unlike LCP, in which it is assumed that the species almost entirely recognizes the landscape, in the circuit theory method, routes are selected based on random walkers (Cushman et al. 2013).

Despite the importance of corridors in conservation planning and reserve selection studies, published research addressing both structural and functional aspects of corridors are so rare that we could find only one applicable study, representing in a riverine ecosystem (Van Looy et al. 2014). Most studies of habitat connectivity are solely concentrated on either structural (Clerici and Vogt 2013; Darvishi et al. 2015; Duarte et al. 2013; Saura et al. 2011) or functional corridors (Breckheimer et al. 2014; Graves et al. 2007; Patthey 2003; Pelletier et al. 2014). To fill this research gap, we tried to show the differences between structural and functional corridors using a case study on a large body mammal species, wild sheep (*Ovis orientalis*), in a terrestrial ecosystem.

Wild sheep occur in arid and semiarid habitats in Iran, and is a vulnerable species according to the Red List of the International Union for Conservation of Nature (IUCN) (Valdez 2008). Wild sheep populations have been extirpated in many areas throughout their geographical range due to hunting, habitat destruction and competition with livestock (Valdez 2008; Ziaei 2008). There are currently protected areas in Iran, where wild sheep can be seen (Bashari and

Hemami 2013), but those areas have been selected on an ad-hoc basis (Momeni Dehaghi et al. 2013) without considering connectivity. Currently, migration of wild sheep in central Iran is faced with threats such as hunting and road construction (Ziaei 2008). Here we compared the association between structural and functional corridors of wild sheep in the central Iran. To address this question, we first used habitat suitability modeling to determine high-quality habitats, graph theory to model a proxy of functional corridors and image processing techniques to delineate structural corridors of wild sheep. We then compared the modelled functional corridors and structural corridors.

Methods:

Study area

The study area is around 33,500 km2 of semi-arid lands of the central part of Iran. This area is located between 52°37'42" - 55°26'25" E and 32°26'58" - 34°19'15" N with elevation 600-3100 m and maximum annual precipitation of 98 mm. Current reserves containing wild sheep in the study area are Siahkouh National Park and protected area, Abbasabad Wildlife Refuge and Kouh-e-Bozorgi and Kalateh No Hunting Areas (Fig.1).

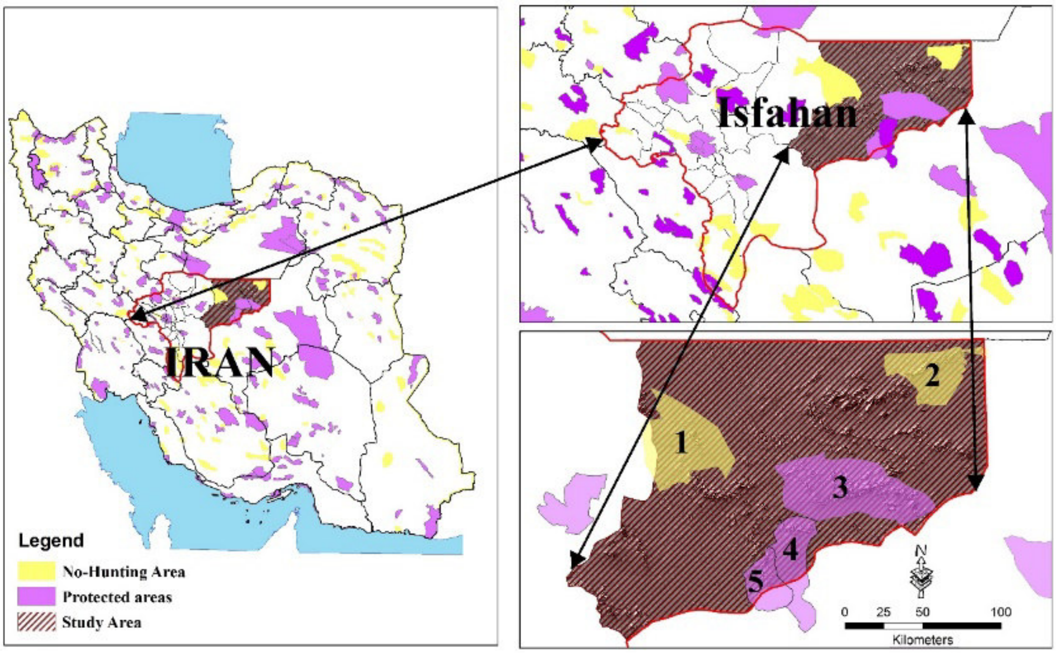

Figure 1- Location of the study area and current reserves in Iran (1: Kouh-e-Bozorgi No Hunting Area, 2: Kalateh No Hunting Area, 3: Abbasabad Wildlife Refuge, 4: Siahkouh Protected Area, 5: Siahkouh National Park).

Data

Digital elevation model (METI and NASA 2011), as well as the location of urban areas, villages, mines, springs, roads (NCC 2005),WorldClim data (Hijmans et al. 2005), and the Normalized Difference Vegetation Index (NDVI) (USGS 2014) were used in this research.

Habitat Suitability Modeling

The software MaxEnt v3.3.3k (Phillips et al. 2006) was used to produce relative habitat suitability map of wild sheep in the central Iran. One of the benefits of this method over others is that using limited occurrence data can also provide reasonable results (Baldwin 2009; Wisz et al. 2008) that is of particular importance for developing countries such as Iran, where only limited species occurrence data is available (Momeni Dehaghi et al. 2013). In total, 61 presence points of wild sheep were obtained from field visits and previous surveys by the Isfahan Department of Environment (DOE). We used Global Moran's I statistics to test autocorrelation between occurrence data (Li et al. 2007). The pattern of occurrence data was not significantly different from the random state (p-value = 0.114777; z-score = 1.577081), and so all data were used in the habitat suitability modeling process (20% of presence data were retained to test the model). The environmental factors considered in the study area are altitude, distance to human settlements, NDVI, distance to roads, distance to agricultural land, slope, distance to the springs, and the principal component of climatic factors obtained by Principal Component Analysis (PCA) of WorldClim data. A habitat suitability layer of wild sheep in the central part of Iran using nine environmental factors and ten replications was produced in 100m pixel size and then classified into binary format (suitable or unsuitable) using Equal training sensitivity and specificity method.

Mapping functional corridors

Wild sheep functional corridors were identified using circuit theory. The circuit is a network of nodes connected by resistance. Based on Ohm's law, the amount of current “I” that flows through the resistor depends on the input voltage and resistance “R” when a voltage “V” is applied across a resistor (McRae et al. 2008). In a constant voltage, less resistance increases the current. In corridor design, it is assumed that for moving between two nodes the target species will choose a path with the least resistance or environmental cost (Shah and McRae 2008). Therefore, with reduction of habitat suitability, the resistance to movement will increase (Huck et al. 2010; Patthey 2003; Poor et al. 2012; Wang et al. 2008). To design functional corridors of wild sheep, we used a landscape resistance layer derived from habitat suitability (Correa Ayram et al. 2016). To convert habitat suitability layer to the resistance layer, the following equation was used (Atwood et al. 2011):

$$\text{Travel cost or cell resistance} = 1 - \text{pixel suitability} \qquad \text{(eq.1)}$$

Protected areas were defined as nodes, and in the final step, the current of the species' movement between reserves (all to one) was examined using Circuitscape[1] software. To make these proportions more tangible, current values were rescaled to 10-20 range using linear function.

Mapping structural corridors

Wild sheep structural corridors were identified using mathematical morphology method within the Morphological Spatial Pattern Analysis (MSPA) framework (Soille and Vogt 2009). Using this framework, suitable habitats (foreground) were divided into seven categories as below (Clerici and Vogt 2013):

- Core: inner foreground pixels beyond a defined distance from the foreground-background boundary.
- Islet: foreground patch too small to contain core
- Perforation: transition from core to internal background
- Edge: transition pixels between core and external non-core.
- Loop: foreground pixels connecting a core area with itself
- Bridge: foreground pixels connecting at least two disjoint core areas
- Branch: foreground pixels linked to a core, but not connecting to another core

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1 http://www.circuitscape.org/downloads

This classification is highly dependent on "edge-width" variable which controls how a pixel assigns to the core habitats or edge habitats and also defines the minimum core size, and the internal (perforation) and external edge cells (Clerici and Vogt 2013). From the ecological perspective, habitat edge which can have different characteristics (e.g. humidity, invasive species, competition, and predation) in comparison to core habitats, normally is defined base on perception of understudy species from landscape (Clerici and Vogt 2013; Gates and Mosher 1981; Vogt et al. 2007). In this study, MSPA was applied using the maximum edge-width (d) of 1200 m and 600 m in accordance with radius of a circle which has same area to home-range of wild sheep (4.59 km^2) and half of the defined radius respectively.

Between seven categories of MSPA, the Bridge category was considered equivalent to structural corridors (Saura et al. 2011). In the MSPA, "Bridge" is calculated using equation 2 (Soille and Vogt 2009):

$$A = \delta_{X1}^{(s)}[SKEL_{X1}(X)] \qquad \text{(eq.2)}$$

Where A is habitat corridor, X is input binary image, X1 is core pixel, SKELx (Y) is algorithm anchored skeleton of Y using X algorithm as a set of anchor and δx (Y) is geodesic dilation of Y to X.

Overlap of functional and structural corridors

To investigate the association between functional corridor (Current layer) and MSPA categories, we calculated the mean current for each of the seven categories of MSPA (edge-width of 600 and 1200 m). We used bootstrapping (Efron and Tibshirani 1986) to obtain 95% confidence intervals of the mean currents. The pixels of the two layers were resampled randomly 10,000 times (with replication). The 0.025 and 0.975 quantiles of the 10,000 iterations were used as 95% confidence intervals for the mean current in each MSPA category. Even if certain types of structural corridors were to be associated with high currents, they may represent only a small proportion of the current if those types of corridors are rare. We therefore also extracted the proportion of total current associated to each MSPA category in the bootstrap samples.

Results

Habitat suitability of wild sheep

For the wild sheep model (Fig. 2), the area under the curve was calculated as 0.866 ± 0.025 (mean ± SD), which is in the acceptable range (Elith 2002; Phillips and Dudík 2008). According to percent contribution, the most important environmental factors that affect habitat suitability of wild sheep in the study area were altitude, distance to nearest road and distance to nearest spring while according to permutation importance, altitude, distance to nearest spring and the distance to nearest village had the highest impact (Table 1). Results of a Jackknife test on habitat parameters also showed that the highest gain is when altitude is used alone. In addition, the maximum amount of gain reduction occurs when this variable was removed, implying that this variable has information not available in others. Classification of continuous habitat suitability layer using equal training sensitivity and specificity threshold revealed that within the study area, a total of nearly 6,244 km^2 of land is suitable habitat for wild sheep and 2,744 km^2 (i.e. 44% of the total suitable areas) of suitable habitats of wild sheep are currently under protection.

Abbasabad Wildlife Refuge incorporates vast areas of suitable habitats for wild sheep. Kouh-e-Bozorgi no-hunting area and Siahkouh National Park are other reserves with high conservation value for wild sheep. These results were consistent with the perception of local people and conservation officers of wild sheep suitable habitats.

Table 1: contribution of variables in habitat suitability modeling of wild sheep

Variable	*Percent contribution*	*Permutation importance*
Altitude	70.1	52.3
PCA1	0.7	3
NDVI	0.1	0.3
Slope	4.4	3.4
Distance to nearest road	9.3	5.6
Distance to nearest spring	6.4	21.7
Distance to nearest village	4.8	7.1
Distance to nearest city	4	6.5
Distance to nearest mine	0.2	0.2

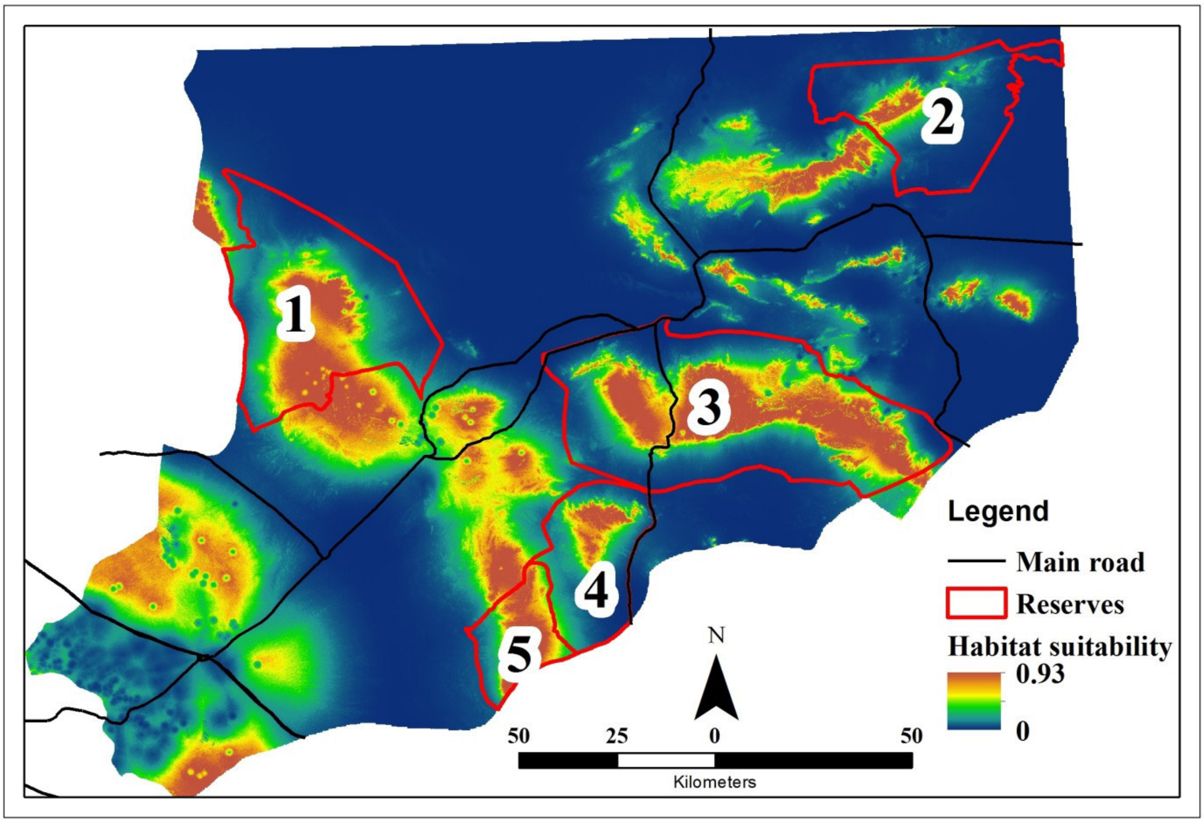

Figure 2- habitat suitability map of wild sheep. In the legend, 0 and 0.93 indicate the lowest and highest suitability respectively. (1: Kouh-e-Bozorgi No Hunting Area, 2: Kalateh No Hunting Area, 3: Abbasabad Wildlife Refuge, 4: Siahkouh Protected Area, 5: Siahkouh National Park)

Functional corridors

According to the current map of possible wild sheep migration (Fig. 3), in situations where the current rate is higher, the possibility of species' migration between protected areas is increased, and removing or modifying these areas will have significant adverse effects on the species' habitat connectivity. The results indicate that the highest current is between Abbasabad Wildlife Refuge and Siahkouh Protected Area, Siahkouh National Park, and Kouh-e-Bozorgi No-Hunting Areas as well as between Kalateh No-Hunting Area and Abbasabad Wildlife Refuge.

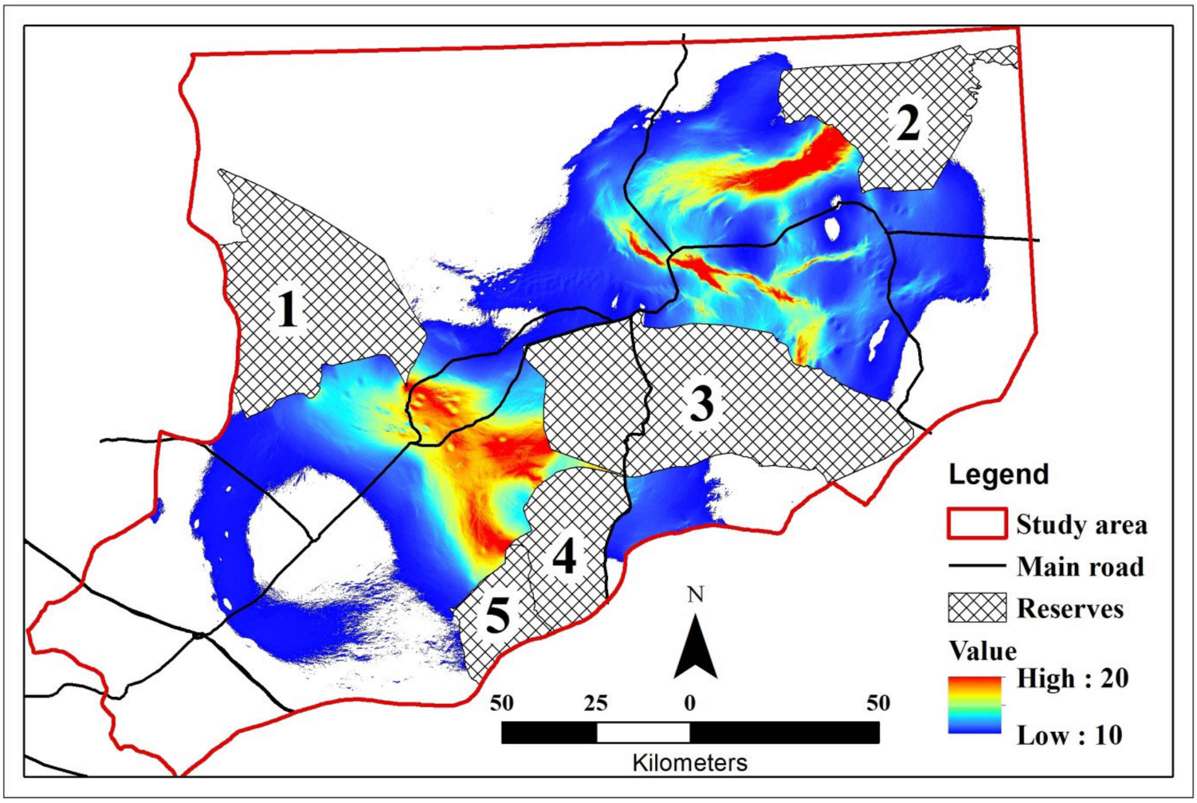

Figure 3-Current map (All to one) of possible wild sheep migration between protected areas located in central Iran (1: Kouh-e-Bozorgi No Hunting Area, 2: Kalateh No Hunting Area, 3: Abbasabad Wildlife Refuge, 4: Siahkouh Protected Area, 5: Siahkouh National Park)

Structural corridors

By considering an edge-width of 600 m (Fig. 4a), suitable habitats classified to 53.8% Core, 2.4% Islet, 0.9% Perforation, 1.0 % Edge, 11.5% Loop, 0.8% Branch and about 29.5% (739 km^2) Bridge, which in this study have been considered as structural corridors. When edge-width is changed to 1200 m (Fig. 4b), percentages changed to 37.2% Core, 8.7% Islet, 0.8% Perforation, 0.6% Edge, 5.8% Loop, 0.4% Branch and about 46.5% (1,166 km^2) Bridge (Table 2).

According to results, nearly 58 and 56 percent of the total structural corridors of wild sheep in the study area is outside the current reserves system when edge-width equals to 600 m and 1200 m respectively. Most of the determined structural corridors outside the protected areas are located between Kalateh no-hunting area and Abbasabad wildlife refuge. Also, habitats between Siahkouh National Park/Protected Area and Kouh-e-bozorgi No-Hunting Area included important structural corridors.

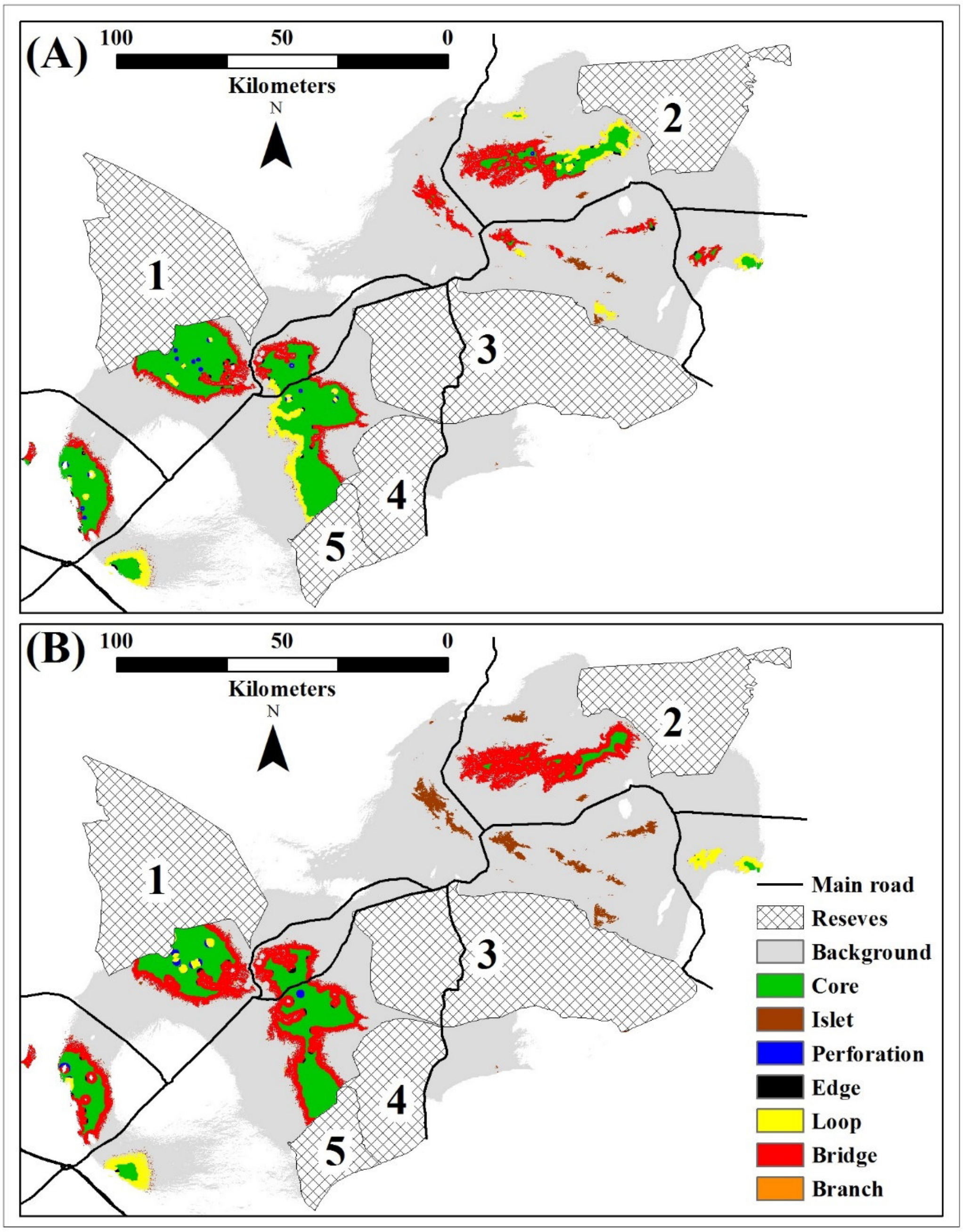

Figure 4- Classification of suitable habitats of wild sheep using MSPA. A) edge-width = 600 m B) edge-width = 1200 m (1: Kouh-e-Bozorgi No Hunting Area, 2: Kalateh No Hunting Area, 3: Abbasabad Wildlife Refuge, 4: Siahkouh Protected Area, 5: Siahkouh National Park)

Table 2- Area of each MSPA classes extracted from suitable habitats of wild sheep

Edge Width (m)	Area of MSPA Class (km^2)						
	Core	Islet	Perforation	Edge	Loop	Bridge	Branch
600	1348.85	59.77	23.54	25.65	289.06	738.97	19.76
1200	932.01	218.32	20.06	14.02	145.01	1166.17	10.01

Functional corridors in MSPA categories

Mean current was highest in Core and Bridge MSPA categories, but differences among categories were small (Table 3). Results were similar when classifying MSPA categories using 600m and 1200m edge widths, aside from a slight shift in current from Core to Bridge when increasing edge width. The same pattern was observed in the percentage of current accounted for by each MSPA category; Core and Bridge had the highest percentage. There was also a slight shift from Core to Bridge when increasing edge width to 1200m (Table 3). The total percentage of current account for by all MSPA categories combined, however, did not exceed 20%.

Table 3- Estimates/statistics of current by MSPA category (600m/1200m edge)

Category/Edge width		Min.	Max.	Mean (95% C.I.)	Perc. of current (95% C.I.)
Core	600 m	10.00	19.18	10.799 (10.792 – 10.810)	11.53 (11.52 – 11.53)
	1200 m	10.00	18.02	10.441 (10.435 - 10.447)	7.705 (7.701 – 7.709)
Bridge	**600 m**	**10.00**	**16.79**	**10.280 (10.275 – 10.284)**	**6.010 (6.001 – 6.014)**
	1200 m	**10.00**	**20.00**	**10.675 (10.668 - 10.681)**	**9.857 (9.851 – 9.862)**
Loop	600 m	10.00	20.00	10.082 (10.081 – 10.083)	2.306 (2.306 – 2.306)
	1200 m	10.00	11.36	10.086 (10.085 - 10.087)	1.158 (1.158 – 1.158)
Islet	600 m	10.00	16.11	10.066 (10.065 – 10.067)	0.4761 (0.4760 – 0.4762)
	1200 m	10.00	16.79	10.082 (10.081 - 10.083)	1.743 (1.743 – 1.743)
Edge	600 m	10.00	19.09	10.030 (10.029 – 10.031)	0.2036 (0.2035 – 0.2036)
	1200 m	10.00	15.01	10.019 (10.018 - 10.019)	0.1112 (0.1112 – 0.1112)
Perforation	600 m	10.00	14.59	10.027 (10.026 – 10.029	0.1868 (0.1867 – 0.1868)
	1200 m	10.00	13.06	10.024 (10.023 - 10.025)	0.1592 (0.1592 – 0.1593)
Branch	600 m	10.00	15.29	10.023 (10.023 – 10.024)	0.1567 (0.1567 – 0.1568)
	1200 m	10.00	13.79	10.016 (10.016 - 10.017)	0.07939 (0.07937 – 0.07940)

Discussion and conclusion

One of the main goals of this study was to analyze the overlap of structural and functional corridors of wild sheep, a threatened species in semi-arid area of central Iran. To address this goal, we used mathematical morphology and circuit theory to map structural and functional corridors of wild sheep respectively.

In accordance with Van Looy et al. (2014) our results revealed a mismatch between structural and functional corridors, suggesting that conservation planning cannot rely on structural corridors alone.

While we did find differences in mean current (expected use by animals) among MSPA categories, those differences were small (less than 10%). More importantly, our results suggest that most (about 80%) of the sheeps' movements between protected areas occur outside of MSPA categories (including structural corridors). Protecting structural corridors may therefore have limited efficacy in this region. The exact proportion of animal movement occurring in structural corridors likely depends on the configuration of protected areas and structural corridors. Nevertheless, these results are in agreement with observations from local communities and conservation officers. Mapping of structural corridors shows that there is no structural corridor between Abbasabad Wildlife Refuge and Kouh-e-bozorgi No-Hunting Area, but local communities and conservation officers nevertheless report wild sheep still migrating between these two reserves. In addition, identified functional corridors completely support field observations regarding the preferred path for migration of the wild sheep between Abbasabad

Wildlife Refuge and Kouh-e-bozorgi No-Hunting area. This is a case, functional corridors have higher priority to conservation in comparison with structural corridors. A contradictory case which shows the importance of functional and structural corridors together is migration path of wild sheep between Kalateh No-hunting Area and Abbasabad Wildlife Refuge. According to the current map, the arrangement of suitable habitats of wild sheep provides the possibility of migration between Abbasabad Wildlife Refuge and Kalateh No-Hunting Area. Base on the results, when the edge-width of MSPA is 600 m, considerable amount of structural corridors were detected in this region. By changing edge-width to 1200 m, most of these structural corridors changed to Islet category. These Islets can act as stepping stones, isolated suitable habitat patches for wild sheep which are used for migration (Harker 2000; Hilty et al. 2006; Kramer-Schadt et al. 2011), a hypothesis which is in agreement with observations of conservation officers. Therefore, we can conclude that structural corridors are still an important part of the habitat for species to conserve (King and With 2002; Vogt et al. 2007), at least in some areas.

Although accuracy assessment of our results is mainly based on conservation officers' observations, we solicited information from only the experienced ones in our study with a good knowledge of the study area and species. Of course to obtain more robust results in future research, application of tracking methods and gene flow analysis are suggested. On the other hand, to produce landscape resistance against the movement of wild sheep, we used inverse of habitat suitability as a common method. Comparison of our results with resistance layers derived from land-cover, topography, and level of human disturbance are also suggested for future studies.

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