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Snow Leopard habitat vulnerability assessment under climate change and connectivity corridor in Xinjiang Uygur autonomous region, China

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Climate change is recognized as one of the greatest challenges to global biodiversity. The endangered snow leopard (*Panthera uncia*), an apex predator in high-altitude mountain ecosystems, serves as an important indicator of ecological health. Understanding the impacts of climate change on snow leopard distribution patterns is essential for developing effective conservation strategies. Based on the BIOMOD2 model, this study assesses the current distribution of suitable habitats and project future changes under various climate scenarios, as well as evaluates the protection gap and corridor construction in Xinjiang Uygur Autonomous Region, China. The results indicated the total area of suitable habitat for snow leopard in Xinjiang is approximately 686,200 km^2 under the current climate conditions. The area of suitable habitat remains relatively stable or slightly increases under low emissions scenarios, while predictions show a gradual decline under moderate and high emissions scenarios. Currently, suitable habitats are fragmented, with low connectivity among patches, posing threats to the snow leopard population. Vulnerable habitats are primarily located in the Altai, northwestern Junggar Basin, and the central Tianshan Mountains. Potential future suitable areas are projected emerge in the Kunlun Mountains. It is suggested that greater focus be placed on unprotected climate refugia, enhancing the connectivity of habitat corridors, fostering cross-border cooperation, and implementing long-term monitoring efforts. This study provides valuable insights for conservation strategies aimed at mitigating the impacts of climate change on snow leopard populations in Xinjiang, China.

Keywords Large carnivores, Species distribution model, Habitat suitability, Climate refugia, Conservation strategy

Climate change is a major driver of global biodiversity loss, influencing species distributions and ecosystem dynamics[1]. Rising temperatures, altered precipitation patterns, and more frequent extreme weather events accelerate habitat loss, fragmentation, and shifts in species ranges[2,3]. These changes particularly threaten large carnivores like the snow leopard, whose specialized habitat requirements and dependence on prey species make them highly vulnerable to climate-induced disruptions[4]. Additionally, climate change has reduced the overlap between snow leopards and their primary prey[5], forcing snow leopards to broaden their diet, which has intensified resource competition with other sympatric carnivores[6,7]. Furthermore, climate change has led to an upward shift in the tree line, expanding the habitat range of common leopard (*P. pardus*), which in turn compresses snow leopard habitats, intensifies interspecies competition, and ultimately threatens their long-term survival[8].

The snow leopard is an apex predator in high-altitude ecosystems of Central and South Asia, adapted to cold, rugged environments. It primarily preys on ungulates such as blue sheep (*Pseudois nayaur*), goats, and ibex

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(*Capra spp.*)[9,10]. Climate change is significantly affecting snow leopard habitats through loss and fragmentation, as well as declines in prey populations[4]. Rising temperatures are shifting treelines and reducing alpine zones, resulting in a loss of up to 30% of snow leopard habitat in the Himalayas[11]. Additionally, increased temperatures are altering vegetation types in high-altitude areas, reducing the availability of alpine meadows, and affecting the interactions between snow leopards and their prey[5]. Climate-induced changes are prompting prey species like blue sheep to migrate, which compels snow leopards to descend to lower elevations. This migration can lead to increased crop damage by blue sheep and exacerbate livestock predation by snow leopards[12], thereby escalating the risk of human-wildlife conflict. Furthermore, accelerated melting of glaciers has also made poaching and illegal hunting easier in steep, hard-to-reach valleys, which disrupts the habitats of snow leopards and reduces their population[4]. Investigating the impact of climate change on snow leopards is essential for understanding how their habitats and populations may shift, which is critical for developing informed conservation strategies to ensure their survival.

Xinjiang Uygur Autonomous Region (hereinafter Xinjiang) is located in the northwest of China and borders eight countries with a land border of more than 5,600 km, and is characterized by its complex and diverse terrain, and respects a critical habitat for snow leopards (Xu et al., 2014; Xiao 2019). The snow leopard populations in Xinjiang are predominantly found in the Altai, Tianshan, and Kunlun mountain ranges and Pamir[14]. These high-altitude meadows, rocky terrains, and snow-covered regions provide suitable habitats for snow leopards, which rely on the mountainous terrain for concealment while hunting and require extensive territories to maintain population stability[15–17]. Moreover, Xinjiang serves as an ecological corridor connecting to neighboring countries - Russia, Kazakhstan, Kyrgyzstan, Tajikistan, Pakistan, Mongolia, India and Afghanistan - that also host significant snow leopard habitats[18]. Thus, Xinjiang is integral to the regional connectivity of snow leopard populations.

Species Distribution Models (SDMs) are essential tools in ecology and biogeography, integrating species occurrence data with environmental variables such as climate, topography, soil characteristics, and vegetation types to predict potential species distributions at the landscape scale[19–21]. In recent years, SDMs have been widely applied to examine the relationship between species distributions and climate change[22,23], predict the spread of invasive species[24,25], monitor and model functional groups and keystone species[26,27], delineate protected areas for endangered species and assess the impacts of human impacts on threatened wildlife[12,28].

Due to Xinjiang's sensitivity to climate change and ecological shifts[29], the trends in its snow leopard habitat can provide valuable data for understanding the impact of global climate change on alpine ecosystems. This study uses the BIOMOD2 model, incorporating species occurrence data and bioclimatic variables, to predict snow leopard habitat changes in Xinjiang under various climate change scenarios. We aimed to: (1) assess current and future snow leopard distribution, (2) evaluate habitat fragmentation and connectivity, and (3) propose conservation strategies to address protection gaps under climate change.

Methods

Study area

Xinjiang Uygur Autonomous Region is located in the northwest of China and is the largest province in terms of area. It has the second-largest potential habitat for snow leopards in China, making Xinjiang a crucial area for snow leopard conservation. Situated in Central Asia, Xinjiang shares borders with eight countries within the snow leopard's range, including Russia, Kazakhstan, Kyrgyzstan, Tajikistan, Pakistan, Mongolia, India, and Afghanistan. This unique geographical position makes Xinjiang an important region for transboundary snow leopard conservation[18]. The terrain in Xinjiang is highly diverse, featuring high-altitude regions such as the Tianshan, Altai, Kunlun Mountains, and the Pamir Plateau, which are suitable habitats for snow leopards[14], as well as other geographical units like the Junggar Basin, Qaidam Basin, and the Taklamakan Desert. The region encompasses various ecosystems, such as forests, grasslands, deserts, and wetlands. The southern areas are characterized by a warm temperate climate, while the northern areas have a typical temperate continental climate, with an average annual temperature of 7.6℃ and annual precipitation ranging from 8.1 to 571.7 mm[29]. These climatic and geographical conditions contribute to the ecological diversity of Xinjiang, providing a variety of habitats for snow leopards and other wildlife. The main mammal species include snow leopard, Eurasian lynx (*Lynx lynx*), Tibetan brown bear (*Ursus arctos*), wild yak (*Bos mutus*), Tibetan antelope (*Pantholops hodgsonii*), Goitered Gazelle (*Gazella subgutturosa*) and Przewalski's horse (*Equus ferus*).

Species records

A total of 668 snow leopard occurrence records in Xinjiang were collected through camera-trap monitoring (71 records), footprints or scrape (144 records), genetically verified scat samples (31 records), the Global Biodiversity Information Facility (GBIF) database (2 records), Mapping Biodiversity of China (MapBio) database (16 records) and literature on snow leopard distribution retrieved from the Web of Science and China National Knowledge Infrastructure (CNKI, 404 records). These records were exclusively derived from wild populations, excluding museum or captive specimens. Literature-based records were obtained from camera-trap detections, direct observations by field researchers and conservation staff, as well as credible media reports. To ensure the accuracy of the model and mitigate spatial autocorrelation caused by closely spaced distribution points[30], 10 km thinning distance is used as thinned the occurrence records in geographical space[31]. The number of snow leopard occurrence record was reduced to 309 (Fig. 1).

Environmental variables

We selected 30 environmental variables pertinent to the geographical distribution of snow leopards, categorized into four groups (Table S1): (1) Climate factors: Nineteen bioclimatic variables for current (average for 1970–2000), 2050s (average for 2041–2060) and 2070s (average for 2061–2080) climate conditions were obtained from

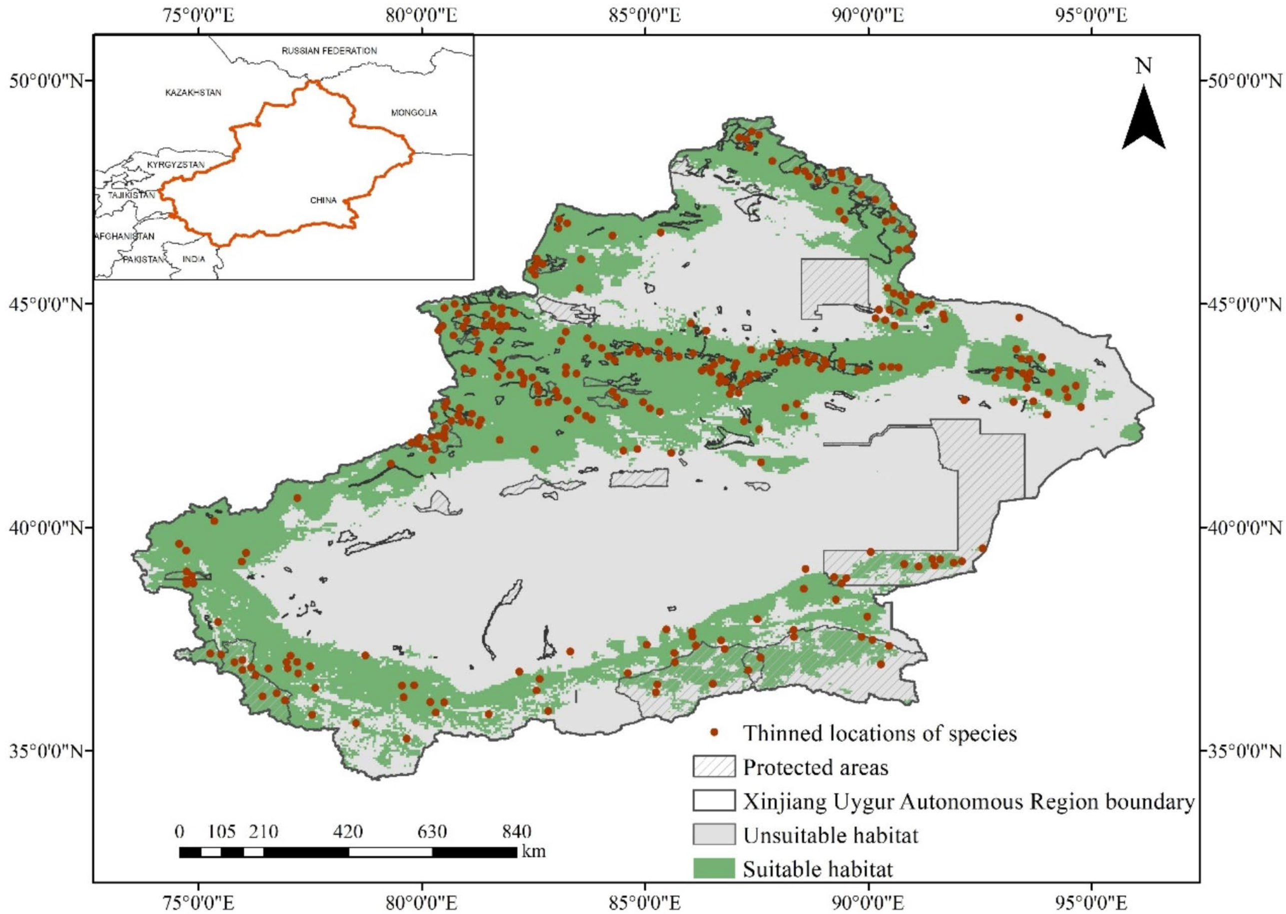

Fig. 1. Snow leopard occurrences and suitable habitat distributed in Xinjiang Uygur Autonomous Region, China. SDMs were generated using R v4.2.2 (https://www.r-project.org) and the biomod2 package v3.5.1 (https://CRAN.R-project.org/package=biomod2). Maps were created using ArcGIS v10.5 (https://www.arcgis.com).

the WorldClim database with a resolution of 2.5 min. Future projection was derived from IPSL-CM6A-LR global climate models of the IPCC-CMIP6, which features moderate temperature and precipitation estimates[32]. These projections were based on the SSP1-2.6, SSP3-7.0, and SSP5-8.5 emission scenarios within the framework of Shared Socioeconomic Pathways (SSPs). (2) Biological factors: Net Primary Productivity (NPP) with a resolution of 500 m was obtained from MOD17A3HGFv006 data provided by the LP DAAC database[33]. Normalized Difference Vegetation Index (NDVI) was obtained from MOD13A2v061 data available from the LP DAAC with a resolution of 1 km[34]. Water source data was retrieved from the OpenStreetMap platform. (3) Topographic factors: Elevation data was obtained from a digital elevation model with a resolution of 30 m, provided by the Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences. Slope and aspect were calculated from elevation using ArcMap 10.5 (ESRI Inc.). (4) Human activity factors: The Human Impact Index (HII; v2, 1995-2004) with a resolution of 1 km was downloaded from Socioeconomic Data and Applications Center[35]. Human Footprint (HFP) data for 2000–2018 was sourced from the dataset published by Mu (2022). Information on roads and railways was retrieved from the OpenStreetMap platform. Land cover data with a resolution of 100 m was obtained from Copernicus Land Monitoring Service[36], integrating various types of physical coverage at a global scale.

All variables were resampled at a 5 km^2 resolution and put into the same projection using ArcGIS 10.5 (ESRI Inc.). ENMTools R package was used to determine multicollinearity of variables and perform variable importance analyses by enmtools.vip function[37]. We removed the variables that highly correlated (>0.8) and contributed <1% to the model[38]. Finally, nine environment variables were kept to build the habitat suitability model, including isothermality (bio3), mean temperature of wettest quarter (bio8), precipitation seasonality (bio15), precipitation of driest quarter (bio17), net primary productivity (NPP), elevation (DEM), distance from water source (waterway), human impact index (HII) and land cover (LUCC).

Habitat suitability model

The BIOMOD2 model is a widely used tool for species distribution modeling that integrates multiple algorithms to predict the potential impacts of environmental changes on species distributions[39]. This ensemble modeling approach allows for robust predictions by combining outputs from various models, such as Generalized Linear Models (GLM), Random Forests (RF), and Boosted Regression Trees (BRT), among others[40]. BIOMOD2 offers a rapid model comparison platform within the same dataset, aiding in the selection of the most suitable model. The model is valuable for investigating the effects of climate change on species distributions by simulating future scenarios based on projected climate variables. BIOMOD2 R package was used to construct the current and future habitat suitability model of snow leopard by ensemble model. In order to improve the appropriateness and accuracy of the model prediction, 10,000 pseudo-absence points were randomly generated outside 40 km buffer zone based on the maximum daily movement distance of snow leopard[41,42].

The true skill statistic (TSS) and the area under the curve (AUC) of receiver-operating characteristic (ROC) plots were used to evaluate the accuracy of the model[43,44]. A TSS value between 0.7 and 0.9 proves that the model performs well, so ensemble models with TSS > 0.7 are selected for modeling. The value of AUC ranges between 0.5 and 1, and the closer the value is to 1, the better the model prediction is[45]. We randomly selected 75% of the snow leopard distribution points as the training set, combined with geographical environment elements to calibrate the models. The remaining 25% distribution point data is used as a test set to evaluate the accuracy of the prediction results. We repeated this process (calibration and evaluation) 10 times. The model results are represented as probability raster maps with values ranging from 0 to 1000, where higher values indicate a greater likelihood of distribution. Based on the threshold corresponding to the maximum TSS value of the model, the study area was classified into suitable habitat (raster values ≥ threshold) and unsuitable habitat (raster values < threshold).

Gap analysis of protected areas and vulnerability assessment

We evaluated the effectiveness of existing protected area in supporting snow leopard populations. We overlaid the current and future suitable habitats onto the spatial boundaries of these protected areas using ArcGIS 10.5.

To assess the vulnerability of snow leopards under climate change, we analyzed changes in suitable habitat for the current period, the 2050s, and the 2070s, and categorized habitats into four types based on the following criteria[46,47]: (1) Vulnerable habitat: areas predicted to transition from suitable to unsuitable habitat by the 2050s and 2070s; (2) New suitable habitat: areas predicted to transition from unsuitable to suitable habitat by the 2050s and 2070s; (3) Climatic refuge: areas where current and future (2050s and 2070s) suitable habitats overlap; (4) Unsuitable habitat: areas where current and future (2050s and 2070s) unsuitable habitats overlap. Additionally, we employed three indices to evaluate the impact of climate change on snow leopard habitat suitability: (1) Percentage of suitable habitat area change (AC), (2) Percentage of current suitable habitat lost by the 2050s and 2080s (SH_L); (3) Percentage of increased suitable habitat area for the 2050s and 2070s (SH_I). The calculation of these indices is as follows:

$$\mathrm{AC} = (\mathrm{SH_F} - \mathrm{SH_C}) / \mathrm{SH_C} \times 100\%$$
$$\mathrm{SH_L} = (\mathrm{SH_C} - \mathrm{SH_O}) / \mathrm{SH_C} \times 100\%$$
$$\mathrm{SH_I} = (\mathrm{SH_F} - \mathrm{SH_O}) / \mathrm{SH_F} \times 100\%$$

where SH_F represents the area of suitable habitat predicted for snow leopards under the 2050s and 2070s climate scenario, SHc represents the area of habitat that is currently suitable, and SHo represents the area of suitable habitat common to both the present and the 2050s and 2070s[48,49].

Habitat fragmentation evaluation

Using the current distribution pattern of patches in the suitable habitat of snow leopard, we employed the landscape analysis software Fragstats v4.2[50] to calculate landscape indices reflecting the spatial utilization patterns of the snow leopard. Previous studies have successfully used similar landscape metrics to assess habitat fragmentation and connectivity for endangered species[51–53]. This study selected area metrics, including number of patches and largest patch index; edge metrics, including total edge and edge density; shape metrics, including area-weighted mean shape index, area-weighted mean fractal dimension index, and perimeter-area ratio; and aggregation metrics, including contagion, landscape division index and splitting index. These metrics have proven effective in examining the spatial distribution of suitable habitats and evaluating ecological connectivity for species[54,55].

Habitat connectivity analysis

The least-cost path (LCP) model and circuit model were employed to predict ecological corridors using the Linkage Mapper Toolkit in ArcGIS 10.5. Core habitat patches were defined as those with a suitable habitat area exceeding 500 km², based on the average home range of the snow leopard[56]. The inverse of the suitable habitat output from the BIOMOD2 model was utilized as a measure of movement resistance for the snow leopard. Using the core habitat patches and the resistance raster, LCP was calculated to map ecological corridors. Additionally, the Centrality Mapper modules within the Linkage Mapper Toolkit were employed to estimate centrality values.

Results

Model validation and environmental variables

The ROC average value was 0.972 and the TSS average value was 0.847 of ensemble model, indicating both high predictive accuracy and reliability for predicting the potential distribution of the snow leopard (Fig. S1).

The percent contribution of each environment variable ranked from highest to lowest was as follows (Fig. S2, S3): distance from water source (waterway, 58.02%), Isothermality (bio3, 17.7%), mean temperature of wettest quarter (bio8, 15.27%), elevation (dem, 12.22%), precipitation of driest quarter (bio17, 11.68%), net primary productivity (NPP, 10.47%), precipitation seasonality (bio15, 6.95%), human impact index (HII, 4.52%) and land cover (LUCC, 3.41%).

The suitable habitat and effect of climate change

Under the current climate conditions, the total area of suitable habitat for snow leopards is 68.62×10^4 km^2, accounting for 41.21% of the total study region, and suitable habitats were predominantly located in northern, central and southern Xinjiang (Table 1; Fig. 1). By the 2050s, the area of suitable habitat is projected to increase relative to current conditions, but this trend will vary among the three Shared Socioeconomic Pathways (SSPs). Under SSP126, the area of suitable habitat is expected to reach a maximum of 69.85×10^4 km^2, representing a 1.79% increase. For SSP370, the area of suitable habitat is projected to be 69.20×10^4 km^2, an increase of 0.84%. For SSP585, the projected area is 68.79×10^4 km^2, indicating a modest 0.25% increase. By the 2070s, the area of suitable habitat under SSP126 is anticipated to increase slightly to 68.82×10^4 km^2, indicating a 0.30% rise from current levels. In contrast, under SSP370 and SSP585 scenarios, the area of suitable habitat exhibits a declining trend, with SSP585 showing the most significant reduction and resulting in the smallest habitat area (66.26×10^4 km^2), a decrease of 3.43% (Table 1).

Coverage of protected areas

The results of the gap analysis reveal that existing protected areas currently protect 15.17% of suitable habitat, covering approximately 10.41×10^4 km^2, while 84.83% of suitable habitat remains outside protected areas. Although the area of suitable habitat protected is projected to slightly increase under various scenarios by the 2050s and 2070s, the protection gap remains exceeding 80% (Table 1).

Vulnerability assessment

The model predictions indicate that the percentage of current suitable habitat lost by the 2070s is higher compared to the 2050s across all scenarios. Additionally, with the exception of the SSP126 scenario, the percentage of increased suitable habitat area in the 2070s is greater under SSP370 and SSP585 than in the 2050s. Specifically, SSP585 shows the highest percentage of both current suitable habitats lost and increased suitable habitat area by the 2070s (Table 1).

To be specific, by the 2050s, the percentage of current suitable habitat lost under various scenarios is 8.95% for SSP126, 10.91% for SSP370, and 12.34% for SSP585, with the vulnerable habitats concentrated in the marginal areas of Altai Mountains and eastern Tianshan Mountains as well as northwestern Junggar Basin. The percentage of increased suitable habitat area is 10.55% for SSP126, 11.65% for SSP370, and 12.56% for SSP585, primarily located in the Kunlun Mountains. A certain area of current and future unchanged suitable habitat persists, totaling 62.48×10^4 km^2 under SSP126, 61.14×10^4 km^2 under SSP370, and 60.15×10^4 km^2 under SSP585. These areas may serve as climate refugia for snow leopards. By the 2070s, the percentage of current suitable habitat lost under the different scenarios is 9.89% for SSP126, 14.26% for SSP370, and 17.05% for SSP585. The percentage of increased suitable habitat area is projected to be 10.16% for SSP126, 13.82% for SSP370, and 14.10% for SSP585. The area of unchanged suitable habitat is expected to be 61.83×10^4 km^2 under SSP126, 58.83×10^4 km^2 under SSP370, and 56.92×10^4 km^2 under SSP585 (Table 1; Fig. 2).

Habitat landscape pattern

According to the calculation results of the landscape index (Table 2), the number of patches is 159, suggesting the distribution of suitable habitat is fragmented in space. The largest patch index is 36.81%, indicating that the largest single patch occupies a substantial proportion of the total area, which may provide crucial habitat core areas essential for population stability and ecological functions. Edge metrics reveal a total edge length of 43,429,465.85 m and an edge density of 0.27 m/ha, reflecting considerable edge complexity in the landscape, though the relatively low edge density suggests a more concentrated spatial distribution of suitable habitat. Shape metrics show an area-weighted mean shape index of 11.35, a perimeter-area ratio of 7.59, and an area-weighted mean fractal dimension of 1.17, indicating that while patch shapes are generally regular, there is still considerable boundary complexity. Aggregation metrics reveal contagion index of 35.34%, indicating low habitat

Period	Climate scenario	Total suitable area (× 10^4 km^2)	Loss area (× 10^4 km^2)	Gain area (× 10^4 km^2)	Unchanged area (× 10^4 km^2)	Percentage of suitable habitat area change (%, AC)	Percentage of current suitable habitat lost (%, SH_L)	Percentage of increased suitable habitat area (%, SH_I)	Coverage of protected areas (× 10^4 km^2)		Proportion of conservation gap (%)
									Suitable area	Unsuitable area	
Current		68.62							10.41	12.95	84.83%
2050s	SSP126	69.85	5.65	7.56	62.48	1.79	8.95	10.55	11.68	11.68	83.27%
	SSP370	69.20	6.99	8.30	61.14	0.84	10.91	11.65	12.04	11.32	82.61%
	SSP585	68.79	7.97	9.04	60.15	0.25	12.34	12.56	12.24	11.12	82.21%
2070s	SSP126	68.82	6.29	7.25	61.83	0.30	9.89	10.16	11.66	11.70	83.06%
	SSP370	68.27	9.29	9.92	58.83	-0.51	14.26	13.82	12.82	10.54	81.23%
	SSP585	66.26	11.20	9.85	56.92	-3.43	17.05	14.10	12.80	10.56	80.69%

Table 1. Predictions of the suitable habitat area and the proportion of conservation gap under different climate scenarios in the current period, 2050s and 2070s.

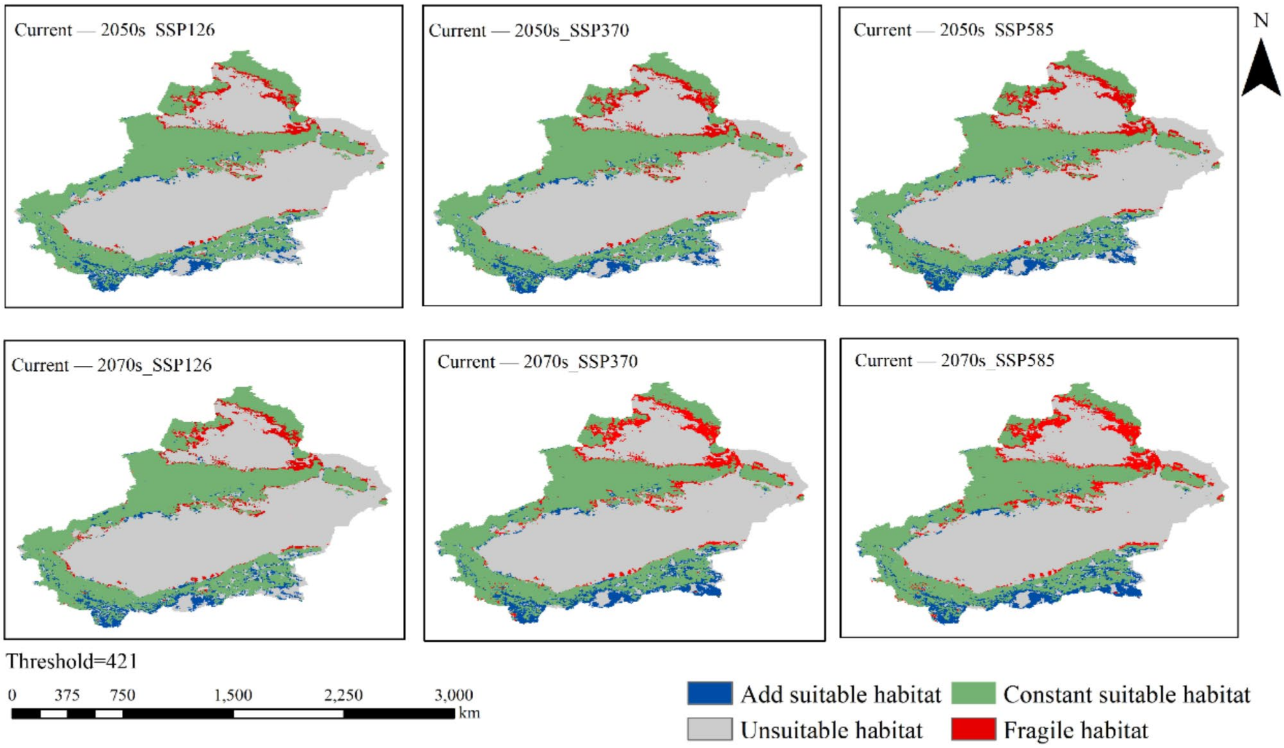

Fig. 2. Vulnerability assessment of snow leopard suitable habitat under climate change in Xinjiang Uygur Autonomous Region, China. SDMs were generated using R v4.2.2 (https://www.r-project.org) and the biomod2 package v3.5.1 (https://CRAN.R-project.org/package=biomod2). Maps were created using ArcGIS v10.5 (https://www.arcgis.com).

Landscape pattern metrics		Current suitable habitat
Area metrics	Number of patches	159
	Largest patch index (%)	36.81
Edge metrics	Total edge (m)	43429465.85
	Edge density (m/ha)	0.27
Shape metrics	Aea-weighted mean shape index,	11.35
	Aea-weighted mean fractal dimension index	1.17
	Perimeter-area ratio	7.59
Aggregation metrics	Contagion (%)	35.34
	Landscape division index	0.59
	Splitting index	2.47

Table 2. Landscape characteristics of current suitable habitat for snow Leopard.

connectivity, while the landscape division index of 0.59 and splitting index of 2.47 are relatively high, indicating significant fragmentation and patch isolation.

Habitat connectivity corridors

There are a total of 11 core patches, covering an area of 65.66×10^4 km^2, which constitutes 95.69% of the total suitable habitat area. The area of largest core patch (CH11) is 53.66×10^4 km^2, accounting for 81.72% of the total area of core patches (Fig. 3, Table S2). This largest core patch connects the Tian Shan, Kunlun and Karakorum ranges, with a centrality value of 53.04, and serves as a crucial habitat for the snow leopard. Following this is the core patch CH10 located in the Altai Mountains region, and the core patch CH9 in the northwest.

There are 7 connectivity corridors were identified between the core habitat patches based on the occurrence records of snow leopard (Table 3; Fig. 3). The average LCP for these corridors is 59.35 km (range 6.12–297.99 km), an average cost weighted distance (CWD) of 338.89 km (range 11.41–2018.69 km) and an average Euclidean distance (EucD) of 47.89 km (range 4.33 to 252.14 km). Among these, corridor L1 exhibits the lowest values for EucD (4.33 km), CWD (11.41 km) and LCP (6.12 km), while corridor L2 shows the highest values for EucD (252.14 km), CWD (2018.69 km), and LCP (297.99 km).

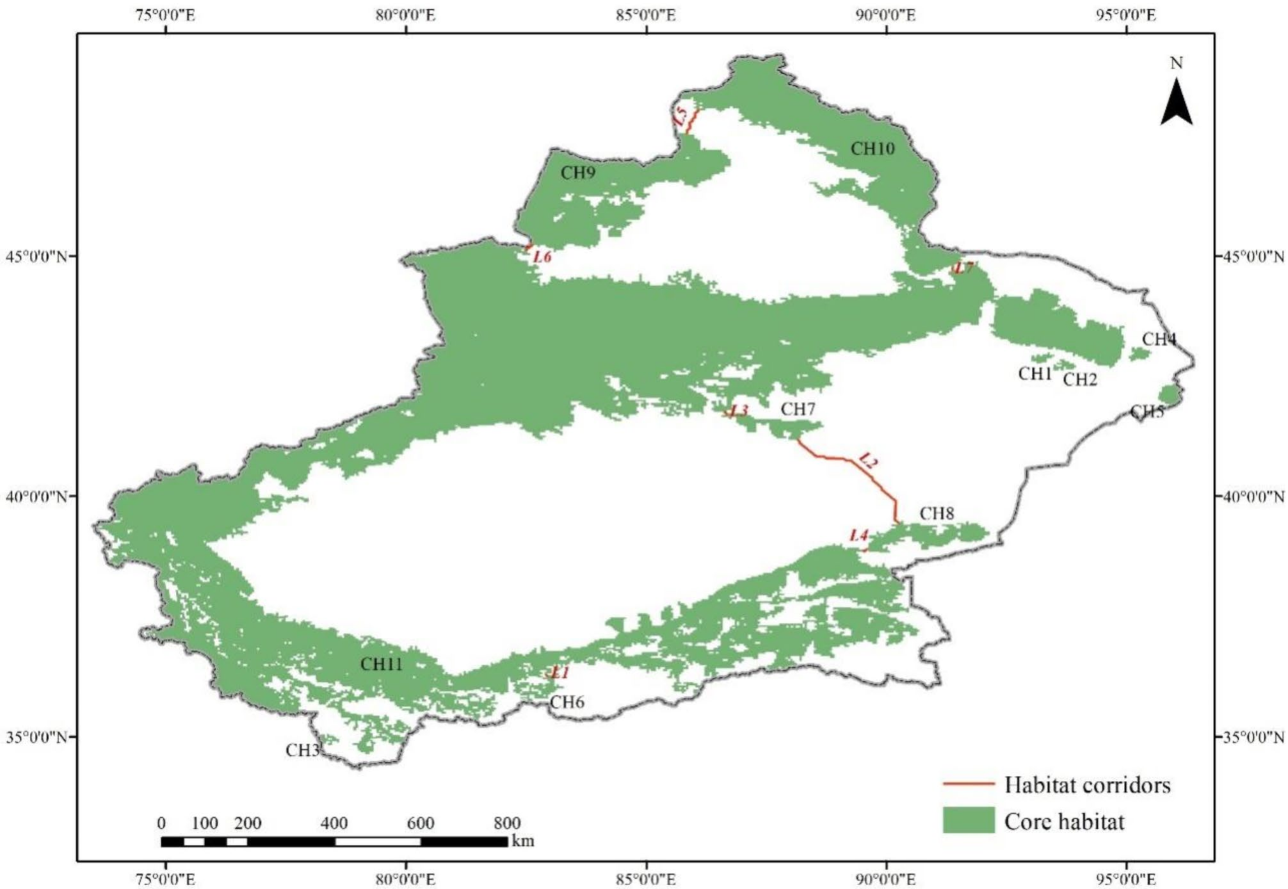

Fig. 3. Ecological corridors between snow leopard current suitable habitat patches in Xinjiang, China. SDMs were generated using R v4.2.2 (https://www.r-project.org) and the biomod2 package v3.5.1 (https://CRAN.R-project.org/package=biomod2). Maps were created using ArcGIS v10.5 (https://www.arcgis.com).

Habitat corridor ID	From patch	To patch	EucD (km)	CWD (km)	LCP (km)	CWD: EucD	CWD: LCP	CFC (Amps)
L1	CH6	CH11	4.33	11.41	6.12	2.64	1.86	10.00
L2	CH7	CH8	252.14	2018.69	297.99	8.01	6.77	0.25
L3	CH7	CH11	4.33	26.31	10.45	6.08	2.52	9.98
L4	CH8	CH11	4.33	26.47	10.45	6.12	2.53	9.97
L5	CH9	CH10	53.54	218.57	63.44	4.08	3.45	2.45
L6	CH9	CH11	12.24	50.33	18.36	4.11	2.74	8.83
L7	CH10	CH11	4.33	20.49	8.66	4.73	2.37	10.68

Table 3. Linkage characteristics of snow leopard current suitable habitat patches in Xinjiang, China. EucD, Euclidean distance, CWD, cost weighted distance, LCP, least-cost path length, CFC, current flow centrality.

The average centrality value for the 7 corridors is 7.45 (range 0.25–10.68). Among these, corridor L7 has the highest centrality, connecting the CH10 and CH11, that is linking the core habitat patches in the Altai, Tian Shan, and Kun Lun mountain ranges. Followed by corridor L1, which connects CH6 and CH11 patch. Both of these corridors have relatively low CWD/LCP values, indicating lower resistance to snow leopard movement within these corridors. In contrast, corridor L2 has the lowest centrality value, at 0.25, and high CWD/EucD and CWD/LCP ratios, suggesting that passage through corridor L8 is more challenging for snow leopards (Table 3; Fig. 3).

Discussion

The impact of climate change on snow leopard habitats has been explored in various regions[4,5,11,21,46,57], yet research specifically focusing on the Xinjiang region remains limited. Xinjiang is a critical habitat for snow leopards, and its geographical and climatic conditions render it particularly sensitive to climate change[29].

Therefore, understanding how climate change affects snow leopard habitats in Xinjiang is essential for developing effective conservation strategies. This study employs the BIOMOD2 model to assess the potential impacts of climate change on snow leopard habitats in Xinjiang. The results indicate that the distance from linear water sources is an important environmental factor in the distribution of snow leopards. The total area of currently suitable habitat for snow leopards is 68.62×10^4 km^2, accounting for 41.21% of the total study region. Under climate change scenarios, suitable habitats for snow leopards in Xinjiang exhibit a certain degree of fragmentation. Vulnerable habitats are primarily located in the marginal areas of the Altai and Tianshan mountains as well as the northwestern Junggar Basin. In contrast, regions projected to experience increases in suitable habitat in the future are mainly situated in the Kunlun Mountains. The average area of unchanged suitable habitat is approximately 60.23×10^4 km^2, which is anticipated to serve as refuges for snow leopards, offering essential shelter against future climate change. These findings provide critical evidence for formulating future conservation strategies and addressing the challenges posed by climate change.

Most studies have shown that environmental factors significantly influence the suitable habitat for species[58–60]. In this study, the variable of distance to linear water sources has a higher contribution percentage, which may indirectly affect habitat selection by influencing the distribution of prey. This supports the findings of Johansson et al.[60], who observed that snow leopards predominantly hunt in drainages. Consistent with the study by Xu et al.[58], it was found that prey availability and stream bed conditions are key factors determining snow leopard habitat use in the Tomur National Reserve of Xinjiang. Furthermore, environmental variables related to temperature and precipitation also show high significance, reinforcing the importance of climatic conditions in snow leopard habitat selection[59,61–63]. Variations in temperature and precipitation directly impact prey distribution and the availability of suitable habitats. For example, precipitation is a crucial determinant of suitable habitats for ungulate species[23]. In the Altai region of Mongolia, snow leopards prefer to inhabit steep south-western slopes at high elevations during winter[64]. The effect of elevation further indicates the specific habitat requirements of snow leopards in mountainous regions, particularly their ability to adapt to extreme climatic conditions. Research suggests that climate change is driving suitable habitats northward and upward, with new suitable areas emerging in higher latitudes[21,57,65]. Net primary productivity (NPP) highlights the importance of resource availability for snow leopard distribution. For example, the density of blue sheep correlates with higher plant diversity in Nepal[66]. Among other factors, the Human Impact Index (HII) and land cover (LUCC) effects are relatively minor. While these factors may influence snow leopard habitat selection in specific areas, their overall contribution to snow leopard distribution is limited. Therefore, we suggest prioritizing the protection of water sources and considering the impacts of climate change when formulating conservation policies for snow leopards in Xinjiang.

Numerous studies have demonstrated that snow leopard habitats exhibit significant vulnerability to climate change under various emission scenarios and across different geographic regions[5,21,46]. Our findings suggest that under the low-emission scenario (SSP126), suitable habitat for snow leopards in Xinjiang remains relatively stable or may even experience slight increases, likely due to the modest rise in global temperatures and its mitigating effects on high-elevation, cold climate environments. Conversely, under medium and high-emission scenarios (SSP370 and SSP585), significant temperature increases lead to a gradual reduction in suitable habitats, particularly under the high-emission scenario for the 2070s. The pronounced decline in suitable habitats indicates that climate warming could have severe negative impacts on snow leopard habitats, especially in the Himalayan region[5,11]. Forrest et al.[11] found that under high-emission scenarios, China would experience more extensive habitat loss than Nepal and Bhutan due to its larger habitat area. Similarly, Li et al.[46] observed that under moderate emission levels, the area of suitable habitats for snow leopards on the Tibetan Plateau is projected to shrink. In contrast to snow leopards, other large carnivores coexisting in the same range exhibit varied responses to climate change. For example, the common leopard, being a highly adaptable species, is expected to experience an increase in habitat suitability as climate change transforms unfavorable conditions into more favorable ones[67]. Wolves (*Canis lupus*), under the combined effects of climate change and land-use change, are projected to see an expansion in their habitat suitability and distribution range[68], with their high mobility aiding in adaptation to environmental changes[69]. However, brown bears (*Ursus arctos*) may face a more moderate habitat loss under low-emission scenarios, with potential new habitats forming at higher elevations. In contrast, under high-emission scenarios, their habitat suitability is almost entirely lost due to the lack of available uphill space for movement[70]. Similarly, Eurasian lynx (*Lynx lynx*), being dependent on cold climates, are unlikely to see any unsuitable habitats becoming suitable under future climate conditions, further constraining their distribution[71]. Additionally, climate change has been shown to contribute to an increasing intensity and spatial extent of livestock grazing pressure, as land suitability expands and optimal sowing seasons shift[72]. This intensifies competition between livestock and wild ungulate species, leading to negative responses from wild prey to the environmental degradation caused by grazing pressure, which impacts snow leopard populations. Further consequences of rising temperatures, including permafrost degradation and declining groundwater levels, promote the transition from meadows to grassland ecosystems, negatively affecting forage productivity[72,73]. These findings underscore the critical importance of mitigating climate change in the future, especially considering the drastic contraction of snow leopard habitats under high-emission scenarios. Global climate action will be vital for the conservation of snow leopards and their habitats.

Nature reserves play a crucial role in the survival of snow leopards and their prey. Xu et al.[13] demonstrated that the population density of snow leopards within nature reserves is significantly higher than the overall average density of this species across Xinjiang. Despite this higher density within reserves, existing studies indicate that the maximum habitat loss for snow leopards is predicted to occur outside protected areas, suggesting that current conservation areas are still insufficient in covering suitable habitats under climate change scenarios[5]. Our gap analysis results show that although the area of suitable habitat covered by protected areas is expected to increase in the 2050s and 2070s, over 80% of suitable habitats remain unprotected. Given the extensive range of snow leopard habitats and the significant impact of climate change, this considerable protection gap could have profound effects on ecosystem stability and biodiversity. Based on IUCN snow leopard distribution data and Protected Planet database, Alexander et al.[74] identified 138 nature reserves within the snow leopard range in China, including the Altun Mountain National Nature Reserve in Xinjiang, which is a key component of the largest reserve complex. Furthermore, Global Snow Leopard and Ecosystem Protection Program (GSLEP) in 2013 identified 23 snow leopard landscapes globally, with only three of these landscapes located in China, covering just 6% of the total area of all identified snow leopard landscapes. Two of these landscapes are located in Xinjiang, namely the Tashkurgan and Tomur Feng nature reserves. Li et al.[75] have shown that insufficient management capacity is one of the main threats to snow leopards in Xinjiang. To address this challenge, China is accelerating efforts to establish a system for protected areas with national parks as the mainstay and has completed the layout planning of potential zone such as the Kunlun Mountains, Tianshan Mountains, Altai Mountains, and the Karakoram-Pamir region in Xinjiang. This initiative aims to protect representative large-scale natural ecosystems, fill existing protection gaps, and provide essential support for the long-term survival of snow leopards and their prey.

The potential habitats of snow leopards in Xinjiang are primarily distributed across the Kunlun Mountains in the south, the Tianshan Mountains in the central region, the Altai Mountains in the north, and the Karakoram Mountains and Pamir Plateau in the west[14]. Among these, the Tianshan region is regarded as a critical refuge for snow leopards in Xinjiang, playing a significant role in their conservation[13,14]. Gong et al.[63] predicted that high-quality habitats for snow leopards in the central and eastern Tianshan are relatively continuous, extending in an east-west direction along the Tianshan range. Our model predictions indicate that vulnerable suitable habitats are primarily concentrated in the marginal areas of the Altai, eastern Tianshan, and the northwestern part of the Dzungarian Basin. Future climate change could further diminish these suitable habitats, which is closely associated with shifts in the treeline and the contraction of alpine zones[11]. In contrast, the Kunlun region shows an increasing trend in suitable habitats, suggesting that it may serve as an important ecological buffer under future climate scenarios. This is supported by Farrington and Li[76], who found that the mountainous areas north of the Kunlun Mountains (35°N) could become more favorable for snow leopards with rising temperatures and precipitation. Furthermore, model predictions indicate that most of the current suitable habitats will remain stable under future scenarios, suggesting that these areas could serve as important refuges for snow leopards and other species. Li et al.[21] found that stable steppes, such as those on the Tibetan Plateau, provide refuge for snow leopards and their primary prey[53]. While this study identifies several regions that could potentially become climate refugia, the increase in suitable habitats also highlights the possibilities for ecological adaptation under climate change. However, the proportion of suitable habitats covered by existing protected areas is still insufficient to address the threats posed by climate change. Future conservation strategies should prioritize the expansion into these high-risk, climate-sensitive areas, particularly under high emission scenarios where suitable habitats outside of protected areas are likely to face greater threats. To this end, it is suggested to enhance protections for vulnerable regions, and currently unprotected areas that could serve as climate refugia, thereby addressing the shortcomings of the existing conservation network.

Core habitats sustain viable populations, while corridors facilitate animal movement across landscapes, maintaining genetic flow and connectivity between populations on a regional scale[61]. Ensuring habitat connectivity is a crucial in combating climate change and safeguarding the long-term survival of snow leopards and their high-altitude prey species[72]. Effective corridor design is vital for the survival of snow leopards and their prey, as their habitats are often fragmented by both natural and human-made barriers[46]. Large-scale infrastructure projects, mineral exploration, and the construction of linear obstacles accelerate habitat fragmentation[72]. Our landscape index analysis reveals a high degree of habitat fragmentation, with the largest core patches (CH11) connecting the Tianshan and Kunlun Mountains, and CH10 in the Altai Mountains of China, identified as critical habitats for snow leopards. Based on an estimated average density of 1.7 snow leopards per 100 km^2, core patches CH10 and CH11 could potentially support approximately 1,000 and 9,100 snow leopards, respectively[21,77]. Corridor L7 supports snow leopard movement across the Altai-Tianshan-Kunlun landscape, while L6 facilitates movement between the Dzungarian Basin-Tianshan-Kunlun ranges. However, existing roads and railways, such as National Highway G331 and the Jiangnao railway, likely reduce corridor quality by increasing migration resistance between the Altai and Eastern Tianshan regions, while the Lanzhou-Xinjiang Railway and roads near Alashankou further increase migration resistance between the Western Tianshan and Dzungarian Basin. Additionally, Li et al.[38] found that railways and roads to Urumqi fragment the critical connectivity between the Altai Mountains and the Tianshan-Pamir-Hindu Kush-Karakoram landscape unit. The L2 corridor, connecting the Tianshan and Altun mountains, faces greater challenges due to complex terrain and human disturbance. Another major threat to Xinjiang's snow leopard population is the lack of transboundary cooperation. Xinjiang shares borders with several countries within the snow leopard's distribution range, offering the potential for continuous habitat across national borders[78]. One-third of the snow leopard's known or potential range is thought to be located along international boundaries, or within 50–100 km of them[53]. Compared to movement within their own distribution range, snow leopards are more inclined to traverse international borders[61]; however, barriers, such as fencing, contribute to population fragmentation[79]. Therefore, future conservation strategies should focus on effective planning and management of infrastructure development and strengthening transboundary cooperation. Enhancing the connectivity and suitability of ecological corridors, while continuing to protect core patches, will be crucial for the long-term survival of snow leopards.

Although this study provides valuable insights into the habitat distribution of snow leopards under climate change, several limitations remain. First, species distribution models typically rely on existing species occurrence data and climate data to predict future habitat changes. This study utilizes data based on snow leopard occurrence records in Xinjiang; however, the spatial scope of these data is limited and may not fully represent the true distribution of snow leopard habitats. Additionally, this study employs relatively mild climate models to predict habitat changes, and differences in model selection may yield varying results. Therefore, future research should incorporate multiple climate models to assess the extent and uncertainty of habitat changes under different scenarios. Second, this study simplifies certain interspecies interactions, such as the dynamic relationships between snow leopards and their prey, as well as with other predators or competitors. While these ecological interactions play a crucial role in habitat selection and population dynamics, the primary focus of this study was on the impact of climate change, and complex species interactions were not thoroughly explored. Future studies should take a broader ecosystem approach, exploring interspecies relationships and particularly the effects of prey populations and competitors on snow leopard habitat use. Furthermore, the predicted corridors in this study were based on suitable habitat data for snow leopards in Xinjiang. However, potential corridors located at the borders should be interpreted with caution, particularly regarding their connectivity with habitats in neighboring countries. This study underscores the significance of transboundary cooperation in the conservation of snow leopards in Xinjiang. Nonetheless, numerous challenges impede the implementation of transboundary conservation policies, including political barriers and unequal resource distribution. These challenges complicate the effective realization of conservation cooperation. Therefore, future research should further evaluate the implementation of existing transboundary conservation policies, explore more effective policy frameworks, and promote international collaboration to enhance regional snow leopard conservation initiatives.

Climate change poses a significant threat to snow leopard populations and their habitats. Rising temperatures and shifting precipitation patterns may lead to habitat fragmentation and changes in prey availability, impacting snow leopard survival. The Himalayas and the Tibetan Plateau, key snow leopard habitats, are particularly vulnerable to climate change. For instance, the upward shift of the treeline may increase habitat overlap between snow leopards and sympatric species such as the common leopard, exacerbating competition for space[80–82] and prey[6], disrupting ecological cascades and heightening human-wildlife conflicts[67]. Additionally, glaciers in snow leopard habitats are retreating at rates higher than the global average[11,83], reducing water availability for both snow leopards and their prey[84]. As freshwater resources become scarcer, snow leopards may be forced to expand their range into lower-altitude or human-dominated areas, further intensifying conflicts, particularly in regions where water sources are already limited and shared between wildlife and local communities. Addressing these challenges requires a globally integrated approach to snow leopard research and conservation. By synthesizing data from different regions, researchers can identify common threats and successful conservation practices, enabling the development of more targeted, region-specific management strategies while fostering international cooperation. Furthermore, studying sympatric species provides valuable ecological insights into interspecies interactions and resource competition, which can inform conservation strategies aimed at mitigating human-wildlife conflicts, maintaining ecosystem stability, and preserving biodiversity.

Conclusion

The study assessed the impact of climate change on suitable habitats for snow leopard in Xinjiang, evaluated the conservation effectiveness of existing protected area, and identified climate refugia and habitat corridor areas. The results indicate significant habitat fragmentation and low connectivity among habitat patches for snow leopards in Xinjiang. Under climate change scenarios, the area of suitable habitat remains relatively stable or even slightly increases under low emissions scenarios, while it progressively decreases under moderate and high emissions scenarios. Vulnerable habitats are primarily located in the Altai, the northwestern region of the Junggar Basin, and central areas of the Tianshan Mountains. In the future, areas with increased suitable habitat are projected in the Kunlun Mountains region. We suggest that future nature reserves be established in currently unprotected areas identified as climate refugia, strengthen long-term monitoring efforts, restore and enhance corridor connectivity and suitability, assess and improve existing border isolation facilities, and promote cross-border cooperation. These findings provide valuable insights for addressing the challenges posed by climate pressures on the future distribution of snow leopards in Xinjiang and for advancing the development of the snow leopard network in China.

Data availability

The datasets generated for this study are available upon request to the corresponding author.

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YZ, DL, JL and WC conceived the ideas. All authors contributed to the data collection. WC analysed the data and wrote manuscript. YZ and DL reviewed and edited the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

Additional information

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