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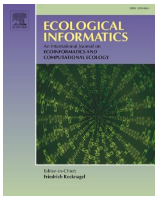

Ungulates conservation in the face of human development: Mining and roads' influences on habitat and connectivity in Iran's central plateau

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ABSTRACT

Anthropogenic activities such as mining and road construction pose significant threats to ungulate species in the central Iranian plateau. We conducted a comprehensive study focusing on three key ungulates: wild goat (*Capra aegagrus*), urial (*Ovis vignei*), and jebeer gazelle (*Gazella bennetti*). These species rely heavily on migration corridors for functional connectivity, making them vulnerable to the habitat fragmentation caused by human development. Our research integrates ensemble habitat suitability modelling and connectivity analysis to assess the impacts of mining and road construction on the core habitats of these ungulates and their habitat connectivity. Ensemble models predicted large suitable habitats for all three species; however, a considerable portion of these habitats was compromised by the development of mining roads, highlighting the urgency of conservation actions. We found that wild goat habitats were patchy and fragmented, whereas urial and jebeer habitats were more expansive and better connected. Analysis of core habitats identified critical areas for the species survival. For instance, an important core area for wild goats was located in the central part of the landscape, whereas the core habitat for urials was situated in the eastern part. Multiple core areas were identified for jebeer gazelles, highlighting the diverse habitat preferences of the species. We found extensive overlap between the core habitats of the three species and conservation areas (approximately 80%). Connectivity simulations revealed strong conservation network coverage (between 81 and 91%), emphasizing the importance of conservation areas. Our findings underscore the immediate need for conservation interventions to mitigate the impacts of road development on ungulate habitats and migration corridors in central Iran. This research contributes vital information for informed decision-making in conservation planning and sustainable development in the region.

1. Introduction

Ungulates can modify the composition of plant communities and habitat structure (Ramirez et al., 2018; McCarley et al., 2020; Velamazan et al., 2020), affect ecosystem functions (Beguin et al., 2016) and ecosystem services (Lecomte et al., 2019; Velamazan et al., 2020). Long-distance movements of ungulates are one of the most spectacular ecological phenomena, yet these movements are threatened (Ito et al., 2013). Habitat loss and fragmentation by anthropogenic activities are the main factors leading to the disruption of long-distance movements by ungulates. Such activities could have severe consequences and may cause regional extinctions or drastic population declines for ungulates (Bolger et al., 2008; Harris et al., 2009; Zhang et al., 2024).

Anthropogenic habitat fragmentation has emerged as a predominant driver of wildlife population decline and extinction, necessitating urgent attention in conservation biology (Brook et al., 2008; Mohammadi and Fatemizadeh, 2021; Rezaei et al., 2022a, 2022b; Mohammadi et al., 2023; Bosso et al., 2024; Lanzas et al., 2024). The detrimental consequences of fragmentation extend beyond physical displacement, impacting genetic diversity and demographic stability and ultimately jeopardizing the survival of many species (Fischer and Lindenmayer, 2007; Almasieh et al., 2019a, 2019b; Mohammadi et al., 2021a, 2021b; Zhuo et al., 2022; Feizabadi et al., 2023). In response to the increasing influence of human activities on natural ecosystems, preserving and establishing linkages among habitat patches have become imperative (Achieng et al., 2023; Almasieh et al., 2022; Buonincontri et al., 2023; Mohammadi et al., 2022).

Efforts to mitigate the effects of habitat fragmentation often centre

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on safeguarding linkages among core habitats to facilitate the movement and dispersal of wildlife (Almasieh et al., 2023; Luo et al., 2024; Mohammadi et al., 2021b; Teitelbaum and Mueller, 2019). During various stages of their lives, wild animals frequently engage in diverse movements across habitat patches (Jachowski and Singh, 2015; Ofstad et al., 2016). However, the integrity of these natural corridors, which are crucial for wildlife connectivity, is threatened by human activities such as mineral exploration and road construction, posing significant challenges to the survival of species (Almasieh and Cheraghi, 2022; Gonzalez-Velez et al., 2021; Mohammadi and Kaboli, 2016). Prior research has underscored the impact of mining activities on habitat selection by species such as brown bears (*Ursus arctos*), bighorn sheep (*Ovis canadensis*), and Tibetan antelope (*Pantholops hodgsonii*) (Cristescu et al., 2016; Poole et al., 2016; Su et al., 2015). Notably, species such as bighorn sheep and reindeer (*Rangifer tarandus*) clearly avoid mining areas, demonstrating the disruptive effects of these activities (Plante et al., 2018; Poole et al., 2016).

Mining infrastructure (such as railways and roads) may degrade the environment or bisect wildlife migration corridors, which play a key role in maintaining wildlife populations by increasing habitat connectivity, preserving effective population size, promoting gene flow, and facilitating migration, dispersal, and re-colonization (Su et al., 2015). Mining and other anthropogenic factors have direct and indirect effects on ungulates. Direct loss is defined as the loss of any habitat or individual as a result of development within wildlife habitats (Blum et al., 2015). For example, the construction of a mine directly reduces the availability of habitats for terrestrial migrants and can increase the risk of mortality as a result of higher levels of human activity (Blum et al., 2015). Indirect loss is defined as any change in behaviour or habitat use as a result of disturbances (Blum et al., 2015). For example, mule deer (*Odocoileus hemionus*) are less likely to use areas with high noise levels or high volumes of traffic (Sawyer et al., 2009).

Ungulates, including wild goat (*Capra aegagrus*), urial (*Ovis vignei*), and jebeer gazelle (*Gazella bennettii*, also called chinkara or Indian gazelle) (Akbari et al., 2014), are highly dependent on migration corridors for connectivity and vital ecological processes (Burton et al., 2015; Ward et al., 2002; Roever et al., 2013; Nazeri et al., 2015). Conservation of these migration corridors is particularly crucial for ungulate species that have evolved to depend on long-distance movements as part of their fundamental life history strategies (Berger, 2004). The restoration of degraded migration corridors is a time-consuming, labour-intensive, and costly process (Gilad et al., 2013). Therefore, a comprehensive understanding of the effects of mining activities on habitat connectivity and migration corridors is essential for informed conservation efforts.

The central plateau of Iran is home to a diverse range of ungulate species, including wild goat, jebeer gazelle, and urial. These species are currently facing the adverse impacts of extensive mining activities and the development of mining road networks. These road networks exacerbate human encroachment, disrupt the natural habitats of ungulates, and intensify poaching (Benitez-Lopez et al., 2017; Carter et al., 2020; Soofi et al., 2022). Studies, such as Soofi et al. (2022) have found a positive correlation between road density and ungulate poaching in Iran, highlighting the heightened vulnerability of ungulate populations in more accessible areas. This issue is a global concern, particularly in Asian countries such as Iran, where rapidly-expanding road networks contribute significantly to large mammal population declines, poaching risk, and habitat degradation, even within designated conservation areas (CAs) (Carter et al., 2020). Unfortunately, our knowledge of the spatial distribution and effects of anthropogenic factors on spatial connectivity of ungulates in the central plateau of Iran is limited (Almasieh and Mohammadi, 2023). Considering the detrimental effects of mining activities on ungulate populations in Iran, there is a need to systematically investigate the impacts of mining development and road construction on the core habitats and movement corridors of wild goat, jebeer gazelle, and urial within the central Iranian plateau.

This study aims to assess habitat suitability and landscape connectivity for these species and evaluate the level of protection provided by CAs in the central Iranian plateau. The research is guided by five goals: (1) determining the most influential factors affecting habitat suitability, including environmental and anthropogenic variables; (2) identifying the core habitats crucial for the survival of these ungulate species; (3) identifying the primary corridors facilitating landscape connectivity; (4) assessing and prioritizing the relative significance of the identified core habitats and corridors; and (5) evaluating the effectiveness of existing CAs in safeguarding these essential elements for the species.

To address these conservation challenges, this study employs a comprehensive and innovative methodology, combining ensemble habitat suitability modelling with cumulative resistant kernel and factorial least-cost path techniques to predict potential habitats for each species and habitat connectivity, respectively.

We hypothesized that habitat suitability for the species would decrease with increasing distance from conservation areas, reflecting the species' avoidance of human settlements and roads. Through this research, our aim is to deepen the understanding of the relationship between mining activities, road development, and the conservation of critical habitats and ecological corridors for these ungulates across the region.

Given the role of the central Iranian plateau in ungulate conservation in Iran, the impacts of mining development and road construction on the habitats and ecological corridors of these species must be explored. The findings would enhance our understanding of wildlife conservation in the context of human disturbances and offer insights for refining conservation strategies for wild goat, jebeer gazelle, and urial.

2. Material and methods

2.1. Study area

This study was conducted in the central Iranian plateau, specifically within the Yazd province (31.8974° N, 54.3569° E). This region exhibits diverse topography, ranging from 850 to 2860 m in elevation. The prevailing climate is characterized as arid to semi-arid, with limited rainfall, occurring primarily during the winter, resulting in an annual average precipitation of 90 to 250 mm. The mean annual temperature ranges from 14 to 27 °C. Local livelihoods predominantly rely on agriculture and livestock herding. Despite the arid conditions, the area has remarkable biodiversity such as a variety of carnivores, including five canid species (*Canis aureus*, *Canis lupus*, *Vulpes cana*, *Vulpes rueppellii*, and *Vulpes vulpes*), two felid species (*Caracal caracal,* and *Panthera pardus tulliana*), and the striped hyaena (*Hyaena hyaena*). The study area is also inhabited by wild ungulates, such as wild goat, jebeer gazelle, and urial.

Mines and mining roads pose significant threats to wildlife in the Kouh-e-Bafgh CA (88,500 ha), Dare Anjir Wildlife Refuge (175,302 ha), and Ariz Wildlife Refuge (131,330 ha) (Fig. 1). A local mining operation (the Central Iranian Plateau Iron Ore Mines Complex) is currently constructing an unprotected two-lane road that overlaps with the Ariz Wildlife Refuge for 30 km and is expected to carry 1000 vehicles per day (Fig. 1).

2.2. Species occurrence records

Between 2010 and 2022, a comprehensive dataset was compiled consisting of 200 occurrences of wild goat, 210 occurrences of urial, and 190 occurrences of jebeer gazelle in the central Iranian plateau. The data collection process involved two primary sources to ensure robustness:

A subset of the dataset (wild goat: $n = 100$, urial: $n = 150$, and jebeer gazelle: $n = 50$) was directly observed and documented by the research team. The records were collected through on-the-ground observations and information provided by park rangers. The remaining portion of the dataset (wild goat: n = 100, urial: $n = 60$, and jebeer gazelle: $n = 140$)

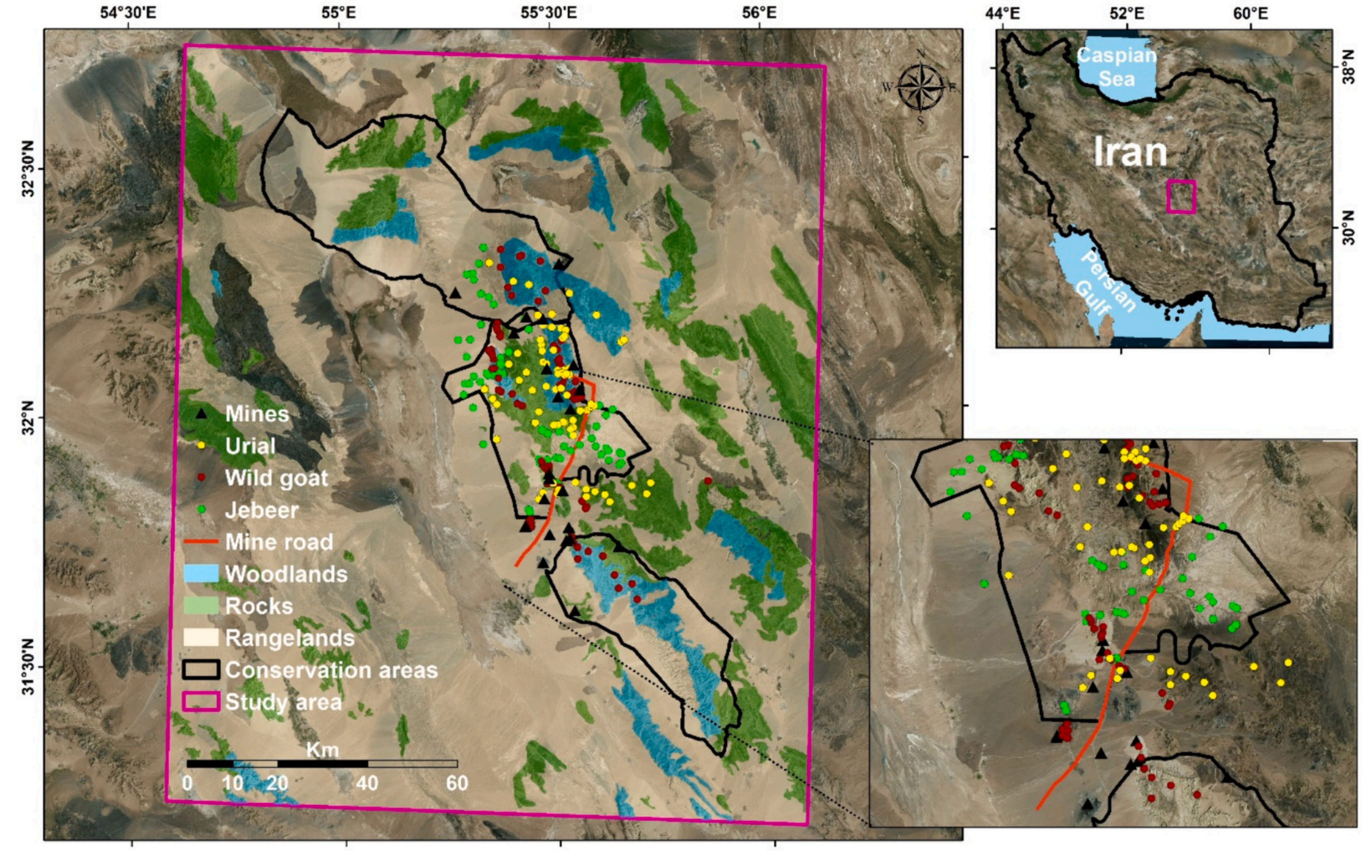

Fig. 1. Central Iranian plateau and the distribution of occurrence points of wild goat (brown), urial (yellow), and jebeer gazelle (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

was acquired through a systematic camera trap survey conducted by the provincial offices of the Iranian Department of Environment in 2019. Camera traps, primarily Cuddeback Capture cameras and a few Cam-Trak cameras, were placed at 150 stations. The cameras, situated approximately 40 cm above ground on natural features such as trees or rock piles, were positioned with a minimum separation of 4 km to ensure effective coverage. Captured data, including photographs, were downloaded every 5–10 days during routine inspections.

To address potential spatial bias in sampling, global Moran's I analysis was conducted in ArcGIS 10.7 (Fig. S1). The results, presented in Fig. S1, indicated no spatial correlation among the occurrence points, affirming the reliability of the dataset. Furthermore, to mitigate spatial autocorrelation, all multiple and duplicate occurrences within a minimum distance of 3 km were excluded from the dataset, ensuring the integrity and representativeness of species occurrence records. Following the spatial filtering process, we retained a total of 110, 105, and 100 presence points for wild goat, urial, and jebeer gazelle, respectively, in the final dataset employed for habitat modelling.

2.3. *Environmental variable selection and processing*

We selected a comprehensive suite of environmental factors according to the ecological requirements of the target species, encompassing topographical, vegetation, and anthropogenic variables (Hemami et al., 2018; Torabian et al., 2018). Topographical variables were extracted from a high-resolution digital elevation model (DEM) derived from the 30-m Shuttle Radar Topography Mission (SRTM), accessed via http://earthexplorer.usgs.gov. Employing the Spatial Analyst Tools in ArcGIS, we computed surface slope, while the Geomorphometry and Gradient Metrics extensions were utilized to calculate surface roughness. Surface roughness, defined as the standard deviation of elevation within a 2.5-km moving window, was calculated according to Hoechstetter et al. (2008).

Vegetation variables were derived from the red and near-infrared bands of Landsat 8 Operational Land Imager (OLI) images captured in 2019 at a spatial resolution of 30 m (http://earthexplorer.usgs.gov). The image analysis tool in ArcGIS was employed to calculate normalized difference vegetation index (NDVI). To incorporate human influences, we generated distance maps for mines, mining roads, and settlements. Additionally, distance to CAs and water resources was calculated to represent landscape-level safety and forage resources, respectively (Kaboodvandpour et al., 2021; Venter et al., 2015). All variables were formatted as rasters with a grid size of 100 m in ArcGIS v.10.4, ensuring a standardized and interoperable framework for subsequent analyses.

2.4. *Multicollinearity assessment*

To assess the presence of multicollinearity among variables, we calculated pairwise Pearson correlation coefficients using a threshold value of 0.7, as suggested by Elith et al. (2006). Our analysis revealed a significant level of collinearity between slope and roughness. Consequently, we excluded roughness from the modelling process. Additionally, we assessed the Variance Inflation Factor (VIF) of the selected variables using the usdm package (Naimi et al., 2014) in R to eliminate variables with VIF > 3 (Zuur et al., 2010). None of the variables were excluded based on VIF (Table 1).

2.5. *Ensemble modelling for species distribution prediction*

To predict the distribution of the selected ungulate species, we employed an ensemble modelling approach using the BIOMOD2 package (Thuiller, 2014) in R v.4.1.0 (R Core Team, 2019) (the scripts are

Table 1
Variables used in habitat suitability modelling for wild goat, urial, and jebeer gazelle in the central Iranian plateau.

Category	Variable (unit)	VIF	References	Data Source
Topography	Elevation (m)	1.60	Almasieh and Mohammadi, 2023 Sarhangzadeh et al., 2013	Digital Elevation Model (DEM, http://earthexplorer.usgs.gov)
	Slope	1.400	Almasieh and Mohammadi, 2023 Sarhangzadeh et al., 2013	Digital Elevation Model (DEM, http://earthexplorer.usgs.gov)
Vegetation	NDVI	1.12	Almasieh and Mohammadi, 2023	MODIS data (MOD13A1 V6 map at 500-m cell size; http://earthexplorer.usgs.gov)
	Woodland density	1.30	Almasieh and Mohammadi, 2023	MODIS data (MOD13A1 V6 map at 500-m cell size; http://earthexplorer.usgs.gov)
Human influences	Distance to mining roads (m)	1.29	Zhuo et al. (2022)	Department of Environment (DoE)
	Distance to mines	1.35	Zhuo et al. (2022)	Department of Environment (DoE)
	Distance to roads (m)	1.40	Amininasab et al., 2023	https://data.humdata.org/dataset/wfp-geonode-iran-road-network-main-roads
	Distance to settlements (m)	1.69	Amininasab et al., 2023	https://mapcruzin.com/free-iran-arcgis-maps-shapefiles.htm
	Distance to CAs (m)	1.20	Almasieh and Mohammadi, 2023	Department of Environment (DoE)
Water	Distance to water resources (m)	1.50	Almasieh and Mohammadi, 2023	Department of Environment (DoE)

available in Supplementary text S1). This methodology enhances predictive accuracy by combining forecasts from multiple statistical models, mitigating the uncertainties and biases inherent in relying on a single modelling method (Araújo and New, 2007; Hysen et al., 2022).

Five statistical models were used in this ensemble framework, including generalized linear models (GLM), maximum entropy (MaxEnt), random forest (RF), generalized boosting model (GBM), and multivariate adaptive regression lines (MARS). To facilitate model training, we employed a 3:1 train-test split for the occurrence points. Additionally, following Barbet-Massin et al. (2012), we generated 1000 random pseudo-absence points (five times the number of occurrence points per species) across the study area. These pseudo-absence points are crucial for model execution and provide a reference for areas that are unlikely to be inhabited by the target species.

The ensemble prediction was generated using a weighted-averaging approach, assigning weights to individual models based on their predictive accuracy on the test data (Thuiller, 2014). Evaluation and comparative analyses were conducted for both individual models and the ensemble model via two widely recognized metrics: the area under the curve (AUC) and the true skill statistic (TSS). AUC values exceeding 0.9 were considered as excellent, 0.9–0.8 as good, 0.8–0.7 as moderate, and < 0.7 as poor (Eskildsen et al., 2013). Similarly, TSS values were categorized as excellent (>0.75), good (0.75 to 0.4), and poor (<0.4) (Eskildsen et al., 2013). This comprehensive assessment ensures a robust understanding of model performance and aids in reliable predictions of species distribution across the central Iranian plateau.

2.6. Modelling landscape resistance

To assess landscape resistance to species movement, we used a negative exponential function to convert the ensemble habitat suitability raster for each species into a resistance surface. The transformation was executed using the following equation:

$$R = 1000^{-1\times HS}$$

Where R represents the cost resistance for a cell, and HS represents habitat suitability (Wan et al., 2019). To standardize the resistance values within a range of 1 to 100, a linear interpolation method was employed. This ensured that the minimum resistance (Rmin) was assigned a value of 1 when HS was equal to 1, and the maximum resistance (Rmax) was assigned a value of 100 when HS was equal to 0 (Wan et al., 2019). This process facilitates a consistent and standardized representation of landscape resistance, allowing for meaningful analysis and interpretation.

2.7. Connectivity analysis: Evaluating landscape connectivity

To assess landscape connectivity, we employed the Universal Corridor Network Simulator (UNICOR; Landguth et al., 2012) to generate two sets of connectivity predictions. The first set was based on the cumulative resistant kernel method (Compton et al., 2007), and the second set was based on the factorial least-cost path method (Cushman et al., 2009).

Factorial least-cost path analysis facilitates the computation of pairwise least-cost paths connecting all occurrence locations (Landguth et al., 2012). Additionally, the resistant kernel algorithm calculates cumulative resistance cost-weighted dispersal kernels around presence points within a user-defined radius. Unlike other approaches, such as least-cost paths or circuit theory, the resistant kernel approach does not assume predestinations from source nodes. It considers various factors, including species density, the number of occurrence records, dispersal ability, and landscape resistance in all directions. This approach provides a comprehensive estimation of the overall movement potential of organisms within the landscape (Compton et al., 2007; Cushman et al., 2013).

To address uncertainties in movement behaviour and dispersal data for the three species, we conducted sensitivity analysis. Four distance thresholds were analysed (50,000, 70,000, and 100,000 cost units), representing 50, 70, and 100 km of movement, respectively, through optimum, low-resistance habitats. This analysis is crucial, considering the significant influence of dispersal ability on predicted functional connectivity, which often surpasses the impact of landscape resistance itself (Rezaei et al., 2022a, 2022b). Resistant kernel connectivity maps were used to identify core areas for each species. Core habitat patches were defined as contiguous areas with resistant kernel values exceeding 10% of the highest values recorded for the species (Mohammadi et al., 2022). This approach ensured the identification of critical areas for each species within the landscape, aiding conservation planning and management.

Connectivity prediction was implemented in UNICOR over the resistance map for the species to find the single-source shortest path between start and end occurrence records (Landguth et al., 2012; Cushman et al., 2013). Furthermore, the continuous factorial least-cost path map was converted to a categorical map based on the same method used for core habitats. To measure the coverage of core habitats and corridors by CAs, the proportion of these areas within CAs was measured (Almasieh and Mohammadi, 2023).

3. Results

3.1. Ensemble habitat suitability model

The ensemble habitat suitability models for the three ungulate species (chinkara, wild goat, and urial) revealed expansive potential suitable habitats (Fig. 2). However, a significant portion of these habitats were intersected by mining roads, indicating potential fragmentation and movement disruption (Fig. 2). Individual habitat suitability maps generated by RF, MaxEnt, GBM, GLM, and MARS algorithms are presented in Supplementary Figs. S2 to S4.

3.2. Model performance

The five component models (GLM, MaxEnt, RF, GBM, and MARS) demonstrated variable performance (Table 2). Notably, the RF model and the GLM model demonstrated the best and worst performance for all studied species, respectively (Table 2).

Table 2
Model evaluation metrics for wild goat, urial, and jebeer gazelle in the central Iranian plateau. The assessment is based on area under the curve (AUC) and the true skill statistic (TSS).

Species	Model evaluation	GLM	GBM	RF	MaxEnt	MARS
Wild goat	AUC	0.954	0.940	0.982	0.948	0.930
	TSS	0.857	0.867	0.903	0.880	0.853
Urial	AUC	0.987	0.991	0.988	0.920	0.985
	TSS	0.869	0.850	0.936	0.925	0.910
Jebeer gazelle	AUC	0.937	0.974	0.980	0.935	0.945
	TSS	0.877	0.820	0.940	0.910	0.885

3.3. Variable contributions to habitat suitability

In the ensemble habitat suitability model, distance to mining roads, distance to roads, distance to CAs, and distance to water resources played important roles in predicting habitat suitability for the three species (Table 3). Response curves detailing the relationship between habitat suitability and environmental variables in the best-performing model (the RF model), are presented in Supplementary Materials

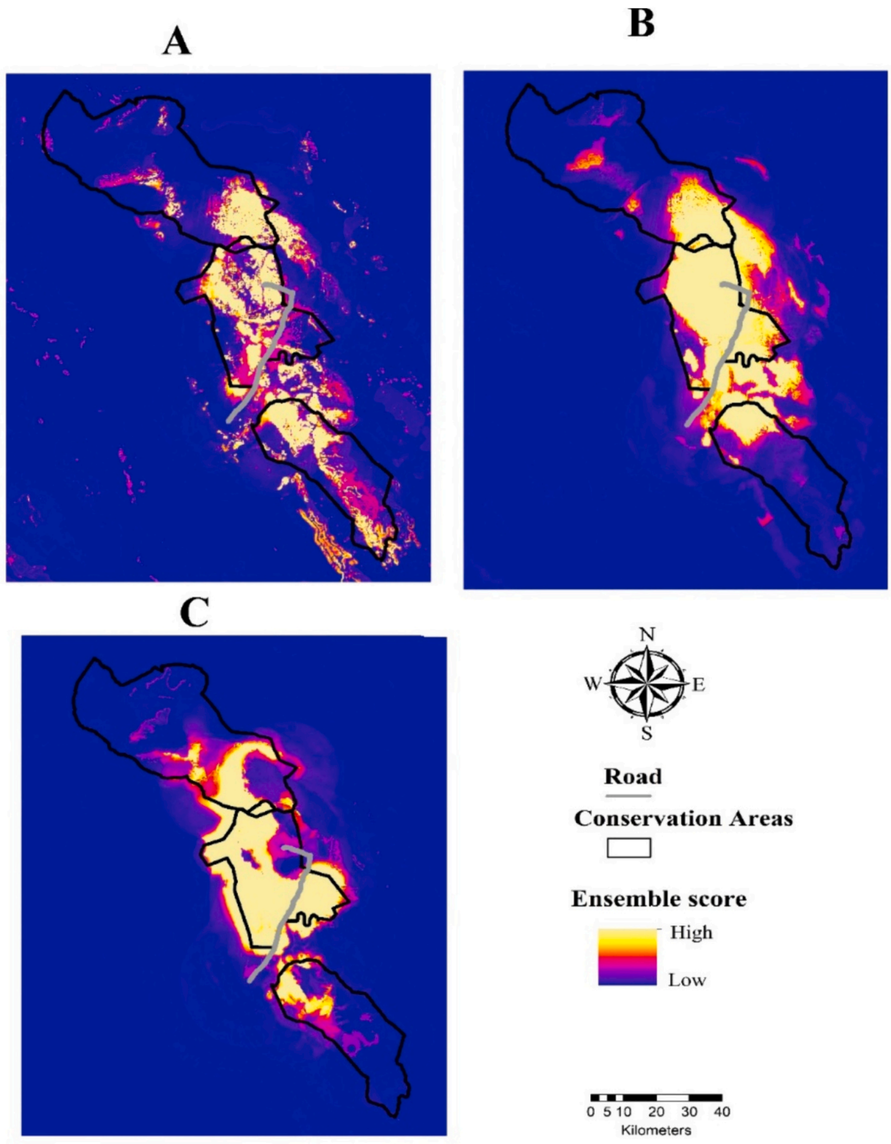

Fig. 2. Ensemble habitat suitability for wild goat (A), urial (B), and jebeer gazelle (C) in the central Iranian plateau. Warmer colours represent greater habitat suitability.

Table 3
Mean contributions of eco-geographical variables to ensemble model predictions for wild goat, urial, and jebeer gazelle.

Eco-geographical Variable	Wild goat	Urial	Jebeer gazelle
Elevation	6	2.5	1.2
Slope	7	8	3
Distance to CAs	10	10	10
Distance to village	5	3	4
Distance to road	15	14	20
Distance to mine roads	20	20.3	20
Distance to water resources	10	13	10
Distance to mines	12	15	14
NDVI	5	8	10.8
Woodland density	2	5	5

(Figs. S5 to S7).

Wild goat: Habitat suitability for wild goats exhibited a positive correlation with distance from roads and a negative correlation with distance from CAs, mining roads, and mines (Fig. S5). In addition, habitat suitability increased with factors such as NDVI, woodland density, and slope. Conversely, predicted habitat suitability diminished with increasing distance from water resources. The relationship with elevation displayed a distinct non-linear pattern, with the highest predicted suitability observed within the elevation range of 1500–2000 m (Fig. S5). Furthermore, habitat suitability decreased with increasing rangeland density (Fig. S5).

Urial: Similar to wild goat, habitat suitability for urial exhibited a positive association with increasing distance from roads (Fig. S6). Urial habitat suitability decreased with increasing distance from CAs, mines, and mining roads. Urial habitat suitability was also positively correlated with increasing NDVI, elevation, and slope. Conversely, habitat suitability decreased with increasing distance from water resources and rangeland density (Fig. S6).

Jebeer gazelle: Habitat suitability for jebeer gazelle demonstrated a sharp decline as the distance from CAs increased (Fig. S7). This species exhibited a preference for elevations between 1300 and 1500 m above sea level (Fig. S7). Habitat suitability for jebeer gazelle also displayed a positive relationship with distance from roads and a negative relationship with distance from water resources, mining roads, and mines (Fig. S7). NDVI positively influenced jebeer gazelle habitat suitability, with increased suitability in areas with higher NDVI (Fig. S7).

3.4. Core habitats, corridors, and connectivity analysis

The primary core habitat for wild goat, denoted as C1, spans 443.25 km^2 and is located in the centre of the study area, whereas the second-largest (C2) habitat covers 398.36 km^2 in the western part (Fig. 3A). Approximately 81.27% of the identified core habitats are within CAs, with an average overlap of 5.33 km with mining roads (Table 4). The habitat corridor for wild goat encompasses 585.79 km^2, with 15.5 km intersecting mining roads (Fig. 4A). Over 85% of the corridor network in the central regions is protected by CAs (Table 5).

Urial: The largest core area for urial (C1) extends over 1200.81 km^2 in the eastern part of the landscape, with 81.21% of predicted core habitats falling within CAs. Approximately 19.33 km of mining roads

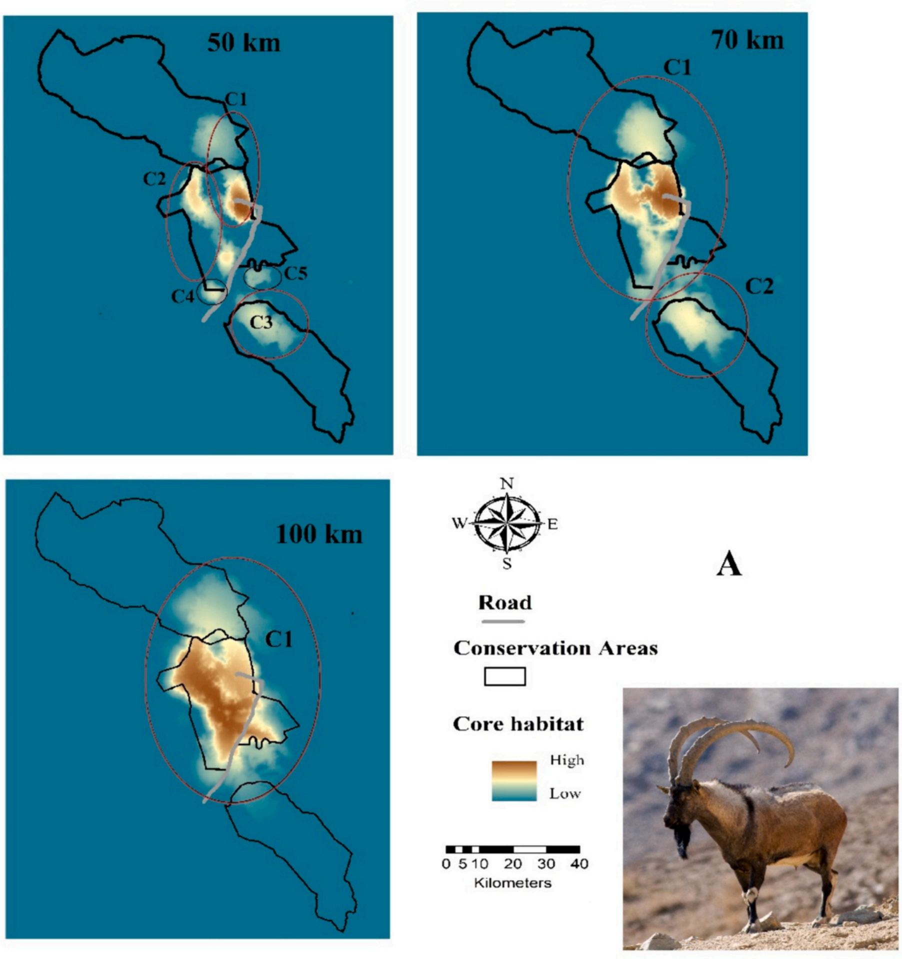

Fig. 3. Core habitat patches for wild goat (A), urial (B), and jebeer gazelle (C) at three levels of dispersal ability (50, 70, and 100 km), along with CAs and mining roads.

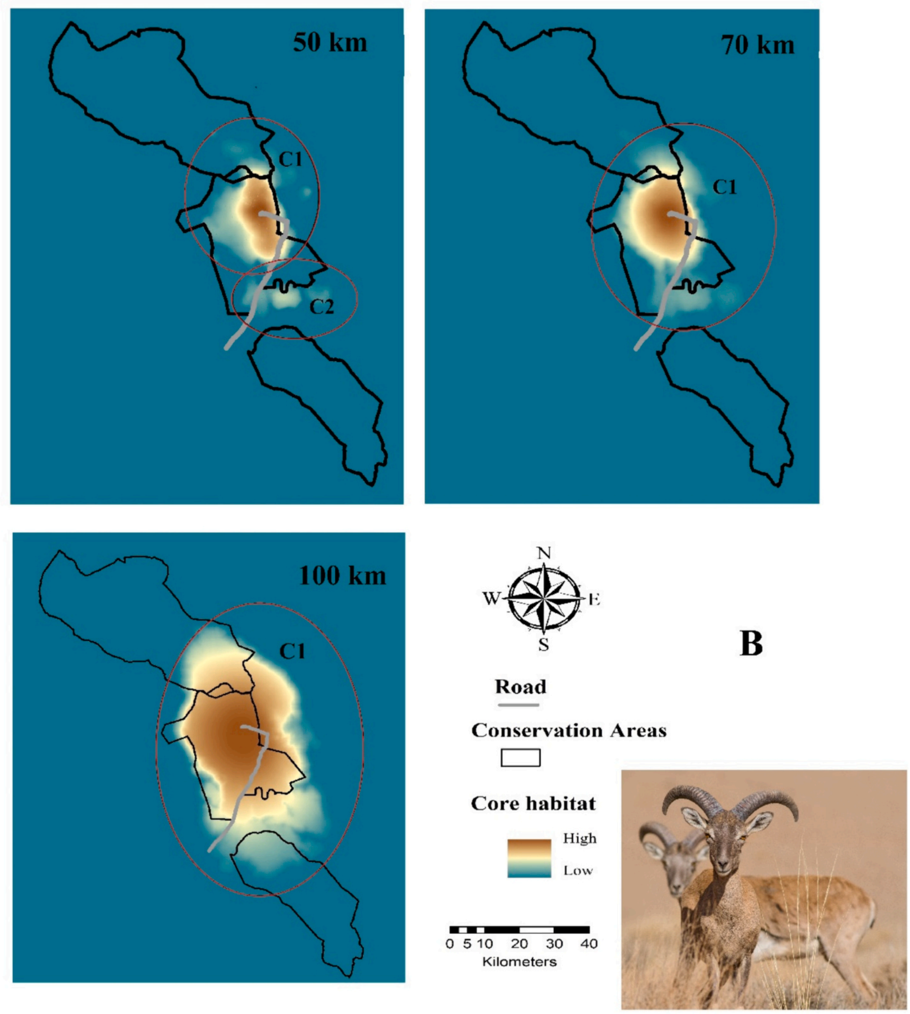

Fig. 3. (*continued*).

overlap with urial habitats (Table 4). The habitat corridor for the species covers 652.92 km^2, and intersect 22 km of mining roads. In the eastern section, 89% of the corridor network is covered by CAs (Fig. 4B, Table 5).

Jebeer gazelle: Three core areas were identified for jebeer gazelle (107,233.67 km^2) at a dispersal distance of 50,000 cost units, with two having areas exceeding 3000 km^2 (Core 1 and 2). These cores are situated in the north-western and south-eastern parts of the landscape (Fig. 3C). On average, 20.33 km of mining roads intersected the identified jebeer gazelle core habitats (Table 4). Multiple jebeer gazelle corridors (7.8 km) are intersected multiple times by roads. Most corridor networks occur in the western region. Approximately 91% of the predicted corridor paths for jebeer gazelle are within CAs (Fig. 4C, Table 5).

4. Discussion

This study investigated the habitat fragmentation and declining connectivity caused by the development of infrastructure in the central Iranian plateau. We focused on the impact of mining activities and road construction on three ungulate species (wild goat, urial, and jebeer gazelle). Our findings mirrored global patterns, highlighting the impact of roads on habitat loss and fragmentation (Mohammadi et al., 2023). This study provides a detailed analysis of a region experiencing rapid development. Similar to other studies worldwide, our work underscores the need for improved practices such as careful site selection for mining operations and robust environmental impact assessment (EIA). Additionally, mitigation strategies such as wildlife crossings and habitat restoration are crucial (Forman et al., 2003). Collaboration with conservation organizations is essential to promote responsible practices and minimize human-wildlife conflict, particularly in the context of achieving the UN's sustainable development goals (SDGs).

We employed an approach based on ensemble modelling techniques and sensitivity analysis, enhancing the accuracy and reliability of our habitat suitability models (Cariboni et al., 2007). These models are valuable for conservation planning and aid in the identification of priority areas for management (Crawford et al., 2020; Wintle et al., 2005). While extensive suitable habitats were identified, the pervasive negative impact of mining roads on core habitats and connectivity emerged as a challenge for all three species. This aligns with previous research by Jantz and Goetz (2008), Goetz et al. (2009), and Trombulak and Frissell (2000), highlighting the detrimental effects of roads on wildlife (Forman et al., 2003). Additionally, Zhang et al. (2015) documented how road and railway networks in China fragment crucial habitats for endangered species. The overlap between core habitats for the species with mining roads underscores the pressing need for international collaboration to address the detrimental impacts of roads on global biodiversity (Barrientos et al., 2021).

The studies conducted by Makki et al. (2013) and Seiler (2001) draw attention to the adverse effects of road construction on wildlife, with a particular focus on specific species and habitat loss. Makki reported habitat loss for goitered gazelle (*Gazella subgutturosa*) and mouflon (*ovis gmelini*) as a result of freeway construction. Seiler (2001) investigated

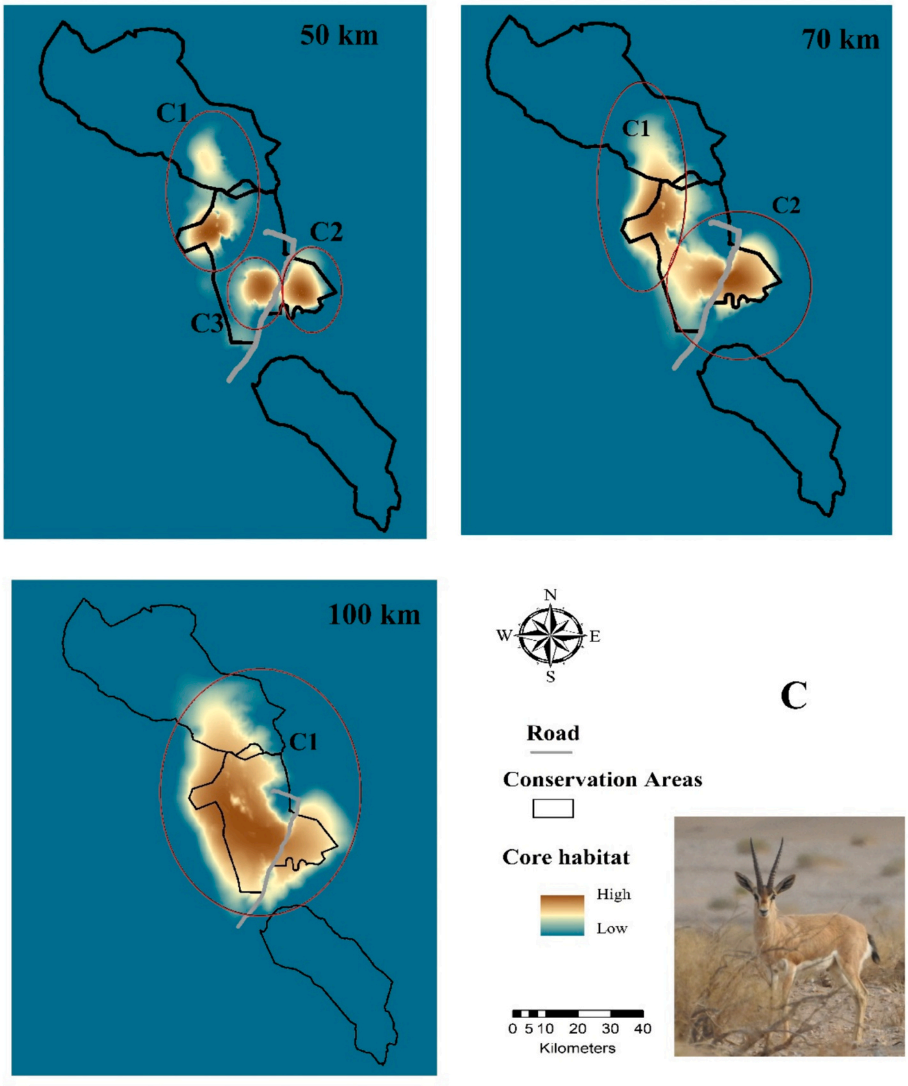

Fig. 3. (*continued*).

Table 4
Area and percentage of wild goat, urial, and jebeer gazelle core habitats covered by current CAs. The threshold for defining highly suitable habitats was determined based on the median value of habitat suitability at presence points.

Dispersal ability	Area of core habitats (km^2)	% of protected core habitats	Length of roads intersecting core habitats (km)
wild goat			
50 km	310.15	85.32	4
70 km	398.36	81.20	5.5
100 km	443.25	80.30	6.5
Urial			
50 km	950.60	83.30	16
70 km	1100.21	82.15	19
100 km	1200.81	78.20	23
Jebeer gazelle			
50 km	930.56	88.30	18
70 km	1050.30	86.32	20
100 km	1232.81	84.29	23

the broader implications of road construction for wildlife, shedding light on the general challenges faced by various animal populations. In comparison to Beier et al. (2008), this study takes a more comprehensive approach by specifically investigating the consequences of mining activities and road construction for ungulate populations in the central Iranian plateau. This focus on a specific region allows for a more in-depth understanding of the unique challenges posed by anthropogenic disturbances in the area. In contrast to Seidler and Plotnikov (2010), the current study provides a more detailed analysis of the impact of roads and other anthropogenic disturbances on ungulate populations, highlighting the unique influence of roads, particularly mining roads, on habitat fragmentation and connectivity. Other researchers have demonstrated that climate change, together with anthropogenic effects such as land use change for agriculture and afforestation, road construction, and mining, could further restrict the suitable habitats of ungulates (Ali et al., 2021; Luo et al., 2015; Luo et al., 2024).

Similar to our results, Almasieh and Mohammadi (2023) showed that distance to CAs was the most influential variable for predicting habitat suitability for jebeer gazelle and goitered gazelle in Iran. Karami and Ghadirian (2016) showed that the population of ungulates in Iran has declined severely outside CAs. In another study, Soofi et al. (2022) reported that ungulate poaching is higher outside CAs. Our results are consistent with those of Almasieh et al. (2023), who showed that

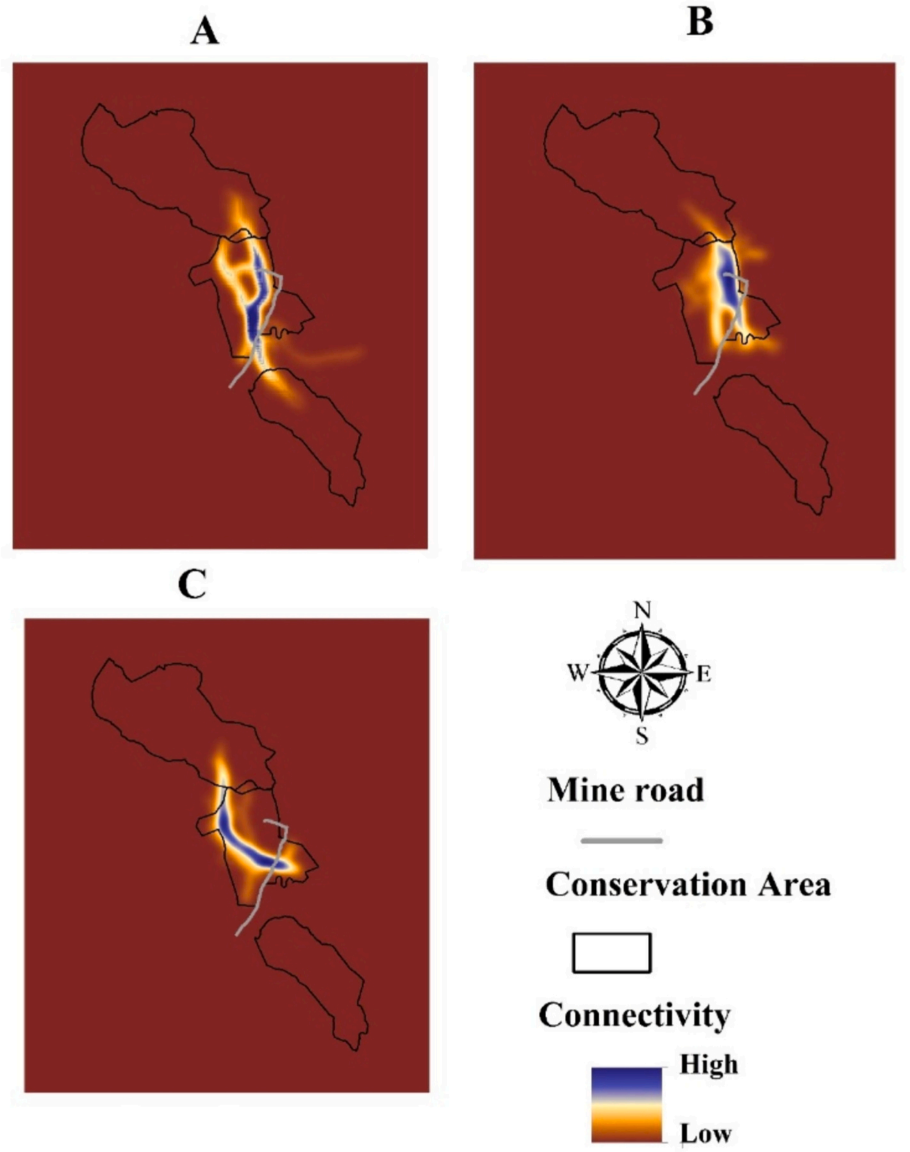

Fig. 4. Corridors for wild goat (A), urial (B), and jebeer gazelle (C) in the central Iranian plateau, estimated with a dispersal ability of 50 km. The connectivity strength of the corridors is visually depicted, ranging from weak (brown) to strong (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Extent and percentage of corridors covered by CAs for wild goat, urial, and jebeer gazelle in the central Iranian plateau. The threshold for defining highly suitable habitats was determined based on the median value of habitat suitability at presence points.

Species	Extent of corridors (km^2)	% of protected corridor	Length of road across the corridor path (km)
Wild goat	585.79	82	15.5
Urial	652.92	89	22
Jebeer gazelle	511.47	91	7.8

distance to roads was the most influential variable for predicting the occurrence of mouflon in Western Iran. In another study Nazeri et al. (2015) showed that wild sheep and onager populations tend to stay close to park ranger stations.

The identification of the spatial patterns in the core habitats of each ungulate species provides valuable insights into the distribution of these populations and their potential for persistence. The overlap of core habitats with mining roads highlights the vulnerability of these species to habitat loss and fragmentation. Connectivity simulations indicate that over 85% of corridor networks for all three species were protected by CAs. However, intersection with mining roads, affecting significant portions of wild goat and jebeer gazelle corridors, raise concerns about the effectiveness of existing conservation measures in protecting these species. This highlights the need for targeted conservation efforts to mitigate road–wildlife conflicts and protect migration corridors. Unlike our study, Niyogi et al. (2021) showed that approximately 63% of the core habitats of four ungulates, including blackbuck (*Antilope cervicapra*), chinkara (*Gazella bennettii*), nilgai (*Boselaphus tragocamelus*), and four-horned antelope (*Tetracerus quadricornis*), occurred outside of CAs. Their results revealed that distance from roads and railways was the most important variable for predicting habitat suitability. In another study, Sıkdokur et al. (2024) showed that intense conflicts between humans and brown bears in Türkiye can be largely attributed to limited coverage by protected areas.

Most CA networks in Iran are fragmented by roads, and road collisions present a serious threat to wildlife (Mohammadi et al., 2023; Rezaei et al., 2023). Most CAs are not large enough to safeguard species against human activities such as mining (Sıkdokur et al., 2024). We identified vulnerable sections of the connectivity network in the landscape, where roads intersected important movement corridors. Our findings are consistent with those of previous research. For instance, Mohammadi et al. (2023), Mohammadi et al. (2021a, 2021b), and Almasieh and Mohammadi (2023) showed that the core habitats of Asiatic cheetah, Persian onager, goitered gazelle, and jebeer gazelle and the corridors that link them are bisected by multiple primary and secondary roads.

This study identifies key variables influencing habitat suitability for three ungulate species in the central Iranian plateau, emphasizing the negative impact of roads and mining infrastructure. The fact that wild goat and urial prefer remote, vegetated areas, and jebeer gazelle prefers specific elevations and proximity to CAs highlights species-specific conservation needs. The inclusion of a sensitivity analysis enhances reliability and addresses the inherent uncertainty in ecological modelling. The correlation between core habitats and protection within CAs supports established conservation principles, while the broader consideration of conservation measures and acknowledgement of the variability of human threats contribute to the comprehensive approach of the study.

One of the most important implications of the current study is highlighting the role of human-ungulate conflict mitigation in corridors to increase the functionality of corridors. In addition to from the role of corridors in enhancing connectivity, they can increase human-herbivore conflicts by promoting movement into areas with high risk of human encounters. Failing to consider human-herbivore conflicts when identifying wildlife corridors may inadvertently create ecological traps with high mortality risks, thereby limiting the dispersal of individuals and undermining the effectiveness of corridors for ungulate movement (Carpio et al., 2021; Pascual-Rico et al., 2021; Rezaei et al., 2022a). In addition, ungulates living in human-dominated landscapes often cannot persist inside conservation areas alone and depend on habitats outside protected areas. A study by Ghoddousi et al. (2020) showed that many conservation areas are not large enough to provide suitable habitats for carnivores.

The predicted unprotected core habitats can be considered as potential areas to establish new, less strict conservation areas, such as community conservation areas.

The implications of the study for conservation planning are substantial, offering valuable insights into core habitats and connectivity that can guide effective conservation (Visconti and Elkin, 2009; Rudnick et al., 2012). The study also acknowledges the role of technological advancements such as remote sensing and machine learning in refining habitat suitability models and providing practical tools for conservation decision-making (Aizpurua et al., 2015; Dujon and Schofield, 2019; Rhodes and Sagan, 2021; Vogeler and Cohen, 2016). These findings translate into actionable measures: prioritizing core habitats, mitigating fragmentation by roads, and engaging local communities to ensure the resilience of vulnerable ungulate populations.

Although studying complex ecosystems can be challenging, this study underscores the importance of interdisciplinary collaboration (Westley and Miller, 2013). Continuous refinement of models is essential given the dynamic and nonlinear nature of ecological processes and the scarcity of long-term data (Bugmann and Weisberg, 2003). The findings of this study offer practical value and provide a roadmap for protecting essential habitats, restoring connectivity, and ensuring the resilience of ungulate populations in the face of escalating human activities.

CRediT authorship contribution statement

Alireza Mohammadi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kamran Almasieh:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis. **Somaye Vaissi:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoinf.2024.102656.

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