Landscape connectivity for two sympatric carnivores in central Iran

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Abstract

Central Iran supports a diversity of carnivores, most of which are threatened by habitat loss and fragmentation. Carnivore conservation requires the identification and preservation of core habitats and ensuring connectivity between them. In the present study, we applied species distribution modeling to predict habitat suitability and used connectivity modeling to predict linkage (resistant kernel and factorial least-cost path analyses) for grey wolf and golden jackal in central Iran. For grey wolf, elevation, topographic roughness and distance from agriculture lands were the strongest predictors; however, for golden jackal, distance from agriculture lands, human settlements and topographic roughness were the most influential variables in predicting the occurrence of this species. Our results also indicated a high potential for large parts of the landscape to support the occurrence of these two canid species. The largest and the most crucial core habitats and corridor paths for the conservation of both species are located in the southern part of the study landscape. We found a small overlap between golden jackal corridor paths and core habitats with protected areas, which has important implications for conservation and future viability of the golden jackal populations. Some sections of core areas are bisected by roads, where most vehicle collisions with grey wolf and golden jackal occurred. We propose that effective conservation of both species would require integrated landscape-level management to reduce mortality risk, as well as protection of core areas and corridors and development of mitigation strategies to reduce vehicle collisions.

1. Introduction

Human-induced habitat loss and fragmentation are the largest global threats to biodiversity (Kaszta, Cushman, & Macdonald, 2020; Mohammadi et al., 2018). Habitat loss and fragmentation can impact ecosystems and species by reducing habitat carrying capacity and increasing mortality risk preventing dispersal of individuals, and thus their genes, across landscapes (Kaszta et al., 2020) This synergistically increases the risk of local extinction (Kaszta et al., 2020; Khosravi, Hemami, & Cushman, 2018). Large carnivores are particularly vulnerable to habitat fragmentation and habitat loss (Broekhuis, Cushman, & Elliot, 2017). They live in low densities and typically have large home ranges (Carroll & Miquelle, 2006; Hilty, Brooks, Heaton, & Merenlender, 2006). Carnivores' large area requirements demand vast and connected habitat areas where they are protected from human persecution. Increasing land use change and habitat fragmentation have threatened carnivore populations by reducing habitat areas and increasing their isolation, leading to a synergy of increased direct human-caused mortality, reduced local carrying capacity, and reduced ability for populations to be integrated by dispersal (Cushman, Elliot, Macdonald, & Loveridge, 2016).

Large carnivores are also particularly vulnerable to vehicle collisions and barrier effects because of their life-history characteristics (Mohammadi & Kaboli, 2016). (They have low population densities, low fecundity, and relatively large home ranges (Grilo, Bissonette, & Santos-Reis, 2009; Mohammadi et al., 2018; Mohammadi & Kaboli, 2016; Parchizadeh et al., 2018). Vehicle collision poses a substantial threat to wildlife species in central Iran (Shahnaseri et al., 2019). Roads, especially those with high traffic, disrupt both structural and functional connectivity for large carnivores, including grey wolf (*Canis lupus*), striped hyena (*Hyaena hyaena*) and golden jackal *(Canis aureus*), and can lead to reduced gene flow among meta-populations (Shahnaseri et al., 2019). Thus, transportation managers need reliable data to identify when and where particular species are susceptible to high road-kill rates to implement mitigation measures during the road design planning and/or exploration stage (Grilo et al., 2009; Santos et al., 2015).

Large carnivore conservation requires both protection of extensive core areas and the establishment of movement corridors among them (Cushman et al., 2018), particularly when core habitat patches are isolated by road networks (McClure, Ware, Carlisle, & Barber, 2017). Connectivity is critical for long-term species conservation and plays a crucial role in maintaining the genetic and demographic processes that ensure long-term viability (Bennett & Saunders, 2010). Connectivity of populations is of paramount importance to both conserve species locally and to secure their range shifts in response to future hazards such as land use change (Cushman, McRae, et al., 2013), and climate change (Karami, Rezaei, Shadloo, & Naderi, 2020; T. Wasserman, Cushman, Shirk, Landguth, & Littell, 2012; T. N. Wasserman, Cushman, Littell, Shirk, & Landguth, 2013). Enhancing connectivity in conservation networks may reduce the negative impacts of habitat loss and fragmentation (Betts et al., 2014).

Connectivity models provide practical tools for assessing potential fragmentation effects of roads on wildlife and help inform management and conservation planning (Almasieh, Rouhi, & Kaboodvandpour, 2019). A wide variety of methods have been proposed for connectivity analysis, including least-cost path modelling (Adriaensen et al., 2003), current flow (McRae, Dickson, Keitt, & Shah, 2008), factorial least-cost path density (Cushman, McKelvey, & Schwartz, 2009), resistant kernels (Compton, McGarigal, Cushman, & Gamble, 2007) and randomized shortest path algorithm (Panzacchi et al., 2016). The factorial least-cost path and cumulative resistant kernel approaches are strong methods to be used in combination to accurately identify core habitats, fracture zones and corridors across a broad landscape (Cushman et al., 2018; Cushman, Lewis, & Landguth, 2014; Moqanaki & Cushman, 2017).

Understanding the different factors that affect species distribution and habitat selection is important for carnivore conservation (Khosravi et al., 2018; Shahnaseri et al., 2019; Mohammadi et al., 2021). Many other habitat suitability models are available. Among which machine-learning models such as random forests (RF) may perform better than the regression-based algorithms (Cushman, Macdonald, Landguth, Malhi, & Macdonald, 2017; Rodriguez-Galiano, Ghimire, Rogan, Chica-Olmo, & Rigol-Sanchez, 2012). Furthermore, ensemble modeling, in which several species distribution models (SDMs) are combined to quantify a range of predictions across more than one set of uncertainty sources, has been found to increase often the accuracy of model predictions (Araújo & New, 2007; Shahnaseri et al., 2019) and decrease the uncertainty associated with using a single SDM (Shirk et al., 2018).

The central region of Iran accommodates a variety of carnivore species. Grey wolf, golden jackal and striped hyena are the most widely distributed carnivores in central Iran. Most conservation efforts for conserving wildlife diversity in Iran have relied on establishing Protected Areas (hereafter, PAs). However, the existing PA network is not efficient for the long-term conservation of most carnivores (Shahnaseri et al., 2019). Due to the reduction in wild prey species density in Iranian PAs (Behdarvand et al., 2014; Mohammadi, Kaboli, & López-Bao, 2017; Mohammadi, Kaboli, Sazatornil, & López-Bao, 2019), occurrence of carnivore species across inhabited rural areas has increased (Mohammadi et al., 2019). Anthropogenic food resources, notably livestock and garbage, also contribute to these carnivores' diet and incentivize carnivores moving to high-risk locations in the landscape near human habitations (Babrgir, Farhadinia, & Moqanaki, 2017; Behmanesh, Malekian, Hemami, & Fakheran, 2019; Mohammadi et al., 2019).

In this study, we addressed three main objectives regarding grey wolf and golden jackal status and vulnerability in central Iran. First, we determined the most significant environmental and anthropogenic factors influencing habitat suitability for both species. Second, we defined core areas for each species using resistant kernel modeling, and identified corridor routes among these core areas using factorial least-cost path modeling. Third, we used spatial randomization of vehicle collision locations to test the predictive ability of resistant kernel and factorial least-cost path predictions of movement (Cushman et al., 2014). The results provide clarity on the drivers of habitat quality for multiple carnivore species, and the patterns of habitat extent and connectivity for these species across Central Iran which is critical for conservation management planning of carnivores in Iran.

2. Material and Methods

2.1 Study area

The study was conducted across central Iran (33°30 to 30°535 N; 48°57' to 57°51' E) (Figure 1). This area is bounded between the central desert and the junction of the Alborz and Zagros faults. Despite the arid and semi-arid environmental conditions, this part of Iran supports a high diversity of large and medium-sized carnivores, including grey wolf (*Canis lupus*), golden jackal (*Canis aureus*), red fox (*Vulpes vulpes*), striped hyena (*Hyaena hyaena*), wild cat (*Felis lybica*), Persian leopard (*Panthera pardus*) and caracal (*Caracal caracal*) (Ansari & Golabi, 2019). The region also supports three ungulate species, including wild sheep (*Ovis orientalis*), goitered gazelle (*Gazella subguturosa*) and wild goat (*Capra aegagrus*). The dominant vegetation types in the study area include the *Artemisia*spp., *Scariola orientalis* , *Astragalus* spp. and*Euphorbia* spp. In this landscape there are two Wildlife Refuges (WRs), two Protected Areas (PAs) for protecting biodiversity (Darvishsefat & Tajvidi, 2006).

Fig. 1: Presence locations and vehicle collisions of the grey wolf and golden jackal in central of Iran (Markazi province). Dem indicates elevation (m).

2.2 Species occurrence data

The occurrence data for the grey wolf and golden jackal were obtained through direct observation and game wardens of the Markazi Department of Environment (hereafter, Markazi DoE, 2016) from 2000 to 2019. To address the effects of spatial bias due to uneven sampling efforts, we calculated the global Moran's I test. The result of the index (1.207; P-value=0.227) showed that the occurrence points were not spatially correlated. Totally, we collected 95 and 113 presence points of the grey wolf and golden jackal, respectively.

2.3 Environmental variables

We selected the most relevant environmental factors to predict their distribution and habitat selection, considering the ecological requirements of grey wolf and golden jackal. The environmental variables were classified into three categories including topography (elevation, slope and topographic roughness), vegetation (vegetation cover, and Normalized Difference Vegetation Index; NDVI), land use (distance to agricultural land). Also, anthropogenic variables were classified into one category including human disturbance (distance to roads, villages, and dump sites).

A digital elevation model (DEM) from the 30m Shuttle Radar Topography Mission (SRTM, downloaded from http://earthexplorer.usgs.gov), was used to calculate slope (using Surface Tool in Spatial Analyst Tools) and surface roughness variables (Geomorphometry and Gradient Metrics toolkit) (Evans, Oakleaf, Cushman, & Theobald, 2014) in ArcGIS 10.2.

To calculate NDVI, we extracted red and near infrared bands of Landsat 8 OLI images for the year 2016 at 30m resolution and calculated the index using the Image Analysis tool in ArcGIS v10.2. For vegetation cover, vegetation types with density higher than 25% from the land cover map of the study area (Markazi DoE, 2016) were extracted. Among land use classes, we extracted agricultural lands from the land cover map of the study area .We calculated Euclidean distance to human settlement, roads and dump sites using the Spatial Analyst tool in ArcGIS 10.2. The degree of multicollinearity between the predictors was tested by calculating the Pearson correlation coefficient between pairs of the variables and based on the threshold value of 0.8 (Elith* et al., 2006). Accordingly, we only identified high degree of collinearity between two variables of slope and topographic roughness.

2.4 Habitat Modeling

We used an ensemble modeling approach to predict habitat suitability for both species. Ensemble modeling is a powerful approach that combines predictions from different models (Araújo & New, 2007). Moreover, the accuracy of the model is increased by fitting several suitability models, the uncertainty associated with using a single model is decreased, and finally, a range of predictions is explored across more than one set of uncertainty sources (Araújo & New, 2007).

Our ensemble models were created by averaging seven different models using the biomod 2 R package (Thuiller, Lafourcade, Engler, & Araújo, 2009). Biomod2 was chosen because it is a well-known and well-established software (Hao, Elith, Guillera-Arroita, & Lahoz-Monfort, 2019). These models included two regression-based models (Generalized Linear Model [GLM], and Multivariate Adaptive Regression Splines [MARS]) and three machine-learning models (Maximum Entropy [MaxEnt], Random Forest [RF], and Generalized Boosting Model [GBM].

2.5 Model performance comparison

We evaluated and compared the performances of each habitat suitability model and the ensemble model for each species using AUC and True Statistic Skill (TSS). We considered a model with AUC $>$ 0.9 as excellent, 0.8-0.9 as good, 0.7-0.8 as moderate and 0.6-0.7 as poor. We took a model with TSS $>$ 0.75 as indicating excellent, 0.4-0.75 as good and $<$ 0.4 as poor (Eskildsen et al., 2013). Variables contribution for each model of each species was calculated in Biomod 2. Besides, the response curves of presence points to the most significant variables in each model were produced and interpreted for each species.

2.6 Resistance surface for connectivity analysis

To estimate landscape resistance, we converted the habitat suitability maps to resistance maps using a negative exponential function using this equation:

R= 1000^$^{(-1xHS)}$

Where R represents the cost resistance value assigned to each pixel and HS represents the predicted habitat suitability derived from the suitability models described above (Mateo-Sanchez et al., 2015; Wan, Cushman, & Ganey, 2019). We rescaled the resistance values to a range between 1 and 10 by linear interpolation, such that minimum resistance (Rmin) was 1 when HS was 1, and maximum resistance (Rmax) was 10 when HS was 0 (Wan et al., 2019).

2.7 Connectivity analyses

We have used the universal corridor network simulator UNICOR; (Landguth, Hand, Glassy, Cushman, & Sawaya, 2012) to create two sets of connectivity predictions including (1) resistant kernels (Compton et al., 2007) and (2) factorial least-cost paths (Cushman et al., 2009). The factorial least-cost path analysis implanted in the UNICOR simulator applies Dijkstra's algorithm to resolve the single-source shortest path issue from every mapped species occurrence location on a landscape to every other occurrence location (Landguth et al., 2012). The analysis produces the sum of predicted least-cost paths from each source point to each destination point. The resistant kernel algorithm calculates the cumulative resistance cost-weighted dispersal kernel around each source point up to a user-defined dispersal threshold. As such it provides an incidence function of the rate of organism movement through every pixel in the landscape as a function of the density and number of source points, the dispersal ability of the species, and the resistance of the landscape (Compton et al., 2007). And also it produces a spatial incidence function of the expected rate of movement of each species through each pixel in the landscape (Cushman, Landguth, & Flather, 2013).

To account for uncertainties regarding the movement behavior of two target species, four distance thresholds were used in the resistant kernel analyses: 50000, 100000, 150000 and 200000 cost units, which represent movement abilities of 50, 100, 150 and 200 km, respectively, through optimum, low resistance habitat (Shahnaseri et al., 2019). Also, we used the connectivity maps to identify core areas for each species. We defined core habitat patches as contiguous patches with resistant kernel values $>$ 10% of the highest recorded for the species (Ashrafzadeh et al., 2020; Cushman, Landguth, et al., 2013). We ranked these key patches based on their strength (sum of kernel values) and size (Cushman et al., 2018). The final ranking value for the core areas prioritization represented the averaged values of these sub-rankings. We quantified the extent and percentage of PAs and corridors for each species that were within the current conservation network to evaluate the effectiveness of the current conservation network in providing connectivity for these species in Iran. We also, intersected the predicted core habitats and corridor path of both study species to identify important areas to both species.

2.8 Spatial pattern and configuration analysis

To evaluate the differences in the spatial pattern and configuration of habitat, we calculated a suite of fragmentation metrics with FRAGSTATS (McGarigal, Cushman, & Ene, 2012). To conduct the FRAGSTATS analysis, firstly we converted the UNICOR resistant kernel outputs into patches by applying a cutoff value (T. N. Wasserman et al., 2013). For each species, any values above the 10th percentile of the highest dispersal scenario were reclassified as 1, representing habitat patches of high connectivity. Everything else was reclassified as 0. Then, we calculated four class level metrics using FRAGSTATS v4.2.1(McGarigal & Cushman, 2002) including: (1) the percentage of the landscape (PLAND), which quantifies the habitat patches of high connectivity as a percentage of the study area; (2) radius of gyration (GYRATE_AM) or correlation length, which provides a measurement of the extensiveness of habitat patches of high connectivity; (3) largest patch index (LPI), which represents the percentage of the landscape comprised by the largest habitat patch of high connectivity; (4) number of isolated patches (NP). These metrics have been used frequently in past connectivity research (Cushman et al., 2016; Cushman & Landguth, 2012; Elliot, Cushman, Macdonald, & Loveridge, 2014; T. Wasserman et al., 2012).

2.9 Grey wolf and golden jackal vehicle collisions

We obtained vehicle collision locations of grey wolf and golden jackal during 2013-2018 from the Markazi DOE. The road crossing data for grey wolf and golden jackal were obtained from a variety of sources including opportunistic direct observation and environmental guards (from 2013 and 2018).

2.10 Evaluating congruence between crossing points and predicted connectivity

We used a spatial randomization testing procedure to evaluate congruence between the locations where grey wolf and golden jackal were observed crossing the road and predict connectivity in each combination of the resistance surface and connectivity model (Cushman et al., 2014). Spatial randomization testing of this kind is recommended in cases where there is spatial dependence among observations and produces an unbiased estimate of the probability of the observed outcome given the data (Cushman et al., 2014).

We compared the median value of predicted connectivity for the 170 golden jackal and 101 grey wolf crossing locations with the distribution of median values of 1 x 10^7 random samples of 170 and 101 sites along the highway within the study area. For each combination of the resistance surface and connectivity modeling approach, we calculated the ranking of the median of observed values within the distribution of the medians of the 1 x 10^7 random samples.

3. Result

3.1 Distribution of grey wolf and golden jackal

Among all the model's RF and GLM represented the highest and lowest performance in predicting habitat suitability for both species, respectively (Table 1). All five employed models produced good discriminating power; however, the models' accuracy was better for golden jackal compared with grey wolf. For grey wolf, elevation, topographic roughness and distance from agriculture lands were the strongest predictors; however, for golden jackal, distance from agriculture lands, human settlements and topographic roughness were the most important variables predicting occurrence in the study area (Table S1).

Golden jackal showed a positive association with increasing distance from agriculture lands, roads, human settlements and elevation (Figure S1). Besides, it showed a decrease in occurrence rate with increasing NDVI, roughness and distance from dumpsites (Figure S1). Grey wolf had a positive association with increasing distance from agriculture lands, roads, human settlements, NDVI (Figure S2). Also, grey wolf showed a decrease in occurrence rate with increasing roughness (Figure S2).

Prediction of the ensemble models for grey wolf and golden jackal revealed that large parts of the landscape had the potential to support the occurrence of both species (Figure 2). However, the predicted suitable areas for gray wolf were more concentrated and spatially demarcated. 75 percent of the area was suitable for grey wolf and slightly less (74%) for golden jackal (Figure S3).

Fig 2. Predicted suitability of the study area for grey wolf and golden jackal based on the combined result of five SDMs.

Table1: Accuracy evaluation of the different models' models (TSS, AUC) used to predict distribution of grey wolf and golden jackal in central Iran.

3.2 **Core habitat:**

Our connectivity simulation modeling for grey wolf revealed that core habitats are extensive, concentrating in the study area's southern parts. Among the identified core habitat, eight are more extensive than 2000 km^2. The largest and most important core area (C1 in Figure 3) is of 49800 km^2 and is located in the south part of the landscape (Figure 3). The second largest and most important core area, based on size (6200 km^2) and strength (sum of kernel value), occurred in the southwestern part of the landscape (Haftadgholleh and Alvand protected areas and Rasvand Wildlife Refuge). Also, an average of 37.84 % of the identified core habitats for the grey wolf is covered by Protected Areas Networks (Table 2). The highest overlap between core habitats and Protected Areas networks was observed in the southern part of the landscape which three CAs (Haftadgholleh and Alvand protected areas and Rasvand Wildlife Refuge) were covered by the most important identified core areas. The largest and most important core area (C1 in Fig 4) for golden jackal, according to size (38800.20 km^2) and strength, is in the south parts of the study area (Figure 4 and Table 2). Among the predicted core habitats of this species, 18.6 % are covered by IUCN Protected Areas Networks.

Fig 3: Grey wolf core areas at dispersal ability 50, 100, 150 and 200 km respectively and network of protected areas and roads.

Fig 4: Golden Jackal core areas at dispersal ability 50, 100, 150 and 200 km respectively and network of protected areas and roads.

Table 2. The extent and percent of core habitats covered by current conservation networks for grey wolf and golden jackal in Central Iran. The median value of habitat suitability for presence points was used as the threshold to define the highly suitable habitats.

3.3 Connectivity

Our connectivity simulation modeling for grey wolf revealed high connectivity areas in the Southern parts of the study area. A total of 25.18 % of the extent of this corridor network is covered with PAs (Figure 5 and Table 3). Most of the identified corridor networks for the golden jackal occurred in the Southern parts of the study area. Of the predicted corridor paths of the species, 19.11 % are covered by Protected Areas Networks (Figure 5 and Table 3). Our analysis showed that most predicted corridor paths for both species are bisected multiple times by roads (Figure 5 and Table 3).

Fig 5. UNICOR corridor pathways for the golden jackal (A) and the grey wolf (B) in Central Iran.

Table 3: The extent and percent of corridors covered by current conservation networks for golden jackal and grey wolf in Central Iran. The median value of habitat suitability for presence points was used as threshold to define the highly suitable habitats.

3.4 Intersection of core habitats and corridor path:

There was one core habitat that was shared by two species (Figure 6). 68.59% of the total extent of predicted core habitats included two species. Predicted connectivity for multiple species was high in the southern and central parts of the study area, which confirms the importance of these two parts of the area in providing habitats and corridors for both species (Figure 6). Around 33 percent (32.67 %) of corridors of both species were overlapped (Figure 6).

Fig 6. Intersection map for predicted core habitats (A) and corridors (B) of grey wolf and golden jackal in Central of Iran. The colors depict different species combinations.

3.5 Landscape Connectivity across four levels of dispersal abilities:

For both species, the percentage of the landscape, correlation length and largest patch index of connected habitat was predicted to increase significantly, and the number of patches was predicted to decrease, with increasing dispersal ability (Table4). Across the four dispersal thresholds and different models, we predict that between 17 and 30 % of the landscape contains connected habitat patches for gray wolf. For golden jackal, 13 to 29 % of the landscape contains connected habitat patches. We predicted that isolated patches for grey wolf and golden jackal ranged between 4-35 and 9-49 respectively across dispersal thresholds and modeling methods (Table4).

Table 4: FRAGSTATS results for four metrics includes: number of individual core patches (NP) largest patch index (LPI), percentage of landscape in connected habitat (PLAND) and correlation length of core habitats (CL). For grey wolf and golden jackal in four levels of dispersal ability (50,000, 100,000, 150,000 and 200000). The core habitats were defined as contiguous units with resistant kernel values >10% of the highest resistance kernel for the species.

3.6 Spatial randomization test:

During the study period (2013-2018), 173 golden jackal and 103 wolf vehicle collisions were recorded. Most golden jackal road mortalities occurred in the spring (n=63) and winter seasons (n=46), while for grey wolf most collisions occurred in summer (n=20) and winter (n=35) seasons (Table 5). We also gathered 101 and 170 additional gray wolf and golden jackal crossing locations, respectively from observation.

Table 5**:** Annual distribution of road mortality for the two study species *Canis lupus* and *C. aureus,* on the Markazi Province's main and secondary roads (Iran).

We found our connectivity model very strongly predicted grey wolf (Figure 7) and golden jackal (Figure 8) highway crossing locations (Table 6). Crossings have a significantly higher connectivity score than the randomly-selected locations ($P < 0.00001$).

Fig 7. Spatial randomization test: the crossing location of grey wolf has a much higher connectivity score than the randomization. A solid vertical line shows the median of 101 crossing locations. Transparent bars show the distribution of the median connectivity values of 10000 random spatial samples across the road network.

Fig 8. Spatial randomization test: the crossing location of golden jackal has a much higher connectivity score than the randomization. Solid vertical line shows the median of 170 crossing locations. Transparent bars show the distribution of the median connectivity values of 10000 random spatial samples along the road network.

Table 6. Maximum, minimum, median, and average value of grey wolf and golden jackal crossing locations compare with 10000 random points.

4. Discussion

Among all the model's RF and GLM represented the highest and lowest performance in predicting habitat suitability for both species respectively. Besides, we used a combination of ensemble modeling and landscape connectivity analysis to identify core habitat patches and connectivity corridors for grey wolf and golden jackal. Secondly, we assessed the extent and percent of core habitats covered by current conservation networks. Finally, we used spatial randomization of vehicle collision locations to test the predictive ability of resistant kernel and factorial least-cost path predictions of movement.

4.1 Influence of environmental variables on grey wolf and golden jackal potential distribution

Ensemble habitat suitability for both species revealed that large parts of the landscape were predicted as potentially suitable habitats for both species. Also, considerable proportions of key core habitats were concentrated in southern parts of the landscape. However, the connectivity modeling results revealed that these extended networks of core habitat areas were well connected by robust and strong movement corridors.

Distance to agricultural lands and topographic roughness were the most important explanatory variables out of those tested in predicting the occurrence of both canid species. Both species showed similar responses to these variables. The probability of golden jackal and grey wolf occurrence increased with increasing distance from agricultural lands and decreased with growing roughness. Our findings were similar to those of Shahnaseri et al. (2019) who showed that distance from agricultural lands was one of the most important variables affecting the presence of grey wolves and golden jackal in central Iran (Isfahan province). Heterogeneous agricultural lands which are structurally highly diverse provide a suitable habitat for many small wild preys (Alain, Gilles, & Yannick, 2006), i.e., an important potential prey for the golden jackal (Hayward et al., 2017; Lanszki, Kurys, Heltai, Csanyi, & Acs, 2015; Shahnaseri et al., 2019; Torretta et al., 2020). Our results, however, show a negative association with agricultural lands suggesting that both grey wolf and jackal avoid agriculture lands or are persecuted by humans.

Golden jackal is highly adapted to live in human-dominated landscapes where they take advantage of various anthropogenic resources (Ćirović, Penezić, & Krofel, 2016; Lanszki, Schally, Heltai, & Ranc, 2018; Torretta et al., 2020). Our result showed that the occurrence of this species would reduce by increasing distance from dumpsites. Our results show that the southeastern parts of the region contain more suitable habitats for jackals and most road mortalities were recorded in the south parts of the study area. This could be due to the greater traffic volume on the south highways and to the high concentration of villages and rural areas in the south parts resulting in increased food resource availability such as dumpsites (Mohammadi et al., 2018; Tourani, Moqanaki, & Kiabi, 2012). The jackal is known as an elusive species that is timid around humans thus the species is primarily nocturnal and under high risk of vehicle collisions at night (Tóth, Krecsák, Sz[?]cs, Heltai, & Huszár, 2009). In order to mitigate the risk of jackal-vehicle collisions that are likely to increase during the summer tourist season, fencing and wildlife underpasses are proposed to be incorporated into road network plans and upgrades in areas with known jackal presence (Foster & Humphrey, 1995; Litvaitis & Tash, 2008).

In contrast to golden jackal, the distribution of the grey wolf was predominantly influenced by non-human related factors (e.g., elevation and roughness), a finding reported for other carnivore species in Iran (Ahmadi et al., 2017; Khosravi et al., 2018). The results of our model suggested that with growing distance to road wolf presence increased (Houle, Fortin, Dussault, Courtois, & Ouellet, 2010; Kabir et al., 2017; Kojola et al., 2016; Whittington, St. Clair, & Mercer, 2005). This finding suggested that wolves may seek to minimize the probability of encountering humans by selecting higher elevation and rougher topography farther from roads (Kabir et al., 2017). Our results in this regard are similar to Ahmadi et al. (2017) who showed that wolf den areas were characterized by the low density of settlements and primary roads. Furthermore, their result showed that wolves primarily establish dens in the sides of elevated steep-slope hills. Our results also revealed that elevation and roughness were important predictors of wolf presence.

4.2 Conservation of connectivity networks and core habitat distribution:

Effective conservation of large carnivores requires identifying predicted core habitats and corridor networks between them (Cushman et al., 2018; Khosravi et al., 2018; Shahnaseri et al., 2019). According to our connectivity analysis the southern parts of the study area were predicted to contain the largest extent of potentially suitable habitats for both target species (Figure 5). We identified four and two important core habitats for grey wolf and golden jackal in the southern part of the landscape, respectively (Figure 3 to 5).

High connectivity areas in the southern parts of the study area are predicted to connect these core habitats (Figure 6).

Most important linkage for both species occurred in the South from East to West which is strong for both species .Our result showed that C1 at larger dispersal abilities was most important core area for both species. For this regards, considering this core area is essential as the most important landscape conservation area for promoting network connectivity.

Our resistant kernel analysis showed that between 32 – 41 % of identified core habitats for grey wolf are covered by Protected Area networks depending on dispersal ability. For the golden jackal we found a lower contribution of the PAs as core habitats (15-21%), which was explained by species' association with human dominated landscapes. Our results for golden jackal connectivity are aligned with the outcomes of Shahnaseri et al (2019). For this canid, the highest overlap between core habitats and protected sites was observed for C1 and C2 incorporating a considerable number of villages. In contrast, the highest overlap between grey wolf core habitats and Protected Areas was observed for core numbers C1, C2, C3 and C4 (Figure 4), with 40 % of core habitats intersecting with the protected area network (Figure 4). However, the coverage of Protected Areas is not sufficient, particularly for those cores in the northern and western parts of the study area, due to the small size and wide separation of protected areas in that part of the study landscape.

The largest protected area in the southern part of the study area supports large numbers of natural prey species including wild goat, wild sheep and Persian gazelle and our model predicted this area is an important habitat core area and connectivity node for both species of canid in central Iran. These core habitats have also been documented to have a high potential for supporting other carnivore species such as red fox (*Vulpes vulpes*) and Persian leopard (*Panthera pardus saxicolor*). However, of Protected Areas' coverage is not sufficient to safeguard core habitats in the northern and western portions of the study area. Therefore, we believe that the proportion of protected area networks should be increased and located along with strategic locations where the new PAs protect both important unprotected core areas and lie along the most important connectivity corridors through the system.

Similar results and recommendations were produced by Moqanaki and Cushman (2016) and Khosravi et al (2018), who found that Protected Area status is the most important predictor of the occurrence and dispersal of Asiatic cheetah and sympatric carnivores (Asiatic cheetah, Persian leopard, caracal, wild cat, sand cat and grey wolf), respectively. Therefore, protected area network coverage should be accompanied by protected connected land to increase functional landscape connectivity for carnivores.

Most protected areas networks in developing countries, such as Iran, are fragmented by roads, and road collisions present a serious threat for carnivores. In this research, vulnerable parts of the connectivity network were found in the southern part of the study area (C1 and C2) where roads intersected important movement corridors (Cushman, McRae, et al., 2013). The vulnerability of these locations is related to the high potential for grey wolf and golden jackal vehicle collisions. Our findings are similar to Moqanaki and Cushman (2016) (Moqanaki & Cushman, 2017) and Khosravi et al (2018) (Khosravi et al., 2018). They showed that primary and secondary roads cross the predicted corridor paths between the core patches. One of our study's most novel aspects is the validation of our predicted connectivity maps with independent data on road mortality and crossing locations of both species. Relatively few studies have independently validated connectivity predictions with movement (Cushman et al., 2014), density (Puyravaud, Cushman, Davidar, & Madappa, 2017) mortality, or genetic data (Mateo-Sánchez et al., 2015; Zeller et al., 2018). Our spatial randomization approach provided strong support for our predicted connectivity value. Predicted connectivity is highly related to the actual patterns of observed road mortality and crossing in the study area for both species, giving important independent validation of our predictions. This significantly strengthens their utility for decision-making.

5. *Conclusion:*

The research presented here focused on identifying suitable habitat, the most important core areas, the strongest potential corridors that connect them and validating these models with independent movement data for grey wolf and golden jackal. Based on our results we recommend: (1) protecting the identified core areas in unprotected lands and along significant corridors among core area patches; (2) encouraging movement across the most important corridors through habitat restoration and protect them from development; and (3) implementing mitigating measures for reducing grey wolf and golden jackal vehicle collisions, especially in main movement corridors in the southern part of the study area.

The study provides significant information for the protection of grey wolf and golden jackal in central Iran. In our study area, we predicted high densities of corridors would support these species' movements, especially in the southern and central parts of the study area. Conservation of these species will likely require protecting key core habitats and the linkages among them. Accordingly, conservation of both species in central Iran should focus on safeguarding core habitats and corridor networks to improve the permeability, habitat quality and reducing mortality risk at the corridors linking them.

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Author contributions

S.R., A.M., conceptualized and designed the project. S.A, collected the data. S.A., A.M., Analyzed the data and interpreted results. S.A., A.M., S.C, wrote the manuscript with support

from R B., T.R., M.N. All authors discussed the results and commented on the manuscript.

Competing interests

The authors declare no competing interests.

Data accessibility statement

The authors agree to deposit their data in Dryad after acceptance.

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Figures :

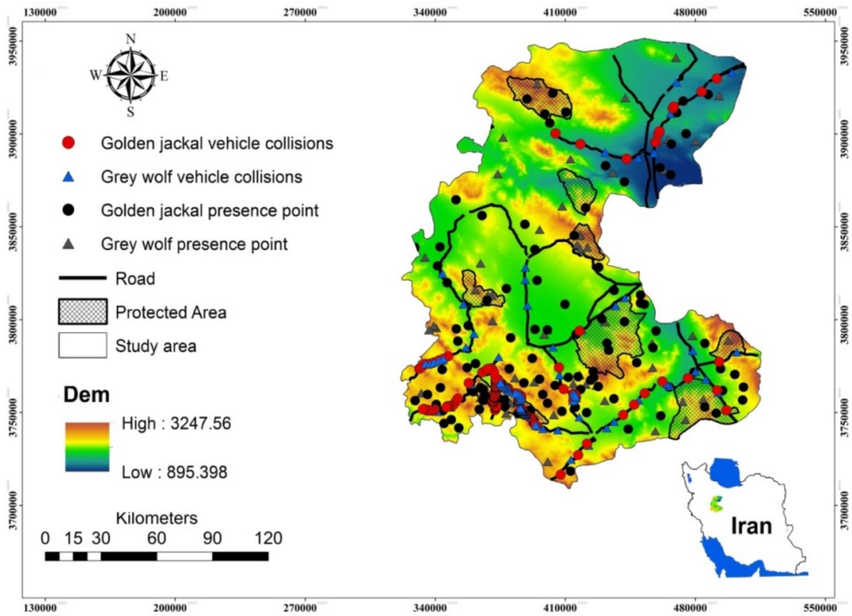


Fig. 1: Presence locations and vehicle collisions of the grey wolf and golden jackal in central of Iran (Markazi province). Dem indicates elevation (m).

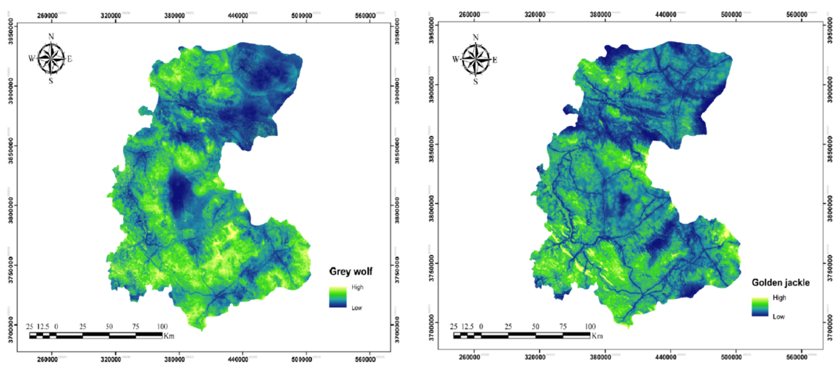


Fig 2. Predicted suitability of the study area for grey wolf and golden jackal based on the combined result of five SDMs.

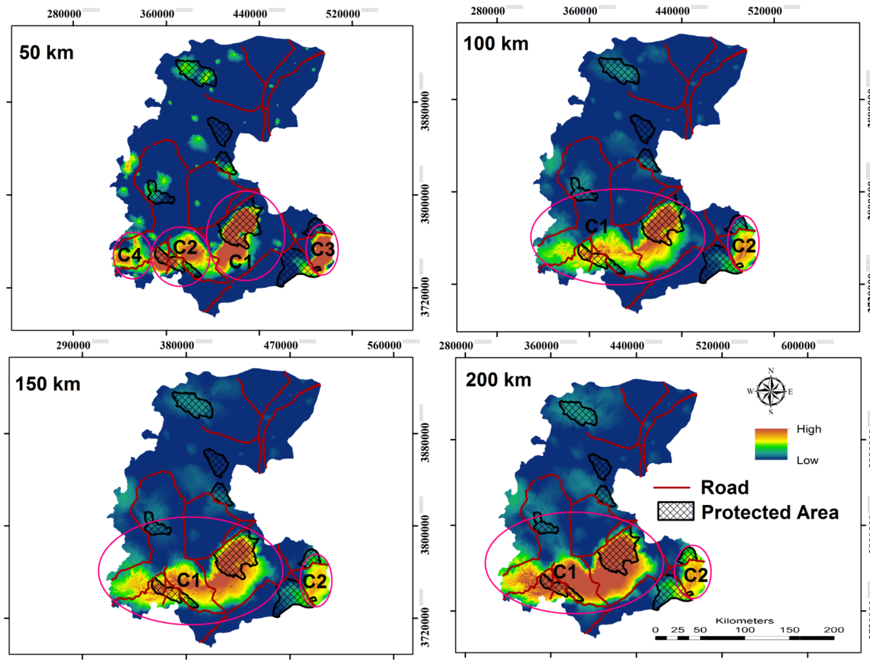


Fig 3: Grey wolf core areas at dispersal ability 50, 100, 150 and 200 km respectively and network of protected areas and roads.

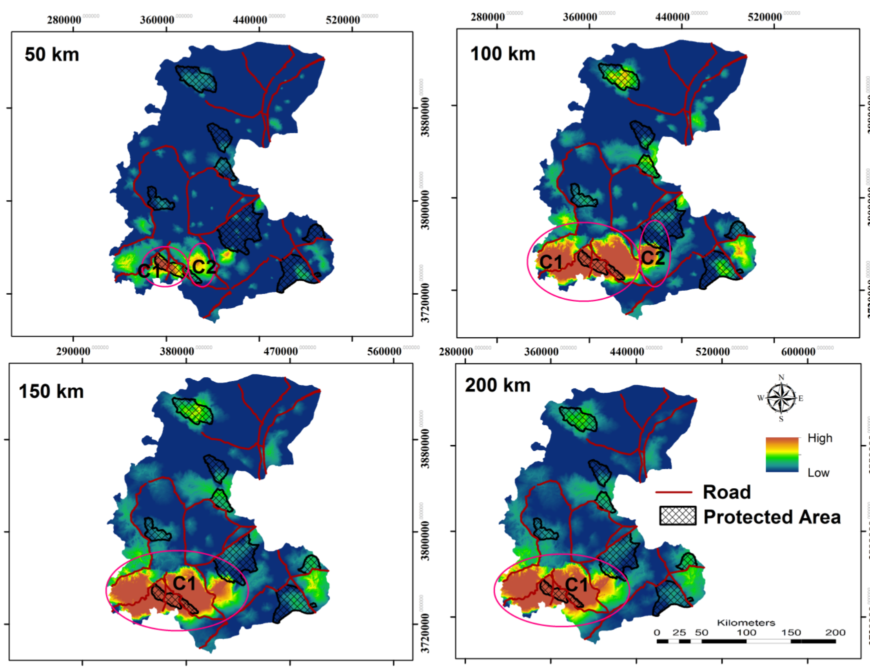


Fig 4: Golden Jackal core areas at dispersal ability 50, 100, 150 and 200 km respectively and network of protected areas and roads.

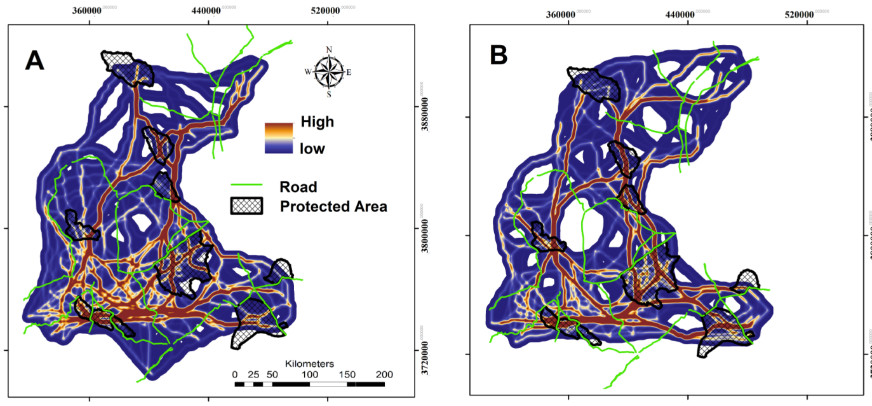


Fig 5. UNICOR corridor pathways for the golden jackal (A) and the grey wolf (B) in Central Iran.

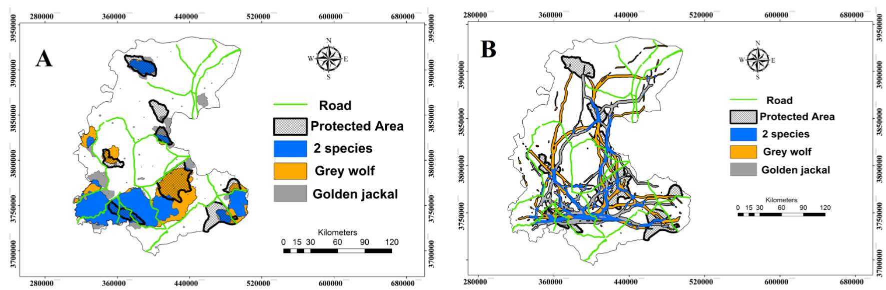


Fig 6. Intersection map for predicted core habitats (A) and corridors (B) of grey wolf and golden jackal in Central of Iran. The colors depict different species combinations.

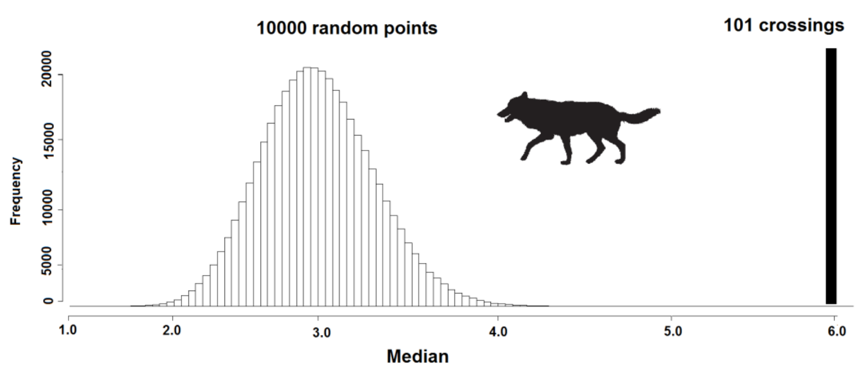


Fig 7. Spatial randomization test: the crossing location of grey wolf has a much higher connectivity score than the randomization. A solid vertical line shows the median of 101 crossing locations. Transparent bars show the distribution of the median connectivity values of 10000 random spatial samples across the road network.

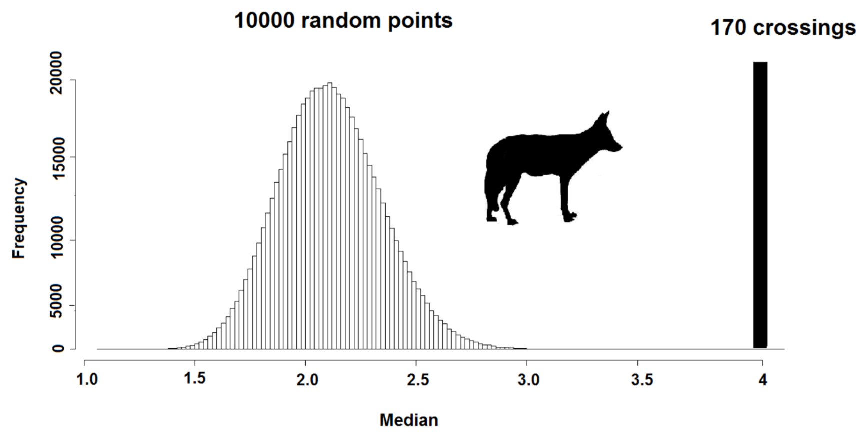


Fig 8. Spatial randomization test: the crossing location of golden jackal has a much higher connectivity score than the randomization. Solid vertical line shows the median of 170 crossing locations. Transparent bars show the distribution of the median connectivity values of 10000 random spatial samples along the road network.

Tables:

Table1: Accuracy evaluation of the different models' models (TSS, AUC) used to predict distribution of grey wolf and golden jackal in central Iran.

Model	Grey wolf	Grey wolf	Golden jackal	Golden jackal
	TSS	AUC	TSS	AUC
GLM	0.530	0.650	0.530	0.690
GBM	0.610	0.810	0.640	0.790
MAXENT	0.780	0.866	0.790	0.840
RF	0.950	0.980	0.910	0.920
MARS	0.590	0.680	0.599	0.710

Table 2. The extent and percent of core habitats covered by current conservation networks for grey wolf and golden jackal in Central Iran. The median value of habitat suitability for presence points was used as the threshold to define the highly suitable habitats.

Species	Extent of core habitats (km^2)	Extent of protected core habitats (km^2)	% of protected core habitats
Grey wolf			
50 km	5059.04	1493.13	40.51
100 km	6885.17	2003.87	39.10
150 km	7953.80	2224.07	38.96
200km	8976.32	2318.49	32.82
Golden jackal			
50 km	3974.24	871.22	21
100 km	5764.71	1120.83	19.44
150 km	7101.28	1313.13	18.49
200km	8545.13	1322.65	15.47

Table 3: The extent and percent of corridors covered by current conservation networks for golden jackal and grey wolf in Central Iran. The median value of habitat suitability for presence points was used as threshold to define the highly suitable habitats.

Species	Extent of corridors (km^2)	Extent of protected corridors (km^2)	% of protected corridors	Length of paved road cross the corridor path (km)
Grey wolf	3725.76	938.42	25.18	149.91
Golden jackal	3387.85	647.51	19.11	119.22

Table 4: FRAGSTATS results for four metrics includes: number of individual core patches (NP) largest patch index (LPI), percentage of landscape in connected habitat (PLAND) and correlation length of core habitats (CL). For grey wolf and golden jackal in four levels of dispersal ability (50,000, 100,000, 150,000 and 200000). The core habitats were defined as contiguous units with resistant kernel values >10% of the highest resistance kernel for the species.

Species	Dispersal ability	NP	LPI	PLAND	CL
Grey wolf	50	35	11.95	17.36	2823.44
	100	24	17.27	23.63	3165.37
	150	6	20.31	27.30	12316.13
	200	4	23.06	30.81	18091.81
Golden Jackal	50	49	8.39	13.64	2271.65
	100	40	13.16	19.79	2263.34
	150	10	15.88	24.37	8274.41
	200	9	19.82	29.33	9404.16

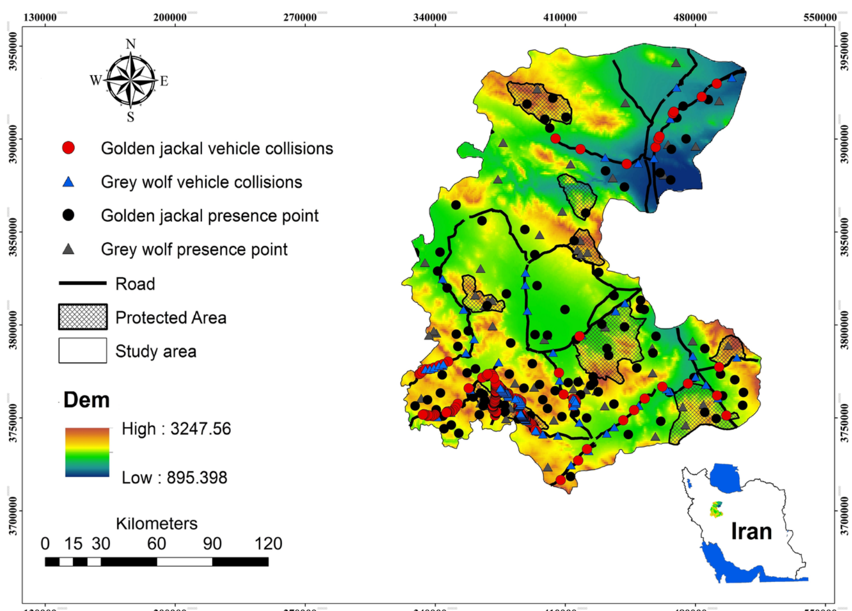
Table 5**:** Annual distribution of road mortality for the two study species *Canis lupus* and *C. aureus,* on the Markazi Province's main and secondary roads (Iran).

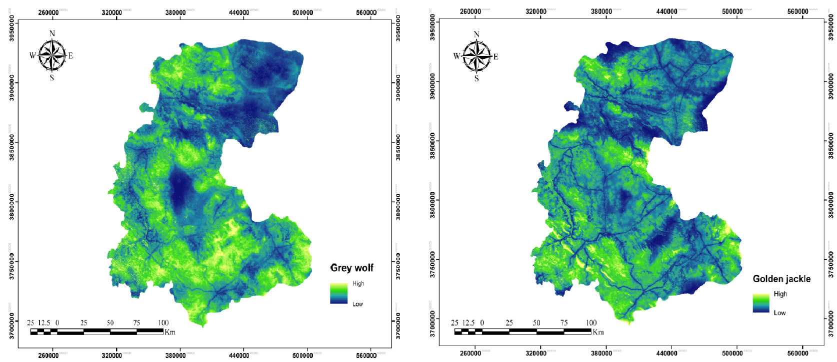
Species	season	2013	2014	2015	2016	2017	2018	Total
Golden jackal	Spring	20	13	5	10	7	8	63
	Summer	10	10	4	3	7	7	41
	Autumn	8	9	1	2	0	3	23
	Winter	13	15	3	9	1	5	46
	Total	51	44	13	24	15	23	
Grey wolf	Spring	4	4	5	1	3	5	24
	Summer	4	3	4	10	4	2	27
	Autumn	5	2	2	3	5	2	19
	Winter	9	6	8	5	5	2	35
	Total	20	15	19	19	17	11	

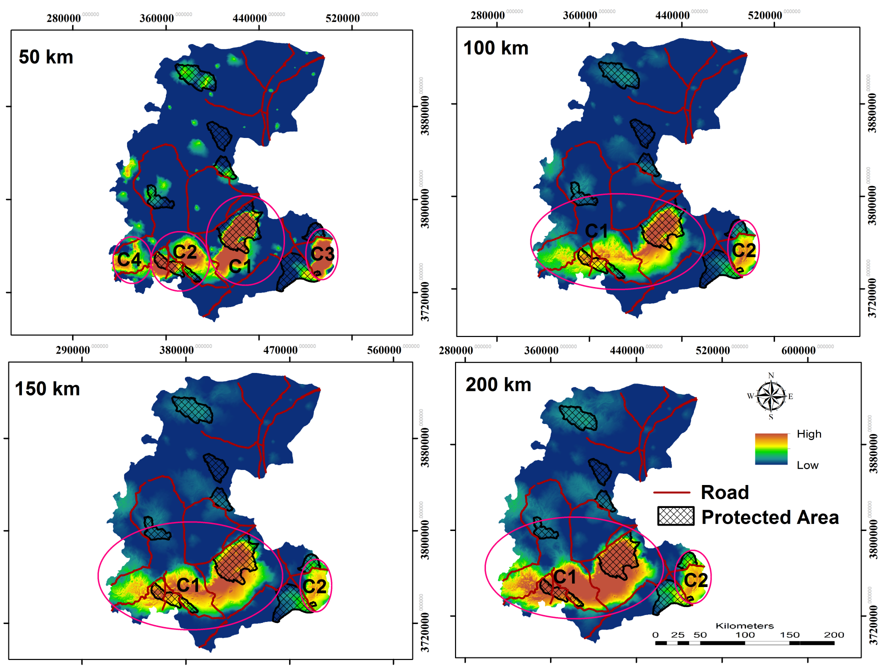
Table 6. Maximum, minimum, median, and average value of grey wolf and golden jackal crossing locations compare with 10000 random points.

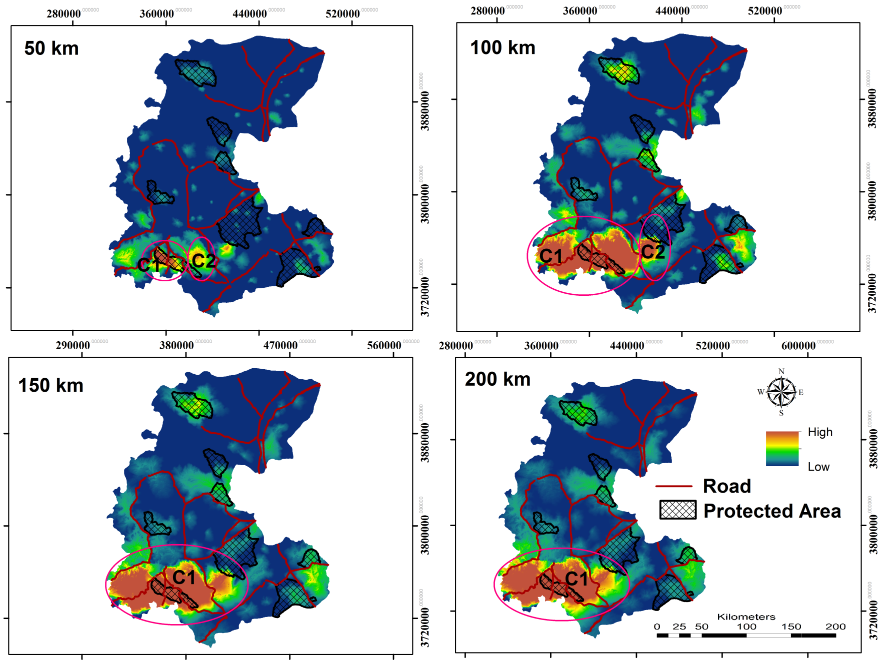
	Crossing locations	Crossing locations	Crossing locations	Crossing locations	Crossing locations
species	Dispersal ability	Max	Min	Median	Average

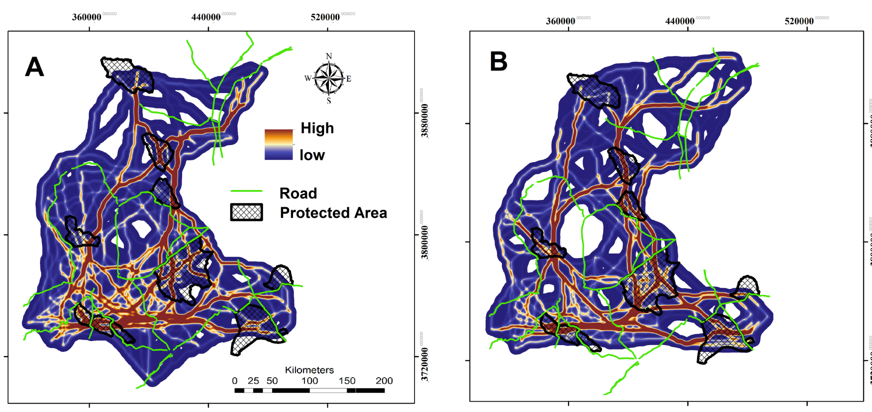
	Crossing locations	Crossing locations	Crossing locations	Crossing locations	Crossing locations
Grey wolf	50	22	1.5	5	5.50
	100	24	3.2	6	6.80
	150	32	3.6	6	7.30
	200	32	3.6	6	8.80
Golden jackal	50	20	1.2	3	4.80
	100	23	2.2	4	5.55
	150	30	3.1	4	7.80
	200	30	3.2	4	8.10
Random points species	Random points Dispersal ability	Random points Max	Random points Min	Random points Median	Random points Average
Grey wolf	50	10	0	0.65	2.12
	100	15	0	0.94	2.13
	150	15	0.25	1.2	2.5
	200	19	0.60	0.80	3.5
Golden jackal	50	11	0	0.36	1.6
	100	12	0	0.75	2.06
	150	14	0.55	0.89	2.50
	200	17	0.80	1.30	2.90

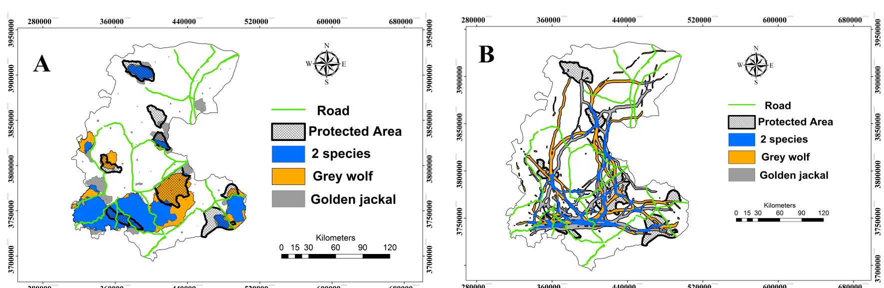


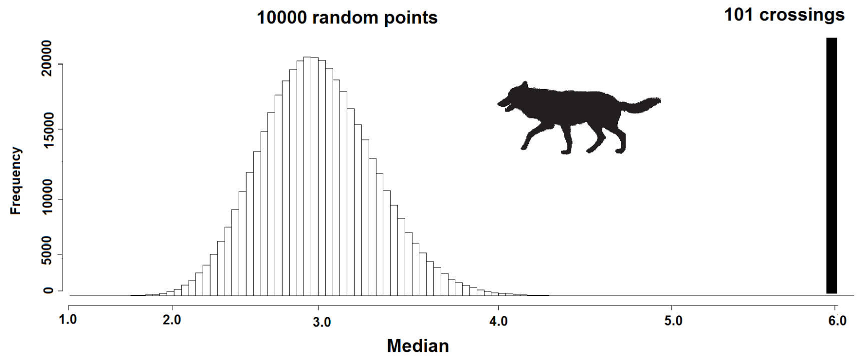

Grey wolf
High
Low
Golden jackle
High
Low

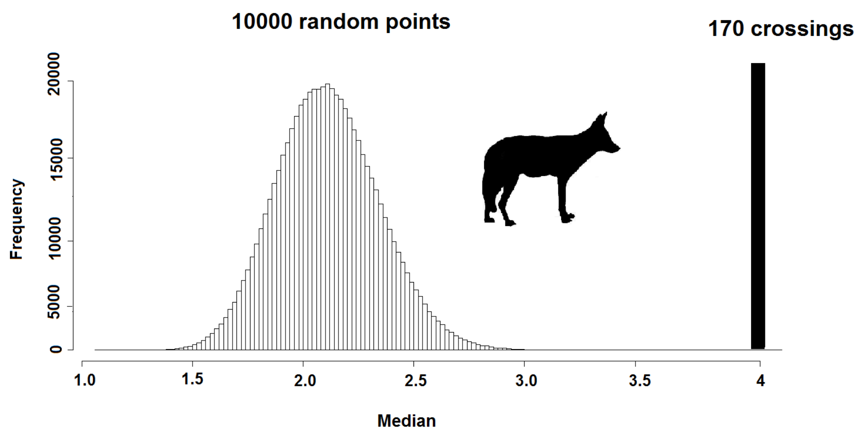

50 km
C1
C2
C3
C4
100 km
150 km
200 km
High
Low
Road
Protected Area
Kilometers


50 km
C1
C2
100 km
C1
C2
150 km
C1
200 km
C1
High
Low
Road
Protected Area
Kilometers
0 25 50 100 150 200


A
High
low
Road
Protected Area
Kilometers
0 25 50 100 150 200
B


A
Road
Protected Area
2 species
Grey wolf
Golden jackal
Kilometers
0 15 30 60 90 120
B
Road
Protected Area
2 species
Grey wolf
Golden jackal
Kilometers
0 15 30 60 90 120


10000 random points
101 crossings
Frequency
0
5000
10000
15000
20000
1.0
2.0
3.0
4.0
5.0
6.0
Median


10000 random points
170 crossings
Frequency
0
5000
10000
15000
20000
1.0
1.5
2.0
2.5
3.0
3.5
4
Median