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Assessment of habitat fragmentation for grey wolf and Persian leopard in some Iranian desert landscapes

Kamran Almasieh[1]✉ & Alireza Mohammadi[2]

Habitat fragmentation and the disruption of connectivity caused by roads are major concerns for the conservation of large carnivores as apex predator. The central arid plains of Iran support a variety of carnivore species, which their populations have sharply decreased because of habitat destruction, deterioration, and fragmentation. This study was conducted in the three conservation areas (CAs) and surrounded landscapes in central plains of Iran, focusing on two large carnivores: the grey wolf and the Persian leopard. The objectives were to predict habitat suitability and identify the environmental variables influencing the distribution of these carnivores. Additionally, the study aimed to predict core habitats and corridors, as well as their integration with CAs. Furthermore, road densities and the number of road crossings relevant to the assessed carnivores were applied. An ensemble modeling approach for habitat suitability, which includes five different algorithms and factorial least cost analysis were applied to predict habitat suitability, core habitats and their connectivity. The results indicated that the most important variables for habitat suitability were distance to CAs, grassland density, and distance to water resources for both carnivores. Three core habitats were identified for the grey wolf, while two core habitats were identified for the Persian leopard. The coverage of predicted core habitats within CAs exceeded 90%. However, the high road density within the corridors for grey wolves (80 m/km²) and particularly for Persian leopards (152 m/km²) in our study area indicated that the habitat was fragmented by roads for the assessed carnivorous species. To enhance connectivity and reduce habitat fragmentation, it is recommended to facilitate the movement of carnivores within corridors by implementing warning signs and speed cameras in areas bisected by roads. Integrated management of core habitats and corridors for the assessed carnivores, encompassing both conservation and road management, should be prioritized by wildlife managers in the study area.

Keywords Central iran, Grey wolf, Habitat fragmentation, Large carnivores, Persian leopard, Road density

Habitat loss and fragmentation have occurred in wildlife habitats due to the rapid growth of the human population and changes in land use within natural environments[1]. Habitat fragmentation, which involves transforming an expansive habitat into smaller unconnected patches[2] has numerous negative effects on wildlife. This ultimately leads to population declines and even the extinction of certain species[3–5]. Given the increasing rates of habitat loss and fragmentation, it is essential to identify and prioritize areas for conservation[6]. To predict core habitats and their connectivity (i.e., corridors), habitat suitability models (HSMs) have been applied, particularly for large carnivores exhibiting cryptic nocturnal behavior[7,8].

Large carnivores are keystone species and apex predators within natural food webs[9,10]. They maintain ecosystem stability by regulating the populations of herbivores and secondary predators across various landscapes[11,12]. Due to their low population density, extensive home ranges, and high habitat quality requirements, large carnivores are particularly vulnerable to habitat fragmentation[13]. A decline in large carnivore populations and their local extinctions can significantly disrupt ecological processes and affect biotic communities, highlighting the urgent need for their conservation in natural habitats[14].

The network of conservation areas (CAs) should preserve core habitats and their connectivity to ensure the sustained presence of large carnivores[15–18]. Furthermore, previous research has identified the detrimental effects

[1]Department of Nature Engineering, Agricultural Sciences and Natural Resources University of Khuzestan, Mollasani, Iran. [2]Department of Environmental Science and Engineering, Faculty of Natural Resources, University of Jiroft, Jiroft, Iran. ✉email: almasieh@asnrukh.ac.ir

of roads on wildlife populations, particularly large carnivores[19,20]. Large core habitats have been fragmented by roads, which facilitate human access to pristine natural areas[21]. Consequently, the conservation of large carnivores is jeopardized by habitat fragmentation and the disruption of corridors caused by roads[22,23]. Road density within core habitats and corridors, as well as the frequency of road crossings, can be assessed in both predicted core habitats and corridors[24,25].

The central arid plains of Iran are home to a diverse array of carnivores, comprising a total of 18 species, including two large carnivores: the grey wolf (*Canis lupus* Linnaeus 1758) and the Persian leopard (*Panthera pardus tulliana* Valenciennes, 1856)[26]. The populations of these carnivores have drastically declined due to habitat loss, degradation, and fragmentation[27]. Habitat fragmentation caused by road construction poses a significant threat to large carnivores in Iran, particularly the Persian leopard[28–30]. Additionally, desertification driven by climate change and human activities in the central plains of Iran has adversely impacted critical factors in carnivore habitats, such as water availability and vegetation cover. As a result, habitat patches are at risk of being lost and face challenges in maintaining connectivity[31]. This study was conducted in the central arid plains of Iran, focusing on the grey wolf and Persian leopard, with three primary objectives: (1) to assess habitat suitability and the environmental variables influencing the distribution of these carnivores, (2) to predict core habitats and corridors, as well as their overlap with CAs, and (3) to calculate road densities and the number of road crossings affecting the studied carnivores.

Materials and methods

Study area

The study area is situated in the central plains of Iran, encompassing an area of 24,064.9 km² (Fig. 1). The elevation ranges from 800 to 3,000 m above sea level, with the predominant land cover type being rangelands, which account for approximately 57.5% of the study area. This is followed by rocky mountains (14.9%), bare land (11.9%), woodlands (7.6%), sand dunes and salt flats (5.5%), wetlands and salt lakes (1.4%), agricultural land (1.1%), and urban areas (0.1%). CAs cover 15.2% of the study area, including the Dareh-Anjir Wildlife Refuge (WR), Bafgh Protected Area (PA), and Ariz WR (Fig. 1). In Iran, national parks (NPs) are prioritized for conservation, followed by WRs, PAs, and no-hunting areas (NHAs)[32]. NPs correspond to Category II of the IUCN, while WRs, PAs, and NHAs correspond to Categories III, IV, and IV-VI, respectively[32,33]. The density of roads in the study area is 74.4 m/km². In addition to two large carnivorous species, the grey wolf and Persian

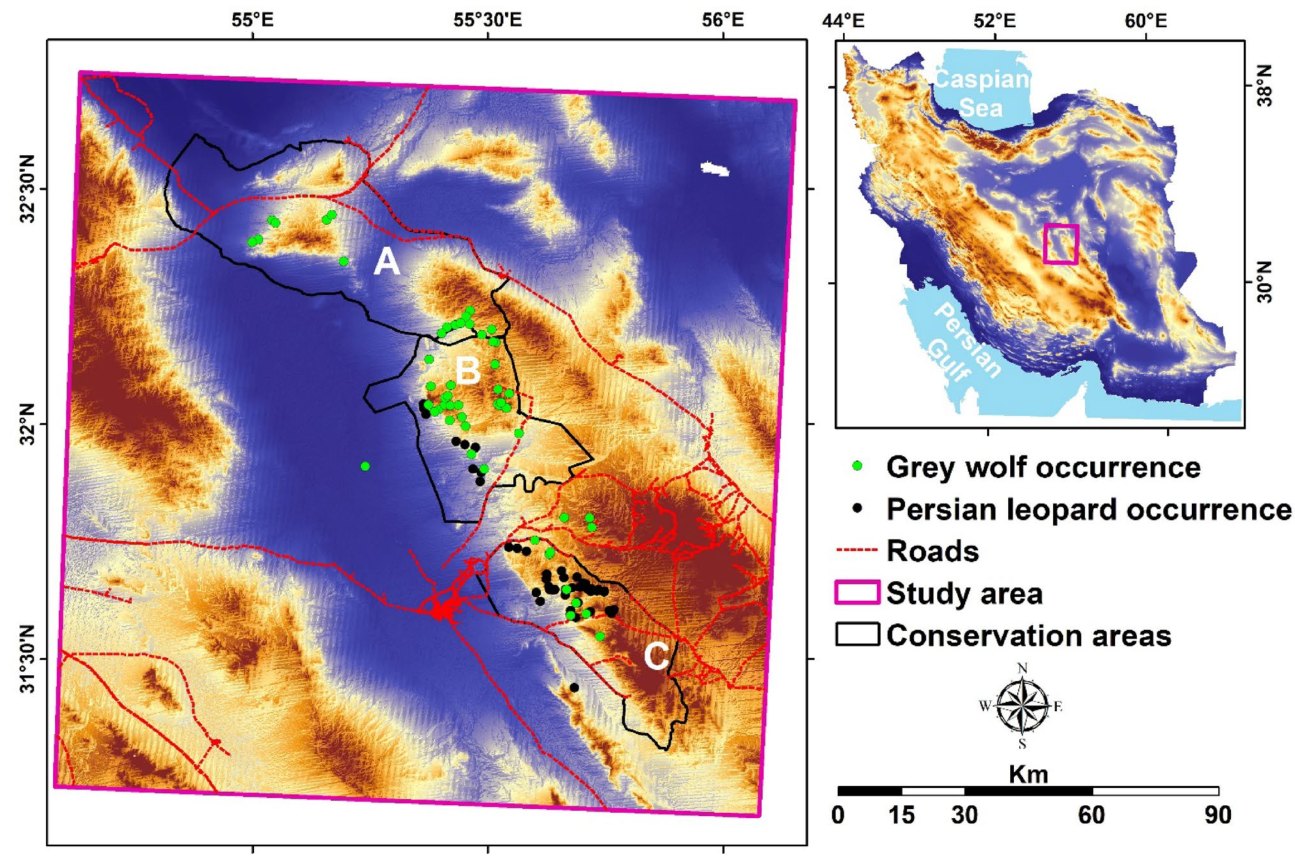

Fig. 1. Study area encompassing three conservation areas: (**A**) Dareh-Anjir wildlife refuge, (**B**) Ariz wildlife refuge, and (**C**) Bafgh protected area, along with occurrence points of grey wolves and Persian leopards in the central plains of Iran. ArcGIS software version 10.1 (https://www.esri.com/en-us/arcgis/products/arcgis-pro/resources) was used to generate the figure.

leopard, the study area is home to other carnivores, including the caracal (*Caracal caracal*), striped hyaena (*Hyaena hyaena*), golden jackal (*Canis aureus*), and red fox (*Vulpes vulpes*)[34,35]. The Asiatic cheetah (*Acinonyx jubatus venaticus*) has not been sighted in these areas for many years. The main herbivores in the study area include the chinkara (*Gazella bennettii*), wild goat (*Capra aegagrus*), and urial (*Ovis vignei*)[34–36].

Studied species

The grey wolf is found throughout the northern hemisphere, spanning the continents of Asia, Europe, and North America[37]. The primary threats to the grey wolf across its range include poisoning, deliberate persecution due to livestock depredation, exaggerated fears regarding the danger posed by wolves, and habitat fragmentation[38,39]. Despite these challenges, the grey wolf is classified as a species of least concern (LC) on the International Union for Conservation of Nature (IUCN) Red List, owing to its widespread distribution and stable global population[40]. However, in recent years, the wolf population in many regions of Iran has significantly declined due to reduced prey availability and conflicts with humans stemming from attacks on livestock and people, with some areas experiencing complete extinction[41].

As one of the eight subspecies of leopards worldwide, the Persian leopard is found across 11 countries in Southwest Asia[42–44]. Major threats to the Persian leopard throughout its range include poaching, loss of prey, habitat destruction and fragmentation, climate change, and desertification[45,46]. As a result, the IUCN Red List has classified the Persian leopard as an endangered species (EN)[47]. The largest population, comprising up to 83% of the total, and the most extensive distribution, covering approximately 200,000 km^2, are found in Iran[47–49]. Factors such as habitat loss and fragmentation, reduction in prey availability, conflicts with herders, contamination of carcasses from hunted animals with toxic substances, the use of wire traps, poaching, and road collisions have led to a significant decline in the Persian leopard population in Iran, with complete extinction occurring in some areas[41].

Occurrence points collection and environmental variables

We obtained occurrence points for grey wolves and Persian leopards in the study area from the Yazd provincial office of the Department of Environment (DoE). These occurrence points were collected by rangers and experts between 2015 and 2022, resulting in 60 occurrence points for the grey wolf and 62 for the Persian leopard. To reduce spatial autocorrelation, we utilized a 1 km radius around each occurrence point. From any two occurrence points within this radius, one point was retained. This process was conducted using the Spatially Rarefy Occurrence Data tool in the SDMtoolbox[50].

All relevant environmental variables, including topography, land cover, habitat safety, water resources, and human disturbance, were taken into account for habitat modeling of the grey wolf and Persian leopard in the study area (Table 1). The Digital Elevation Model (DEM) served as the elevation variable and was downloaded from http://srtm.csi.cgiar.org[51] with a resolution of 250 m. The slope variable was calculated from the DEM using the Spatial Analyst Tools in ArcGIS version 10.1[52] (https://www.esri.com/en-us/arcgis/products/arcgis-pro/resources).

The land cover map of Iran was utilized to identify grasslands, rocky mountains, and woodlands cover types. Density maps of these three cover types were created using a circular moving window with a 5 km radius. MODIS data (MODIS MYD 13Q1 V6 map at a 250 m cell size; http://earthexplorer.usgs.gov) was used to create the Normalized Difference Vegetation Index (NDVI). Distance to CAs and distance to ranger stations (i.e., stations within CAs for monitoring and control to prevent poaching) were considered as surrogates for prey availability and habitat safety. For prey availability, briefly, a similar ensemble habitat modeling using in the present study was carried out for each herbivore species in the study areas (i.e., chinkara, wild goat and urial) separately using occurrence points and relevant environmental layers[36]. Then, ROC curve threshold[53] was used to convert the continuous ensemble habitat suitability for each herbivore into a categorical map as habitat patches. Finally, we

Variables category	Variables	Selected after checking the correlation	Selected after checking the VIF (final selection)
Topography	Elevation	Yes	Yes
	Slope	Yes	Yes
Land-cover	Grasslands density	Yes	Yes
	Rocky mountains density	Yes	Yes
	Woodlands density	Yes	Yes
	NDVI	Yes	Yes
Habitat safety and prey availability	Distance to conservation areas (CAs)	Yes	Yes
	Distance to ranger stations	No	–
	Prey density	No	–
Water	Distance to water resources	Yes	Yes
Human	Distance to roads	Yes	Yes
	Distance to villages	Yes	Yes
	Distance to mines	Yes	Yes

Table 1. Environmental variables using for habitat modeling of the grey wolf and Persian leopard in the study area.

overlaid habitat patches of three herbivores to create layer of prey density as prey availability[36,54]. Distance to water point resources (hereafter, water resources) was included in the habitat modeling due to the significance of water resources for carnivores[24]. Additionally, considering the detrimental impact of roads on carnivores, the distance to roads was also taken into account. Furthermore, other human disturbance variables, such as distance to villages and distance to mines, were considered. Variable maps were resampled to a resolution of 250 m and projected to the WGS 1984 Zone 39 coordinate system. All operations were performed in ArcGIS version 10.1.

To select the final variables, we assessed multicollinearity by evaluating the correlation between variables and calculating the variance inflation factor (VIF). We eliminated variables with a correlation coefficient exceeding 0.7. The `usdm` package[55] was employed in R version 3.6.0[56] to exclude variables with a VIF greater than 3[57]. The distance to CAs, ranger stations, and prey density exhibited correlations higher than 0.7. Consequently, the distances to ranger stations and prey availability were excluded, while the distance to CAs was retained for habitat modeling. In total, eleven variables were considered in the habitat modeling of grey wolves and Persian leopards in the study area (Table 1).

Habitat modeling and core habitats

The biomod2 package[53] in R was utilized to model the habitat suitability of the grey wolf and Persian leopard using an ensemble approach. This method combines predictions from multiple models through average weighting to enhance accuracy[13,27,58,59]. Ten models, which included four regression-based models (Generalized Additive Model [GAM], Generalized Linear Model [GLM], Flexible Discriminant Analysis [FDA], and Multivariate Adaptive Regression Splines [MARS]), five machine-learning models (Generalized Boosting Model [GBM], Maximum Entropy [MaxEnt], Random Forest [RF], Artificial Neural Network [ANN], and Classification Tree Analysis [CTA]), and one profile model (Surface Range Envelope [SRE]) implemented in biomod2. We conducted a primary analysis using ten predictive models. Ultimately, we selected models with an area under the receiver operating characteristic (ROC) curve greater than 0.9 (AUC ranges from 0.5 to 1, with 1 indicating the highest discrimination between occurrence records and pseudo-absence records) and true skill statistics greater than 0.75 (TSS, equivalent to sensitivity plus specificity minus 1) for the final habitat modeling[60]. We utilized 75% of the occurrence records as the training dataset and the remaining 25% as the test dataset[32]. We randomly generated 500 pseudo-absence records across the study area, ensuring they were located outside a 1-km radius around each occurrence record. To enhance confidence in our results, we conducted twenty replicates for each model[61]. The ensemble variable contributions and the most influential variables for habitat suitability were calculated using biomod2. Additionally, the model with the best performance was employed to create response curves of the occurrence records in relation to the variables. To identify core habitats, we converted the continuous ensemble habitat suitability for each carnivore into a categorical map using an ROC curve threshold. We calculated the coverage of core habitats within CAs for each species separately. Furthermore, we assessed road density and the number of cross-sections within core habitats.

Corridor modeling

We converted the ensemble suitability maps into resistance maps through a two-step process. First, we utilized the Rescale by Function tool in ArcGIS 10.1 to rescale each map to a 0–1 range using the linear method[62]. Next, we applied the negative exponential function ($R = 1000^{(-1\times\text{Habitat Suitability})}$) to generate the resistance map, which ranges from 1 to 10, indicating the lowest to highest resistance[63].

We conducted connectivity modeling (i.e., structural corridors) for the grey wolf and Persian leopard using the Universal Corridor (UNICOR) software version 3.0[64] (https://github.com/ComputationalEcologyLab/UNICOR). Corridors were designed over the resistance map and between occurrence points for each species to determine the shortest path from one occurrence record to every other occurrence in the landscape[64,65]. Regardless of the dispersal threshold, UNICOR predicted the least-cost paths from each record to other records to assess all potential connectivity[66]. Furthermore, we converted the continuous connectivity map for each species into a categorical map based on the top 10% of the highest connected areas outside core habitats[49,67]. The coverage of CAs with corridors for each species in the study area was calculated separately. Additionally, road density and the number of cross-sections within corridors were assessed.

Combining core habitats and corridors

The core habitats and corridors of the grey wolf and Persian leopard were analyzed to determine the areas of overlap and the total combined areas. The study area's coverage of CAs with overlapping core habitats and corridors was assessed. Additionally, road density and the number of cross-sections within the overlapped and total combined core habitats and corridors were calculated.

Results

Habitat modeling and variables contribution

After spatial filtering, 54 occurrence points were retained for habitat modeling of the grey wolf and 58 points for the Persian leopard. We selected five models for each species: GLM, MARS, GBM, MaxEnt, and RF, based on thresholds of AUC > 0.9 and TSS > 0.75 (refer to Supplementary Materials, Table S1). GBM and RF exhibited the highest performance for the grey wolf and Persian leopard, respectively. Habitat modeling indicated that the most important factors for predicting the occurrences of the grey wolf were distance to CAs, distance to mines, grassland density, and distance to water resources. Similarly, the key variables for predicting the occurrences of the Persian leopard included distance to water resources, distance to CAs, woodland density, and grassland density (Table S2).

Habitat suitability modeling indicated that grey wolves prefer regions located at elevations between 1,200 and 2,000 m above sea level, as well as gentle slopes with gradients ranging from 0 to 20 degrees. Additionally, grey wolves favor areas with lower grassland density and higher densities of rocky mountains and woodlands. The NDVI initially increased habitat suitability at a value of 0.05 but stabilized at approximately 1.5. The probability of occurrence decreased sharply as the distance to CAs increased, stabilizing at around 5 km. Similarly, as the distance to water resources increased, the probability of occurrence gradually decreased and then stabilized at about 30 km. The probability of occurrence also decreased gradually with increasing distance from villages, stabilizing at approximately 12 km. Other human-related features, such as roads and mines, negatively affected habitat suitability. The probability of occurrence increased with distance from these features, stabilizing at approximately 20 km (see Supplementary Materials, Fig. S1).

Persian leopards prefer habitats located at elevations between 1,200 and 2,000 m above sea level, particularly on steep slopes with gradients exceeding 5 degrees. Similar to grey wolves, Persian leopards favor areas with lower grassland density and higher concentrations of rocky mountains and woodlands. NDVI initially increased habitat suitability at a value of 0.07 but stabilized around 1.5. The probability of occurrence decreased sharply as the distance to CAs increased, stabilizing at approximately 5 km. As the distance to water resources increased, the probability of occurrence gradually declined and then stabilized at about 20 km. Human-related features, such as roads, villages, and mines, negatively affected habitat suitability. So that, the probability of occurrence increased with distance from these features, stabilizing at approximately 10 km (Fig. S2).

The ensemble suitability map indicated that the northern, central, and southern regions of the study area exhibited the highest suitability for grey wolves (Fig. 2). Additionally, the central and southern portions of the study area demonstrated the greatest suitability for the Persian leopard. The optimal habitat suitability models for GLM, MARS, MaxEnt, GBM, and RF are presented in Figs. S3 and S4.

Core habitats and corridors

Three core habitats, encompassing approximately 1,830 km², were identified for the grey wolf, representing 7.6% of the study area (Fig. 3; Table 2). The largest habitat patch, Core2, is situated in the center of the study area and covers approximately 920 km² (Fig. 3). The second-largest habitat patch, Core1, is located in the northern part of the study area, covering approximately 475 km² (Fig. 3; Table 2). The predicted core habitats exhibited coverage of about 93% with CAs (Table 2). The highest percentage of coverage with CAs was observed in Core1 and Core2, both achieving 100% coverage. The road density within core habitats was 38.8 m/km², with Core3 exhibiting the highest road density at 74.8 m/km² and four road cross-sections (Table 2). Connectivity for the grey wolf in the study area was maintained between core habitats from north to south (Fig. 3). Corridors spanned an area of 261.6 km², with 70% of this area containing CAs, a road density of 80.2 m/km², and eight road cross-sections (Fig. 3).

Two core habitats, encompassing approximately 780 km², were identified for the Persian leopard, representing 3.2% of the study area (Fig. 3; Table 2). The largest habitat patch, Core2, is situated in the southern part of the study area, covering about 480 km² (Fig. 3). The predicted core habitats exhibited a coverage of approximately 92% with CAs (Table 2). The highest percentage of coverage with CAs was recorded for Core1, which achieved 100%. The road density within the core habitats was 49.5 m/km², with the highest density of roads recorded at 58.4 m/km² in Core2, where three cross-sections were intersected by roads (Table 2). The core habitats located

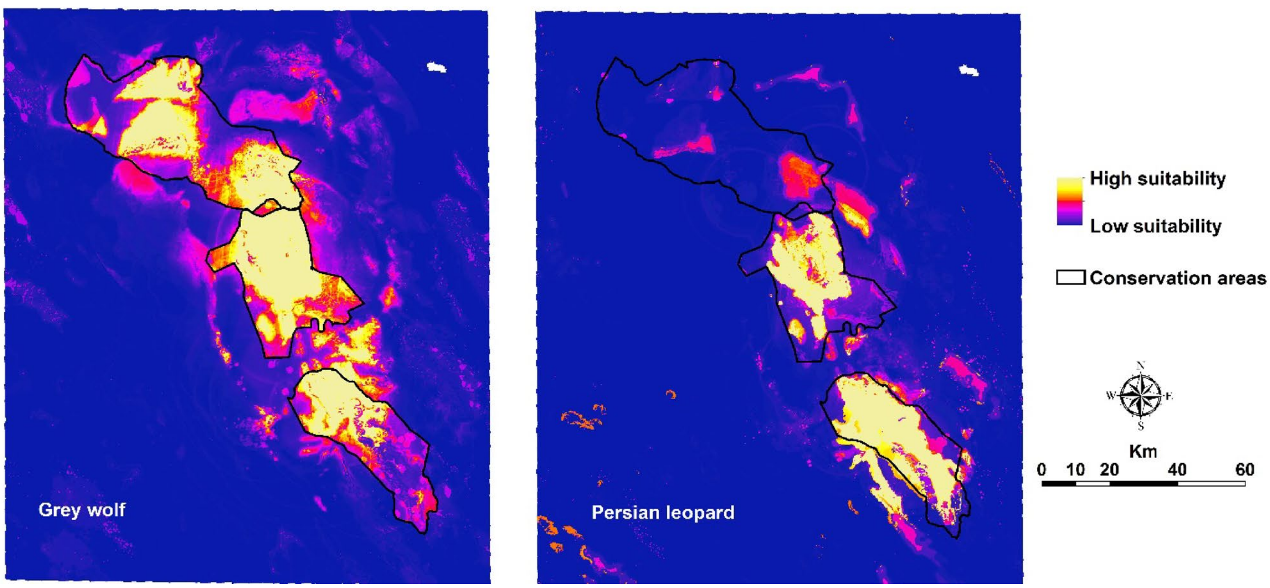

Fig. 2. Ensemble habitat suitability map for the grey wolf (left) and Persian leopard (right) in the study area based on five models of Generalized Linear Model (GLM), Multivariate Adaptive Regression Splines (MARS), Maximum Entropy (MaxEnt), Generalized Boosting Model (GBM), and Random Forest (RF). ArcGIS software version 10.1 (https://www.esri.com/en-us/arcgis/products/ arcgis-pro/resources) was used to generate the figure.

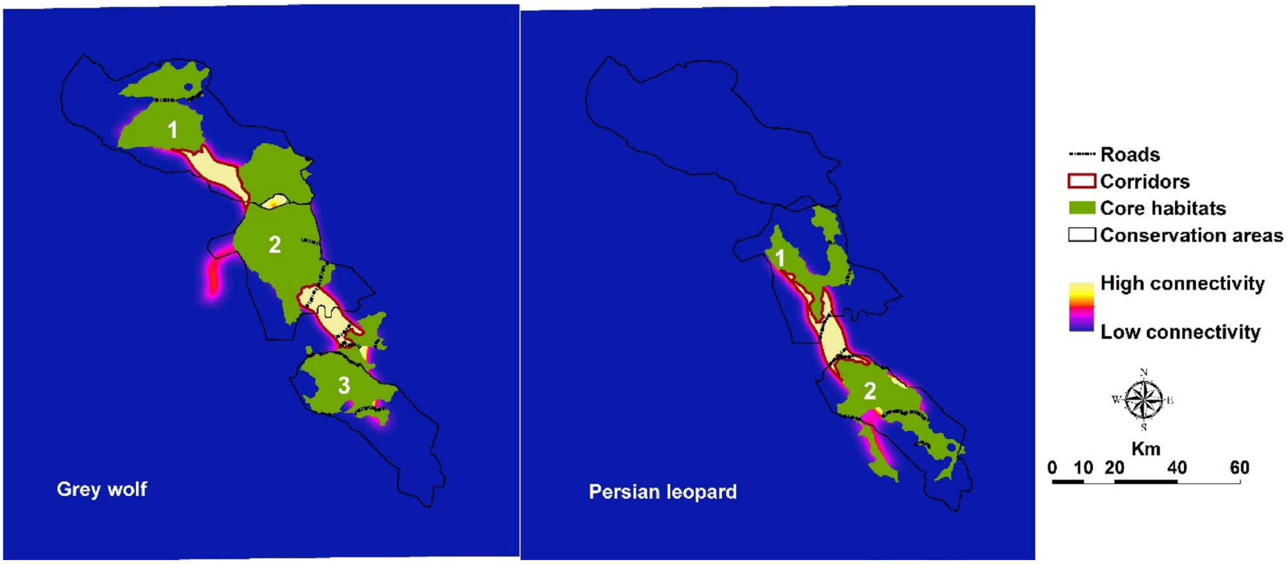

Fig. 3. Core habitats and corridors for the grey wolf (left) and Persian leopard (right) in the study area. ArcGIS software version 10.1 (https://www.esri.com/en-us/arcgis/products/arcgis-pro/resources) and UNICOR software version 3.0 (https://github.com/ComputationalEcologyLab/UNICOR) were used to generate the figure.

Species	Core habitats	Area (km^2)	Coverage by CAs (%)	Road density (m/km^2)	Cross section by roads
Grey wolf	Core1	473.4	100	33.5	2
	Core2	920.8	100	24.7	2
	Core3	440.5	76.4	74.8	4
	All	1834.7	93.2	38.8	8
Persian leopard	Core1	300.6	100	21.6	2
	Core2	480.1	87.4	58.4	3
	All	780.8	91.8	49.5	5

Table 2. Properties of core habitats and corridors for the grey wolf and Persian leopard in the study area.

between the center and southern regions of the study area maintained connectivity for the persian leopard (Fig. 3). Corridors spanned an area of 152.1 km^2, accounting for 46.9% of the total area with CAs. The road density in these corridors was 151.8 m/km^2, and there were two cross-sections intersected by roads (Fig. 3).

Combined core habitats and corridors

Overlapped core habitats encompassed an area of 577.5 km^2, with 100% coverage by conservation areas (CAs), a road density of 40.1 m/km^2, and three road cross-sections. The total overlaid core habitats spanned an area of 2,030.2 km^2, accounting for 90.8% of the CAs. The road density in these areas was 42.5 m/km^2, with ten road cross-sections. Overlapped corridors covered an area of 6.7 km^2, also with 100% coverage by CAs and no roads present. The total overlaid corridors encompassed an area of 406.9 km^2, with 60.9% coverage by CAs, a road density of 108.2 m/km^2, and four road cross-sections. Finally, the total area of overlaid core habitats and corridors was 2,380.8 km^2, representing 85% of the CAs, with an overall road density of 51.6 m/km^2 and 14 road cross-sections (Fig. 4).

Discussion

We investigated habitat suitability, core habitats, and connectivity for two sympatric carnivores in the central arid plains of Iran. Our findings indicate that the majority of the identified core habitats for both species are encompassed by CAs. Additionally, roads intersect critical movement corridors for both species.

Habitat modeling and variables contribution

Kaboodvandpour et al.[68] and Moradi et al.[69] found that the distance to CAs was the second and third most significant variable affecting the habitat suitability of the Persian leopard in western and southwestern Iran, respectively. This finding aligns with the results of the present study. Ashrafzadeh et al.[49] also identified the level of protection as the third most important variable for felid species, including the Persian leopard, in Iran. In this study, the distance to CAs was determined to be the most critical variable for the grey wolf. Rezaei et al.[70]

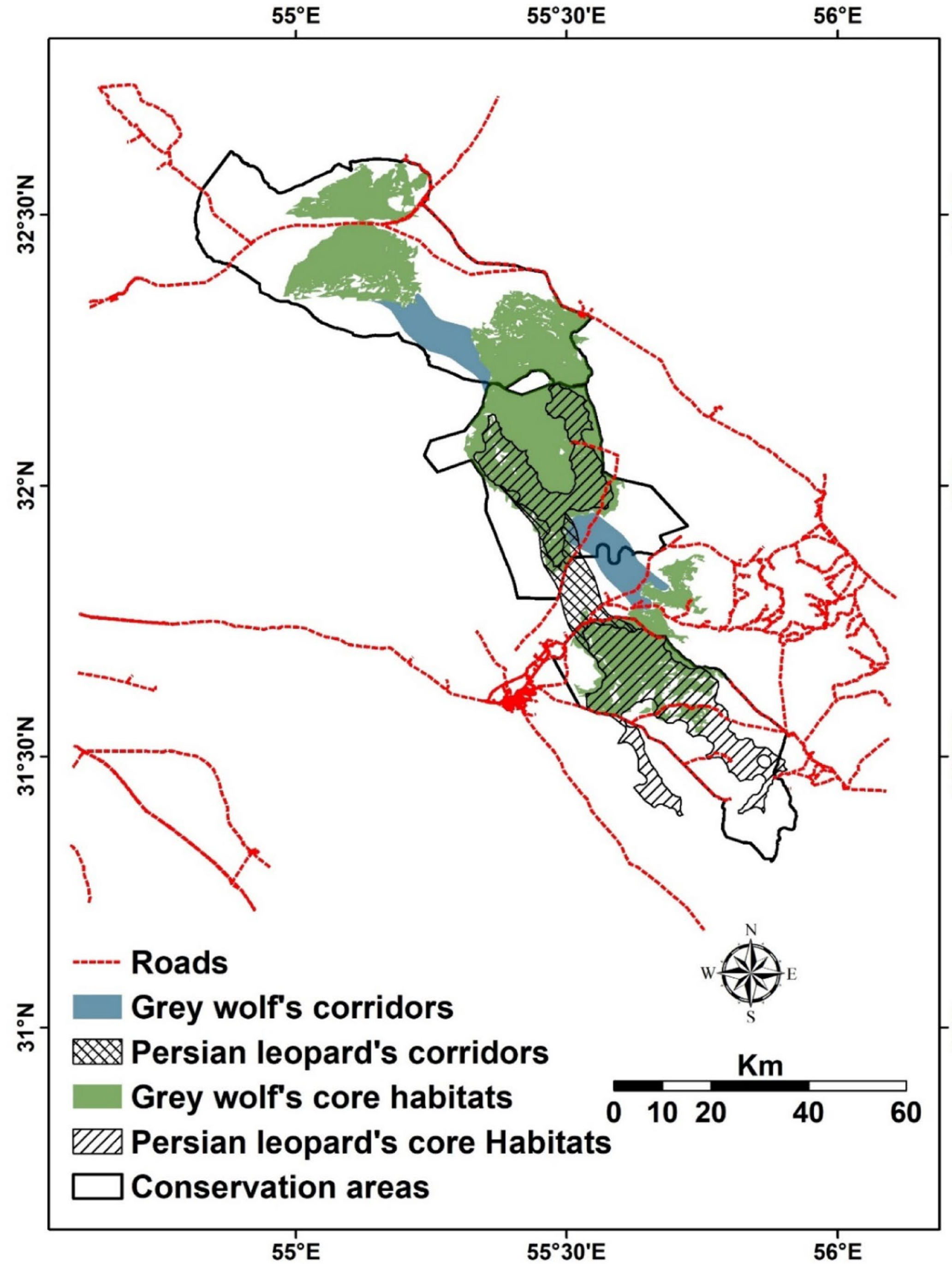

Fig. 4. Overlaid core habitats and corridors for the grey wolf and Persian leopard within the study area. ArcGIS software version 10.1 (https://www.esri.com/en-us/arcgis/products/ arcgis-pro/resources) and UNICOR software version 3.0 (https://github.com/ComputationalEcologyLab/UNICOR) were used to generate the figure.

similarly identified the distance to CAs as the third most important variable for the habitat suitability of the grey wolf in central Iran (Markazi Province). Kaboodvandpour et al.[68] recognized the distance to water resources (i.e., rivers) as the fifth most important variable. However, in the current study, this variable (i.e., distance to water resources) is regarded as the most significant factor. In the central plains of Iran, which experience drier conditions compared to the western regions, there is a greater reliance on water resources. Additionally, due to the scarcity of rivers in central Iran, which are predominantly dry throughout the year, the persian leopard depends more on water point resources than on rivers. Poursalem et al.[71] also identified the distance to water resources as the second most important variable in southwestern Iran, which shares similar climatic conditions with our study area. In the present study, the distance to water resources was identified as the fourth most important variable for the grey wolf. Similarly, Kabir et al.[72] and Rezaei et al.[31] found that the distance to water resources (i.e., rivers) was the second and third most important variable, for the habitat suitability of grey wolves in northern Pakistan and central Iran (Markazi Province), respectively. For the persian leopard in western Iran, vegetation density was the fourth most important variable for habitat suitability[68]. Related variables, such as woodland density and grassland density, were ranked third and fourth in importance, respectively, in the present study. Another related variable, distance to forests, was also identified as the fourth most important factor influencing the habitat suitability of the persian leopard in Iran[73]. Grassland density was the third most important variable for grey wolves in the present study. Shahnaseri et al.[74] also identified grassland density as the second most important variable for habitat suitability of grey wolves in the central plains of Iran (Isfahan Province).

In general, grey wolves occupied a wider suitable habitat in the study area than Persian leopards. This resulted in more core habitats for wolves (three core habitats for wolves versus two for leopards) and consequently greater habitat connectivity (two connectivity areas for wolves versus one for leopards). A study by Mohammadi et al.[75] showed that wolves, unlike leopards, consistently prefer inhabiting areas regardless of their proximity to villages. This aligns with their adaptability in scavenging for a broad spectrum of food sources, including mountain-dwelling ungulates such as urial, wild goats, gazelles, livestock, and even waste materials[76].

Previous studies revealed that the coverage of core habitats with CAs for grey wolves was approximately 40% in central Iran[31] (Markazi Province) and 54% in central Iran[77] (Isfahan Province). For Persian leopards, this coverage was approximately 20% in western Iran[68]16% in the Iranian Caucasus[15]24% in northeastern Iran[78]and 26% across Iran[73]. The coverage of corridors with CAs for grey wolves was approximately 25% in central Iran[31] (Markazi Province). For Persian leopards, the coverage was reported to be between 22 and 26% in Iran[49,73] and approximately 20% in western Iran[68]. The extensive coverage of core habitats (93% and 92%) and corridors (70% and 47%) with CAs for grey wolves and Persian leopards, respectively, in comparison to other regions in Iran, indicates a significantly better conservation status for these two large carnivore species in the study area than in other parts of Iran.

Previous studies on road density within core habitats for other carnivores reported a value of 70 m/km² for striped hyenas in southwest Iran[24]. In contrast, the road density within core habitats for the carnivores assessed in the present study exhibited lower values. Road density within corridors for grey wolves in central Iran (Markazi Province) and Persian leopards in Iran was approximately 40 m/km²[70,73] (Mohammadi et al., 2022; Rezaei et al., 2022). However, the high road density within corridors for grey wolves (i.e., 80 m/km²) and especially for persian leopards (i.e., 152 m/km²) in our study area indicates that the habitat was fragmented by roads for the assessed carnivorous species. In addition, the high road density in leopard corridors mirrors global trends where infrastructure fragments critical habitats for large carnivores[21,22]. Notably, roads near CAs (e.g., Ariz WR) act as barriers to dispersal, increasing mortality risks through vehicle collisions—a phenomenon documented in Iran[36,79] and analogous landscapes[80,81] (Pagany, 2020; Červinka et al., 2015). Mitigation measures such as fencing, warning signs and speed control, successfully implemented for Asiatic cheetah (*Acinonyx jubatus venaticus*)[82]should be prioritized in our study area to enhance connectivity.

Our findings on the coexistence of grey wolves and Persian leopards in the study area reflect niche partitioning driven by prey availability and topographic heterogeneity. Wolves, as generalist predators, exhibited broader habitat suitability across arid plains, while leopards showed stronger affinities for rugged terrains with dense woodlands—a pattern consistent with global studies of sympatric carnivores[83,84]. This spatial segregation likely reduces interspecific competition, yet both species face escalating threats from habitat fragmentation, underscoring the need for integrated conservation strategies that address shared corridors[85,86].

Implications for conservation

In the present study, there was no issue with protecting the core habitats for both carnivores. However, the habitat corridors, whose connectivity was threatened by roads, posed a challenge. The connectivity between the north and center of the study area for grey wolves was observed within a CA (Dareh-Anjir WR) with no road density. The connectivity prediction revealed limited coverage for corridors of grey wolves and Persian leopards between the central and southern parts of the study area. In this regard, two roads were identified between the central and southern core habitats (between Ariz WR and Bafgh PA). One of these roads was the main road connecting different cities, while the other was a secondary road that intersected the corridors and then entered the CA (Ariz WR), encompassing the core habitats of the evaluated carnivores in the center of the study area. These roads are located on the border of the central (Ariz WR) and southern (Bafgh PA) CAs. To enhance connectivity and reduce habitat fragmentation, it is recommended to facilitate the movement of carnivores within corridors by implementing mitigating measures in corridors bisected by roads[20]. Integrated management of core habitats and corridors for the assessed carnivores (conservation and road management) must be considered by wildlife managers in the study area.

Study limitations and future directions

Our study has two key limitations. First, temporal mismatches between occurrence data (2015–2022) and environmental covariates (e.g., static land cover) may obscure dynamic habitat changes. Future studies could integrate time-series remote sensing data[87,88] to account for annual variability. Second, while we incorporated distance to roads, finer-scale metrics like traffic volume or nighttime illumination[89] could refine risk assessments. Long-term monitoring of GPS-collared individuals is needed to validate predicted corridors and quantify road mortality rates—a critical step for evidence-based mitigation.

Conclusions
This study was conducted in the central arid plains of Iran to predict habitat suitability, core habitats, and corridors of two large carnivores (i.e., grey wolf and Persian leopard). CAs, water resources, and vegetation cover affected the distribution of the assessed carnivores. The assessment of the coverage of core habitats with CAs revealed that protection was acceptable and more extensive than in other parts of Iran. However, reducing habitat fragmentation by roads and facilitating the dispersal of carnivores' individuals, especially between the central and southern parts of the study area, should be taken into account by the DoE.

Data availability
The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Author contributions

K.A. conceptualized and designed the project. K.A. collected the data. K.A. and A.M analyzed the data and interpreted results. K.A. and A.M wrote the manuscript. K.A. and A.M authors discussed the results and commented on the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Ethical approval

The methodology for this study received approval from the Ethics Committee of the Agricultural Sciences and Natural Resources University of Khuzestan (Ethics Approval Number: 1402/42). All methods were conducted in accordance with the relevant guidelines and regulations.

Additional information

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Correspondence and requests for materials should be addressed to K.A.

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