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Research Article

Investigating climate-driven corridor networks for Golden Jackal (*Canis aureus*) in Northern Parts of Iran

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Abstract

This study aims to examine the evolving network of corridors resulting from climate change and the emergence of new barriers affecting *Canis aureus*. We employed species distribution models (SDMs) to evaluate the potential effects of climate change on *Canis aureus* under both current and future SSP585 climate scenarios for the year 2070. We utilized the Linkage Mapper tool to identify the least-cost paths under two climate scenarios. We discovered 20 core habitat areas with an average size of 29791 km^2 for this species, with Linkage Mapper detecting 34 links between them with an average length of 84.3 km in the current scenario. In contrast, we identified 20 core habitats with an average size of 6091 km2 under the future scenario, showing changes in their positions. We identified 39 links between them, averaging 50.4 km in length. There are 145 road intersections in the current scenario, which decreases to 87 in the future scenario. The overlap of least-cost paths with cropland areas decreases from 974 to 589, and with urban areas, it decreases from 72 to 50 in the future. Our research underscores the pressing necessity for conservation initiatives to mitigate climate change's repercussions on mammal habitats and corridors in Iran, highlighting the potential impact of our findings on future conservation strategies.

Keywords: Corridor mapping, barriers, roads, species distribution models, linkage mapper

Introduction

Recent studies in Iran indicate that various infrastructures, including roads, railways, urban zones, industries, mines, and agricultural activities, can have significant effects on the country's protected areas (Khosravi & Hemami, 2019; Rahimi et al., 2024a; Rahimi et al., 2023). These studies highlight that such human activities can influence approximately 5.1–30.3% of the total extent of protected areas in Iran (Rahimi & Dong, 2022). In another study, Karimi and Jones (2020) showed that human footprints affect 12.8% of national park areas, 12% of wildlife refuge areas, and 28% of overall protected areas in Iran. However, recent investigations warn of unprecedented challenges related to climate change in Iran (Rahimi et al., 2024b). For example, Vaghefi et al. (2019) employed an ensemble approach incorporating five high-resolution climate models. They found that Iran is expected to experience prolonged periods of extreme maximum temperatures in its southern regions during the 2025–2049 timeframe, compared to the 1980–2004 period.

About Iran's biodiversity, Yousefi et al. (2019) investigated the impact of climate change on the species distribution of 37 species since 2014. Their findings indicated that 30 species are expected to undergo a reduction in their distribution ranges, while seven species may experience expansion. Overall, the study highlights the predominantly adverse effects of climate change on 81% of the species examined, presenting a significant challenge to biodiversity conservation in Iran. To assess the potential effects of climate change on various species in Iran's future, several studies have assessed the anticipated impacts of climate change on various species in Iran's future, such as birds (Moghadam et al., 2021), large mammals (Ashrafzadeh et al., 2022; Ashrafzadeh et al., 2019a; Ebrahimi et al., 2021), small mammals (Mohammadi et al., 2019), and reptiles (Farashi and Shariati, 2017).

However, climate change not only impacts the future distribution of species but also influences the potential corridors between core habitat areas in the future (Ashrafzadeh et al., 2022; Ashrafzadeh et al., 2019b; Mahmoodi et al., 2023; Malakoutikhah et al., 2020; Morovati et al., 2020; Shahnaseri et al., 2019). Previous studies in Iran have effectively addressed the identification of habitat corridors for various species; for instance, Khosravi et al. (2018) devised suitability maps using SDMs for leopard, cheetah, caracal, wild cat, sand cat, and wolf species in central Iran. Hosseini et al. (2019) crafted habitat suitability maps utilizing species distribution models (SDMs) for four Persian leopard species, goitered gazelle, bezoar goat, and urial, followed by employing circuit theory to identify potential corridors linking protected areas. Mohammadi et al. (2021) prioritized core habitats for brown bears in Iran based on SDMs, highlighting the significance of the Alborz and Zagros mountains as primary core habitats for this species.

In Iran, human-wildlife conflicts are intensifying due to growing human populations, habitat alteration, and a decrease in wild prey (Behmanesh et al., 2019). However, few studies have investigated the conflicts between humans and carnivores in Iran, examined local perceptions and attitudes towards these species, or analyzed the patterns and determinants of these conflicts. For example, gray wolves and golden jackals are responsible for livestock losses and occasionally attack humans, leading to significant population declines due to conflicts with rural communities (Behmanesh et al., 2019). A study in Pakistan using 100 questionnaires about human conflicts with jackals found that many respondents were unhappy with the presence of the Asiatic jackal. Most inhabitants visit their agricultural fields daily and spend considerable time with their livestock to protect them (Younus et al., 2018). Additionally, urbanization poses a significant threat to Greece's golden jackal (*Canis aureus*) by causing disturbances and potentially reducing their habitat. Furthermore, the increase in road traffic from human development and tourism raises the risk of jackals being hit by vehicles, which is a serious concern for both human safety and the preservation of the jackal population (Bulmer, 2015). In the Netherlands, urbanization and the presence of wolves have been identified as the main factors limiting the establishment of the golden jackal (Wennink et al., 2019).

However, it remains unclear how climate change will affect the habitat suitability of the golden jackal in Iran. This raises questions about potential alterations in the jackal's movement routes between core habitats through corridors. Additionally, we need to understand to what extent these climate change-induced corridors will intersect with roads and urban areas and whether this will lead to increased road casualties or human-wildlife conflicts on the outskirts of cities. Therefore, this study aims to identify the corridors between the core habitats of the jackal by modeling the current and future habitat suitability under a climate change scenario. Subsequently, we will examine the likelihood of the jackal's presence in agricultural fields, cities, and the intersections of these corridors with the road network in northern Iran.

Material and methods

Golden Jackal

The golden jackal is a medium-sized predator and omnivore found in the southern parts of the Palearctic, South Asia, and northeastern Africa. Currently, the jackal population is restricted to a few clusters divided into seven sub-areas based on criteria like connectivity and isolation. The decline in their population is primarily due to habitat loss resulting from changes in human agro-pastoral activities, leading to reduced day-cover availability and possibly a diminished food base (Moehlman and Hayssen, 2018; Negi, 2014).

Species distribution models (SDMs)

To evaluate the potential impacts of climate change on the emerging corridors and barriers affecting this species, we initially conducted species distribution modeling (SDM). We utilized the resulting habitat suitability as resistance maps for corridor mapping. For this study, we obtained presence data for the species from the Global Biodiversity Information Facility (GBIF) website (www.gbif.org), followed by removing duplicate records and those located outside the study area boundary. Utilizing The spThin R package (Aiello-Lammens et al., 2015) facilitated this process, employing a spatial thinning distance of 20 km between points. This distance was chosen to align with the scale or pixel of the model's environmental layers, ensuring effective mitigation of spatial autocorrelation (Chamberlain et al., 2022). Ultimately, we obtained 58 occurrence points for this species to serve as dependent data in species distribution modeling.

Environmental layers

We acquired climatic layers from the WorldClim database (worldclim.org), with a spatial resolution of approximately 4 km, for current and future climate scenarios based on SSP585. The SSP585 scenario, representing an adverse climate change projection, anticipates a threefold increase in CO2 emissions by 2075 and a temperature rise of 4.4 by 2070 (O'Neill et al., 2016). To address multicollinearity among 19 highly correlated WorldClim variables, we employed the USDM package (Naimi, 2017) to calculate the Variance Inflation Factor (VIF). The modeling process retained variables such as Isothermality (Bio 3), Temperature Seasonality (Bio 4), Mean Temperature of the Wettest Quarter (Bio 8), Mean Temperature of the Driest Quarter (Bio 9), Precipitation of the Driest Month (Bio 14), Precipitation Seasonality (Bio 15), Precipitation of the Warmest Quarter (Bio 18), and Precipitation of the Coldest Quarter (Bio 19).

Model fitting

In this study, we utilized the "FLEXSDM" R package (Velazco et al., 2022) in R software to model the distribution patterns of *Canis aureus* species. Specifically, we employed the MaxEnt model to create habitat suitability maps by integrating presence and climate data. To enhance modeling accuracy, we generated 5,000 pseudo-absence points, which were incorporated alongside the presence points in the MaxEnt model. The output of species distribution models (SDMs) ranges between 0 and 1. We considered values surpassing 0.7, as core habitat areas for landscape connectivity analysis (Rahimi and Dong, 2023).

Model assessment

To evaluate the effectiveness of different models, we utilized three key performance metrics: inverse mean absolute error (IMAE), the area under the ROC curve (AUC), and the Boyce Statistic (BOYCE), employing the "FLEXSDM" R package (Velazco et al., 2022). AUC values between 0.7 and 0.9 are acceptable, while values exceeding 0.9 indicate excellent accuracy and highly precise predictions. Higher IMAE and Boyce Index values signify increased model accuracy. Model performance evaluation was conducted using a 5-fold cross-validation (Fielding and Bell, 1997).

Landscape connectivity analysis

Resistance map

The resistance map incorporates natural elements like slope, elevation, and movement through natural landscapes and human-induced factors that adversely affect the environment, commonly referred to as human footprints. Certain studies solely utilize the human footprint map as the resistance map (Belote et al., 2016). In Iran, the proximity to anthropogenic infrastructure is acknowledged as a significant factor influencing the distribution of carnivores (Khosravi et al., 2019) and, more broadly, the distribution of protected areas (Rahimi and Dong, 2022). In this study, similar to Rahimi and Dong (2023), we transformed the habitat suitability map (generated in the preceding section) into a resistance surface through a linear decay function ($R = 1 - HS$), where R denotes the cost resistance values attributed to each pixel and HS indicates the predicted suitability. Since the habitat suitability map was based only on climatic variables, we summed it with the human footprint map Belote et al. (2016) developed, encompassing roads, railways, farms, and urban areas.

Least-cost analysis

To delineate the least-cost corridors linking core habitat areas, we employed the Linkage Mapper Toolkit (McRae and Kavanagh, 2011). Linkage Mapper is one of the few tools to identify barriers within corridors. It employs Euclidean and least-cost considerations to draw least-cost corridors but requires a maximum dispersal ability for the species under study. For instance, Khosravi et al. (2018) set the maximum dispersion ability at 300 km for large mammals, while other studies specified distances such as 200 km for leopards and brown bears (Rahimi & Dong, 2023). For cheetahs, 150 km for lynxes, 100 km for caracals and palace cats, and 100 km for feral cats (Ashrafzadeh et al., 2020). In our study, we adopted an optimistic perspective regarding the maximum dispersal ability of *Canis aureus*, setting it at 100 km. Typically, such maximum distances are not precisely determined for animals.

Land use, and roads overlapping with LCPs

To understand the typical land cover through which the identified corridors for *Canis aureus* should pass, we overlaid these corridors with the land use map of Iran, produced by Copernicus (Mariela et al., 2020) in 2019. Our focus was specifically on croplands and urban areas (Fig. 1-a), which can impede mammal movement. Additionally, we used the `gIntersection` function from the `rgeos` R package (Bivand et al., 2017) to pinpoint where the corridors intersect with Iran's road network (Fig. 1-b), considering these intersections as barriers to animal movement. This analysis provided insights into the impact of various land covers and human infrastructure on the identified corridors.

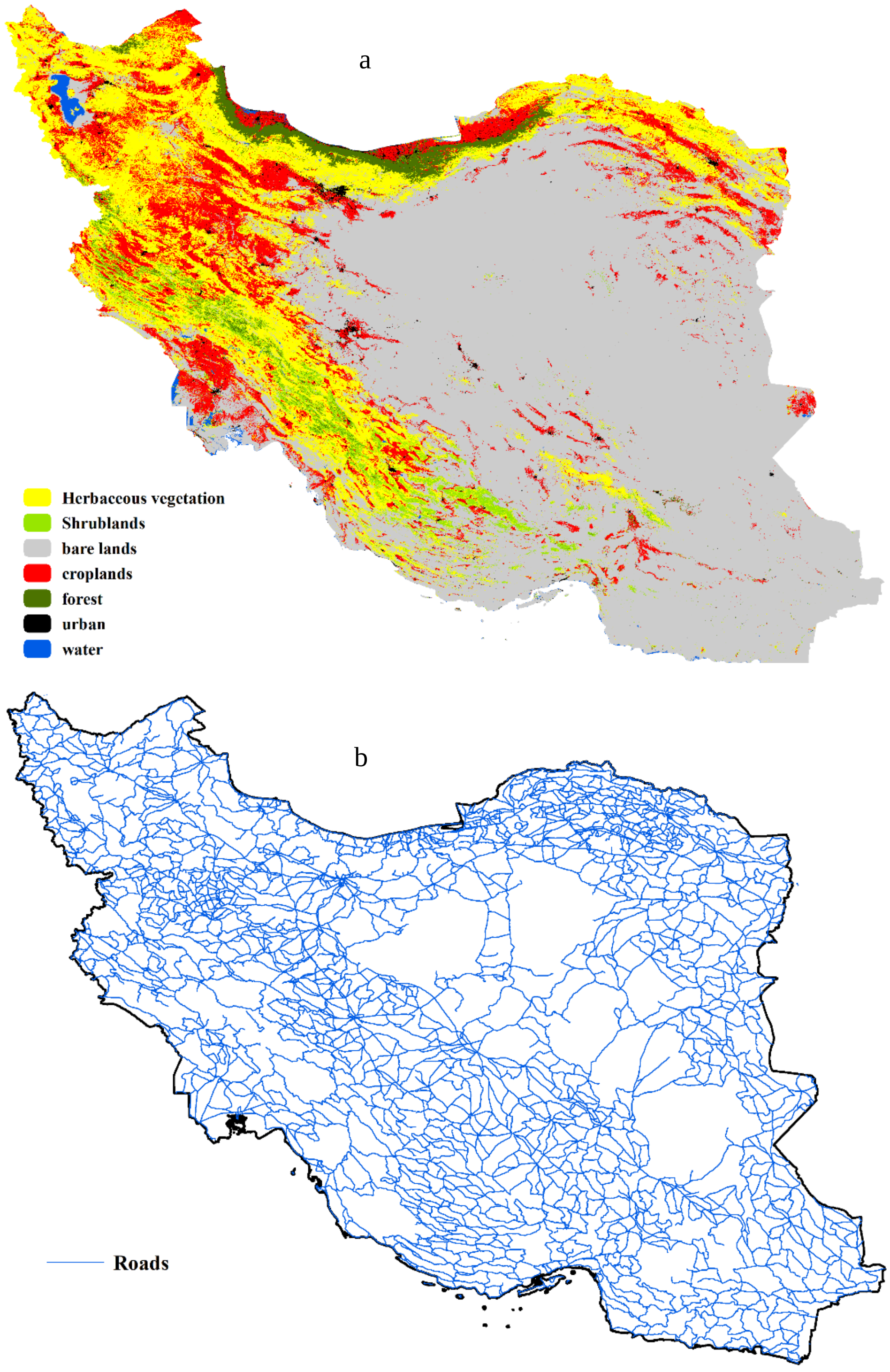

Figure 1. Land use (a) and road network (b) of Iran

Results

Model assessment

Table 1 presents the model validation metrics of the MaxEnt algorithm. Table 1 displays the validation metrics for the MaxEnt model applied to *Canis aureus; the* Area Under the Curve (AUC) value, which indicates the model's discriminatory ability, is 0.89, suggesting acceptable accuracy. The Boyce Index (BOYCE), measuring the model's ability to predict habitat suitability across different thresholds, is 0.98, indicating excellent performance. The Inverse Mean Absolute Error (IMAE), reflecting the average difference between predicted and observed values, is 0.68, suggesting relatively good model accuracy. These metrics suggest that the MaxEnt model performs reasonably well predicting habitat suitability for *Canis aureus*.

Table 1. Model validation metrics, including AUC, BOYCE, and IMAE, were generated using the MaxEnt algorithm for *Canis aureus*.

	AUC	**BOYCE**	**IMAE**
Canis aureus	0.89	0.98	0.68

Habitat Suitability and least-cost paths

Figure 2 depicts the current (a) and future (b) habitat suitability maps. This figure illustrates that under future climate scenarios, the high-suitability areas for *Canis aureus* may increase, and the core habitat areas indicate an increase in their area and potential shifts in their locations. Areas with a suitability value of 1 indicate the highest suitability. Figure 3 illustrates the least-cost paths connecting core habitat areas for *Canis aureus* in the current (a) and future (b) scenarios, showcasing multiple corridors linking adjacent core areas. In the current scenario, we identified 20 core habitats averaging 2979 km^2 in area for this species, with Linkage Mapper detecting 34 links between them averaging 83.4 km in length (Table 2). Conversely, in the future scenario, we identified 20 core habitats averaging 6091 km^2 in area, with Linkage Mapper identifying 39 links between them averaging 50.4 km in length.

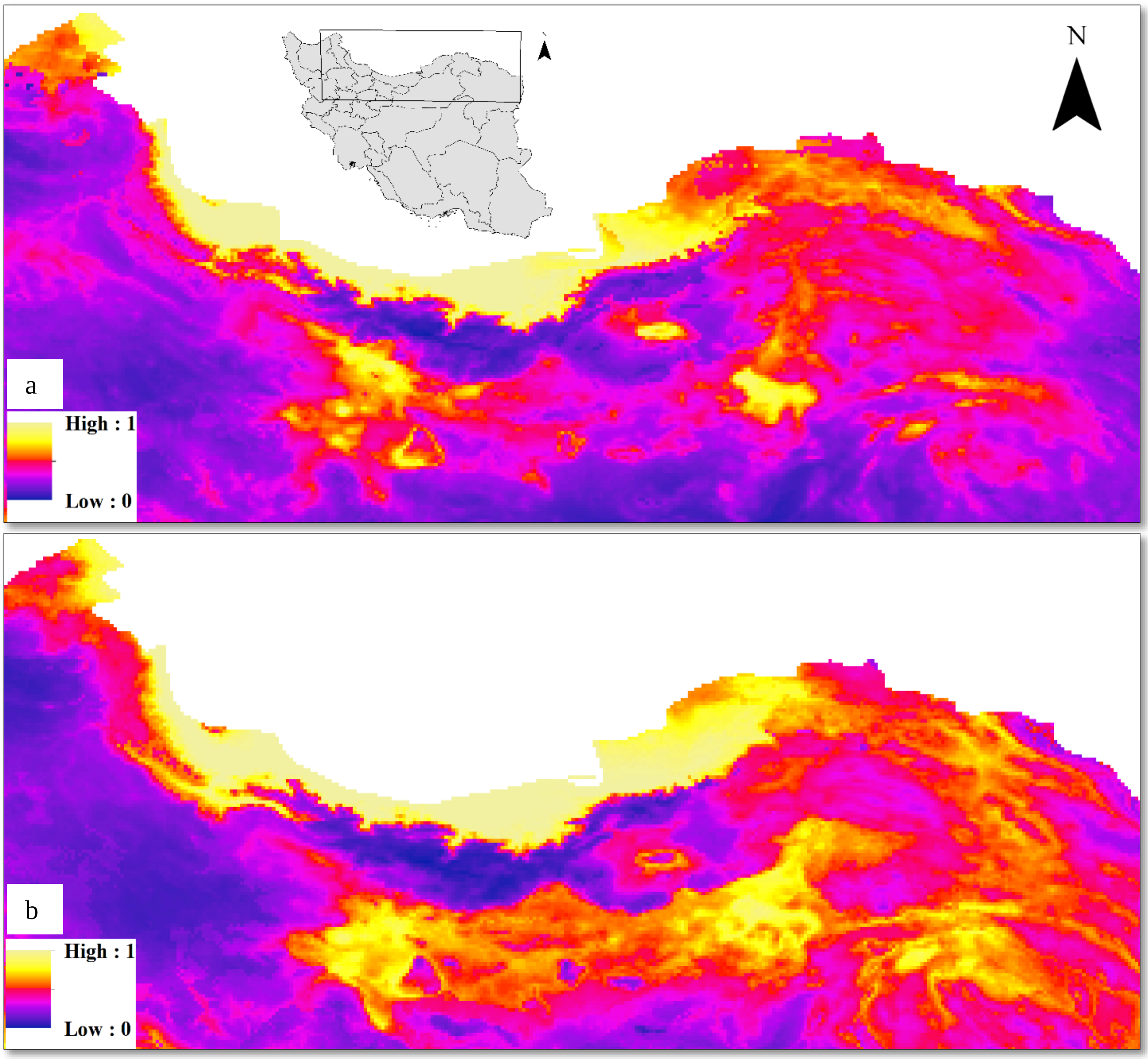

Figure 2. The current (a) and future (b) habitat suitability maps for *Canis aureus*.

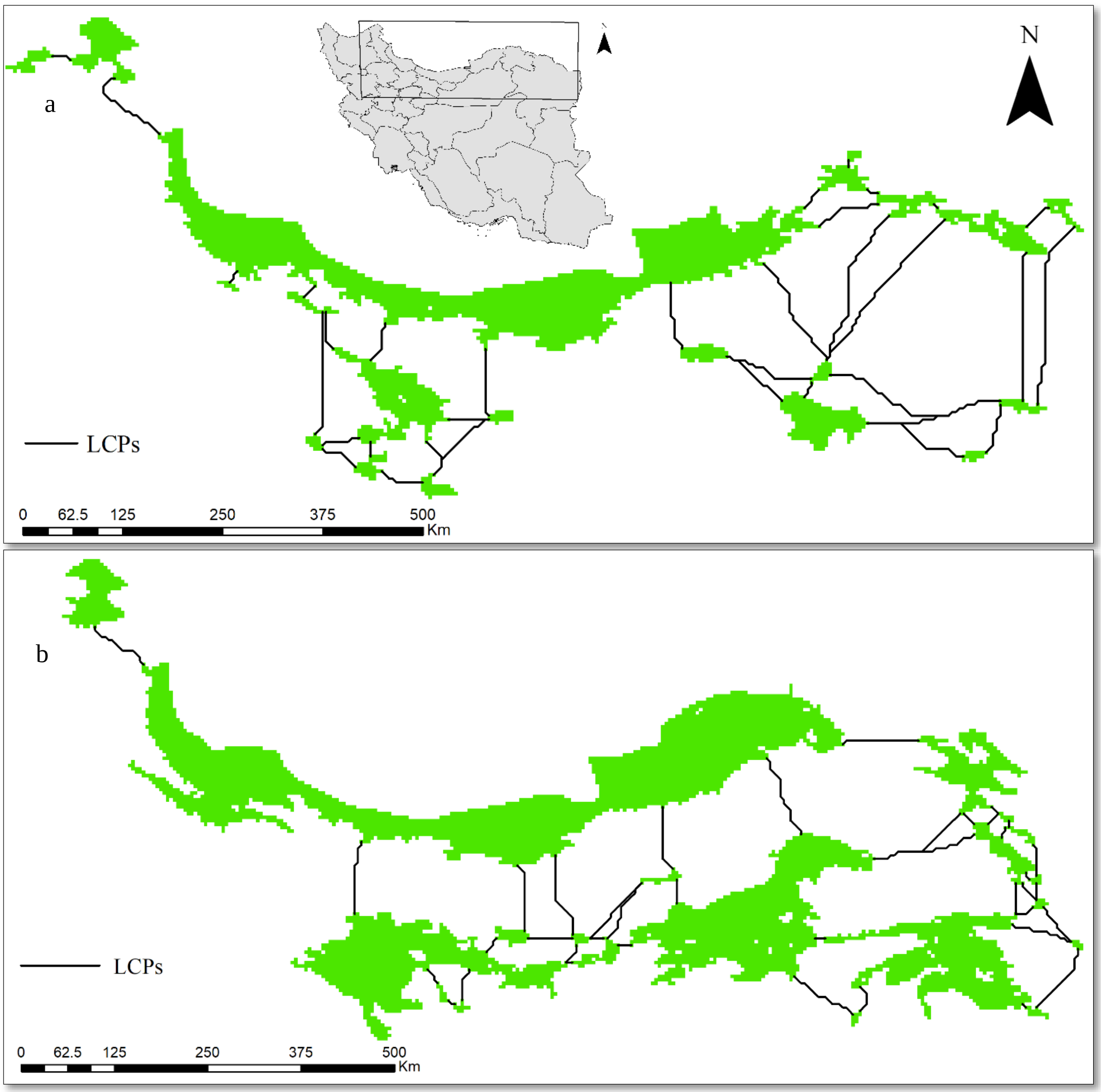

Figure 3. The current (a) and future (b) core habitat areas and the least cost corridor between them.

The following table (Table 2) compares characteristics related to least-cost paths for Canis aureus under current and future scenarios. There are currently 145 road intersections, which will decrease to 87 in the future scenario. The overlap of least-cost paths with cropland areas diminishes from 974 in the current scenario to 589 in the future, and with urban areas, it decreases from 72 presently to 50 in the future.

Table 2. Least-cost path characteristics, road intersections, and land use overlap.

	Mean Core Areas (km^2)	Number	Mean Length (km)	Roads intersection	Cropland	Urban
Current	2979 (8007)	34	83.4 (66)	145	974	72
Future	6091 (12768)	39	50.4 (37)	87	589	50

Discussion

In this study, we applied species distribution modeling (SDM) to create habitat suitability maps for *Canis aureus* in the current and future (2070) under the SSP585 climate scenario. Our results revealed that the primary effect of climate change could be on core habitat areas, as the size and location of these areas for *Canis aureus* changed, although the number of core habitats remained the same. The changes in the position of core habitat areas resulted in alterations in the number and length of new corridors. The reduction in the average length of corridors for the species from 83.4 km to 50.4 km suggests potential positive outcomes. This decrease can be attributed to the increase in the size of core habitat areas, which may result in a reduction in corridor length in the future. Despite this, the expanded core habitat areas hold promise for the species, as they could contribute to the overall effectiveness of the corridors for species conservation.

Every species responds to climate change based on their unique behavioral, physiological, and anatomical traits. Their survival hinges on either migrating to regions with suitable climates or adjusting to the changing environmental conditions. Failure to do so could lead to extinction (Parmesan, 2006). Nevertheless, the rapid pace of climate change often outpaces the ability of many species to adapt through evolutionary processes (Stringer et al., 2009). Recently, there has been increasing attention directed towards understanding the impacts of climate change on future mammal corridors in Iran. For example, Mahmoodi et al. (2023) assessed the potential distribution range of roe deer in northern Iran and introduced connectivity models along with corridor designs for current and future scenarios. They identified that the distribution range of roe deer would significantly expand in response to climate change, encompassing a broader range of habitats with new pathways between new core habitat areas. Rahimi et al. (2024b) also assessed the specific impacts of climate change on Iran's protected areas by applying species distribution modeling to forecast the effects on 394 bird species, 157 plant species, 72 reptiles, and 20 mammals under two climate change scenarios: SSP245 and SSP585 for the year 2070. Their findings showed that in the SSP585 scenario, mammals could experience a substantial increase of 147.3% in 5 species, while 15 species might decline by 71.8%.

Ashrafzadeh et al. (2019b) also anticipated that climatic changes would have adverse effects on the suitable habitats of amphibians, potentially leading to elevational shifts in the range of Lorestan Mountain Newt, consequently, alteration in key linkages between habitat patches under various climate scenarios. Malakoutikhah et al. (2020) utilized an ensemble modeling approach to predict the impact of climate change on the distribution of goitered gazelle (*Gazella subgutturosa*), wild sheep (*Ovis spp*), and wild goat (*Capra aegagrus*) under the RCP 8.5 emission scenario. Subsequently, it determines corridors for the movement of these three ungulates and assesses the probable changes in their suitability due to climate change. They found that climate change could significantly reduce suitable habitats for goitered gazelle, wild sheep, and wild goat by 2070. Consequently, certain core habitat areas may not be passed by the species due to these habitat losses.

However, the primary barriers hindering mammal movement in Iran are roads, which are widely distributed across the country and can intersect with the corridors utilized by these species (Rahimi et al., 2024a). Other studies have highlighted the adverse effects, such as collisions with vehicles resulting in fatalities (Ghadirian et al., 2019; Parchizadeh et al., 2017). Agricultural fields and roads have been identified as the primary human pressures impacting Iran's protected areas (Rahimi and Dong, 2022). Roads in central Iran are also recognized as significant factors contributing to the decline in cheetah populations, with fewer than 43 individuals remaining in the wild (Mohammadi et al., 2018) Rahimi and Dong (2023) also found that brown bears and Persian leopards in Iran encounter numerous human-made obstacles, like roads, when migrating to other suitable areas. They indicated that Least-cost corridors identified by Linkage Mapper generally avoid passing through cities due to their high resistance, highlighting roads as the primary impediments in these species' paths.

However, our findings indicated that *Canis aureus* will likely encounter fewer road intersections as the mean corridor length decreases. Additionally, reducing corridor length means fewer crossings through croplands and urban environments. Specifically, the number of road intersections decreases from 145 to 87, cropland crossings decrease from 974 to 589, and urban environment crossings decrease from 72 to 50. These trends suggest a potential improvement in habitat connectivity and a decrease in potential conflicts between the species and human infrastructure.

Conclusion

Our study utilizing species distribution modeling (SDM) has shed light on the potential impact of climate change on the habitat suitability and connectivity of *Canis aureus* in Iran. We found that while the number of core habitat areas for the species remained constant, the size and location of these areas changed significantly under future climate scenarios. Consequently, alterations in core habitat areas led to changes in the number and length of corridors. Our findings align with the broader understanding that species respond to climate change based on their unique traits, either by migrating to suitable climates or adapting to changing conditions. Past assessments of mammal habitats in Iran typically involved the initial creation of habitat suitability maps using Species Distribution Models (SDMs), followed by identifying potential corridors between core areas. However, recent trends and studies are increasingly focused on assessing the impacts of climate change on the potential future corridors and the obstacles hindering their pathways. Our findings also underscore the urgent need for conservation efforts to mitigate the impact of climate change on mammal habitats and corridors in Iran. Addressing the challenges posed by human-made barriers, particularly roads, is crucial for ensuring mammal populations' survival and long-term viability in the face of climate change.

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